

# Analysis and Synthesis of Smart Wires in an Electric Power System

A Thesis

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## **Dedication**

*To my parents who offered support, guidance, and encouragement.*

## **Abstract**

When electric current overloading on the power system occurs, utilities often rely on traditional methods such as line upgrades or other system improvements for mitigation. Traditional methods often require major capital investment, multi-year lead times, and a fixed project scope. Operating conditions can often change with less than a year notice, particularly in today's current regulatory environment.

Smart Wires offers a flexible approach to mitigate line overload conditions and congestion by means of changing the reactive impedance, granting the ability to transform the energy grid into a dynamically controlled system better positioned to deal with intermittent resources. This thesis addresses a problem shown in a power flow study that reveals overload conditions due to changes in power generation. This research presents a Smart Wires solution as an effective means to mitigate the overload conditions. Smart Wires offers three products: PowerLine Guardian, Power Guardian, and Smart Valve. The Smart Valve is the best option as a solution for the problem statement when considering weight and number of devices.

In order to ensure successful implementation of this technology, it needs to be tested and simulated properly. Automation is used in order to determine how many power flow control devices are needed and to consider the longevity of the solution. Longevity is primarily influenced by load growth, and graphical evidence is given for a solution lasting up to 20 years. This thesis addresses the challenges that can arise from a transmission line whose reactive impedance varies depending on settings. Finally, the problem of time scale analysis and synthesis of the transmission line, with and without Smart Wires, is addressed.

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## **Abbreviations**

ACCC – AC Contingency Calculation

D-FACTS – Distributed FACTS

DSR – Distributed Series Reactor

FACTS – Flexible Alternating Current Transmission System

IEEE – Institute of Electrical and Electronics Engineers

LQR – Linear Quadratic Regulator

PSSE – Power System Simulator for Engineering

PG – Power Guardian

RAS – Remedial Action Scheme

RDTR – Real-time Dynamic Thermal Rating

SSSR – Static Synchronous Series Compensator-type

STATCOM – Static Synchronous Compensator

# Chapter 1

## Background and Scope of Research

### 1.1 Introduction

Equipment deployed on the electric power grid has changed very little over the past half century, and the rigidity of traditional hardware offers little room for adaptation. The world continues to create challenges for the industry, and the industry needs to grow and adapt to address those challenges. Carbon emissions should be cut back in order to address environmental concerns. Additionally, fossil fuels are finite resources that are becoming more and more difficult to extract. Environmental and economic factors are drivers for rapid adoption of renewable energy. However, uncertainty of grid reliability grows as renewable resources start to dominate the industry's generation. Fossil fuel is a dependable baseload that offers operational control and flexibility, while intermittent resources such as wind power and solar power are at the mercy of nature. Hydroelectric generation is renewable and can serve as a baseload, but isn't always available. Power utilities often invest in wind and solar farms that are hundreds of miles away from the intended load – this can be a problem due to the likelihood that the existing grid was built under the assumption of centralized generation. Reliability cannot be sacrificed as billions of people and the wealth of nations that collectively depend on an affordable and reliable supply of electricity. Technology will push the industry towards a cleaner, more flexible and reliable transmission grid.

This thesis focuses on Overhead Power Transmission lines owned by an investor owned utility in northern Minnesota. More specifically, this research will analyze certain contingencies that are likely to occur on the utility's system and will attempt to plan accordingly for any consequential overloading.

System overloading is a common problem in the power industry. Knowing the ampacity, resistance, inductance, capacitance, conductance, and length of a transmission line is

essential in modeling the equivalent circuit of a single transmission line. In order to develop an accurate model of the system as a whole, it is necessary to also consider capacitor banks, motors, generators, protective devices, and historical event and loading data. Simulation programs such as PSSE (Power System Simulator for Engineering – Siemens) and PowerWorld offer a convenient method of predicting problems before they occur and make it possible for the utility to plan accordingly. It is important for the utility to make the necessary upgrades in order to mitigate any problems that are identified by the simulation program.

Overhead transmission lines are operated based on static ampacity ratings which are determined using steady-state heat balance equations. These equations are specified in the national standard defined by the Institute of Electrical and Electronics Engineers (IEEE). Guidelines for calculating the current-temperature relationship of bare overhead line conductors are provided in the IEEE Standard 738 [1]. The IEEE standard assumes that electrical current, conductor temperature, and weather conditions remain constant. The power utility does not operate at their potential transmission capacity, and instead is limited to “near” worst case scenarios and pre-load conditions. All transmission line planning must use the IEEE Standard 738 as guidance when mitigating overload conditions on transmission lines.

Some of the more common methods to mitigate system overload conditions are to make upgrades to the transmission lines, rerouting, or Remedial Action Schemes. Recently, Smart Wires Inc. [2] has offered an alternative solution to mitigate system contingencies by means of rerouting the power flow. The PowerLine Guardian, Power Guardian, Power Router, and Smart Valve are technologies offered by Smart Wires that allow an electric utility to add or subtract impedance from the transmission line that would reroute the current and mitigate overload conditions and congestion [3].

## **1.2 Problem Statement**

A simulation of the system projected for the year 2020 demonstrates a potentially vulnerable system. In particular, one transmission line will be impacted the most. Figure

1.1 and Figure 1.2 shown below demonstrate how the system is impacted – Figure 1 shows the intact system before any outages and Figure 1.2 shows the system after simultaneous outages that result in Line 1-2 overload conditions.

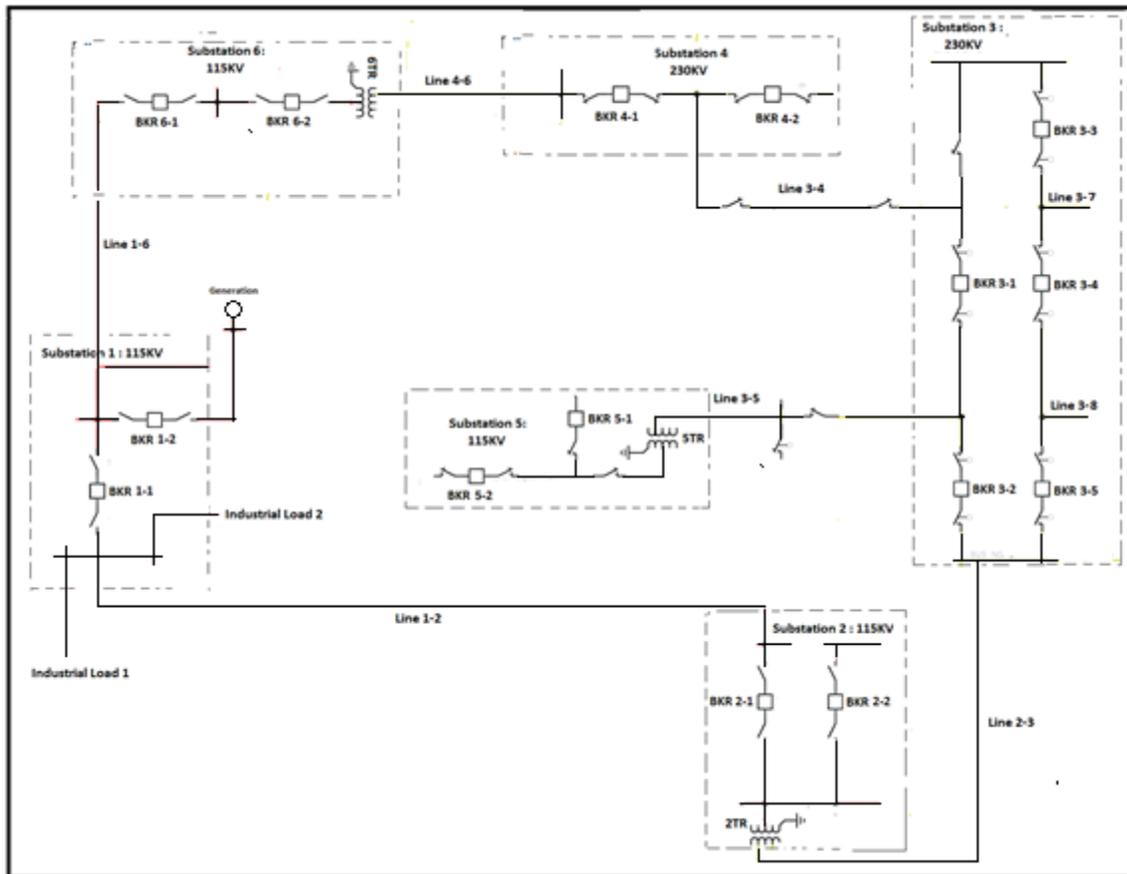


Figure 1.1: System Intact – No Outages

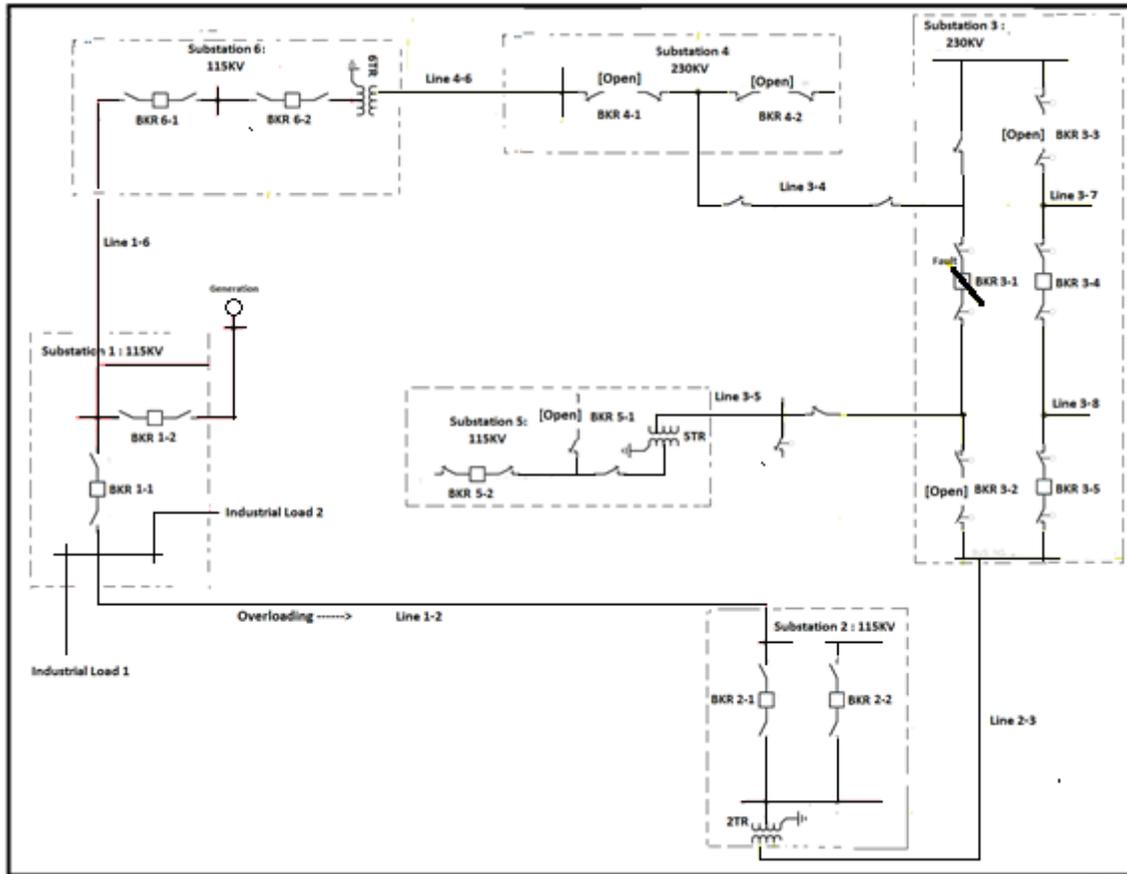


Figure 1.2: Fault on BKR 3-1 - System Overloading

In the event of an internal fault on BKR 3-1, the following breakers would open in order to isolate the fault from the rest of the system: BKR 3-2, BKR 3-3, BKR 4-1, BKR 4-2, BKR 5-1, BKR 5-2. Opening BKR 4-1 and BKR 4-2 results in the opening of Line 3-4 – removing a path from Substation 1 to Substation 3. During this contingency, the only direct path between Substation 1 and Substation 3 is Line 1-2. Line 1-2 is 4/0 copper, has a capacity of 55 MVA or 276 amps, and is 67.8 miles long. According to simulations, Line 1-2 will have overloading of 142.9 % rated power. This research will determine if Smart Wires technology is capable of reducing the loading on the line to below 100% rated power in the event of an internal fault on BKR 3-1.

Table 1.1 below demonstrates the amount of overloading on Line1-2 given the following different scenarios:

Industrial Load 1 OFF, Industrial Load 2 OFF

Industrial Load 1 OFF, Industrial Load 2 ON

Industrial Load 1 ON, Industrial Load 2 OFF

Industrial Load 1 ON, Industrial Load 2 ON

Loads ON/OFF	Load (MVA)	Rating (MVA)	% Loading
Indust. Load 1 OFF, Indust. Load 2 OFF	78.6	55	142.91
Indust. Load 1 OFF, Indust. Load 2 ON	75.9	55	138.00
Indust. Load 1 ON, Indust. Load 2 OFF	75.9	55	138.00
Indust. Load 1 ON, Indust. Load 2 ON	73.1	55	132.91

**Table 1.1: Overloading Given Different Industrial Load**

Additionally, this research will introduce a dynamic model that represents both thermal and electrical dynamics of the transmission line. The dynamic model will be used to design a controller for mitigating transients on the transmission line in the event of line faults. The dynamic model and the controller will also consider the impact that Smart Wires technology will have on the system. Since Smart Wires technology increases or decreases the reactive impedance of the transmission line, the methods to develop the model and the controller must consider the impact of having increased inductance or capacitance.

### **1.3 Scope of Research**

- 1) To investigate the technology that Smart Wires has developed and to compare it to other available solutions to determine if Smart Wires is the most efficient and cost effective means to mitigate the contingencies.
- 2) Real time analysis - Are these devices helpful and/or do they solve some problems on the grid, but create other issues? Can injecting too much impedance onto the line result in undesirable outcomes such as higher losses and lower efficiency?
- 3) How best to alternate usage between the devices to ensure equal usage of each Smart Wires device.

- 4) To develop a dynamic model and controller for a transmission line that implements Smart Wires technology.

## 1.4 Chapter Outline

This research is organized as follows:

Chapter 2 presents the power systems background necessary for understanding substation configurations, fault analysis, transmission line models, and simulation software. In order to predict and plan for line outages and system overload conditions, it is necessary to understand the different configurations that buses and breakers can be arranged. The way a substation is configured determines which breakers operate in order to isolate the compromised equipment. Specifically, this chapter discusses the configuration demonstrated by Figure 1 in Section 1.2. Transmission line models are built into simulation software, but conceptual knowledge is necessary when analyzing contingencies and for mitigation planning in the event of overload conditions.

Chapter 3 introduces Smart Wires technology. This chapter encompasses all of the available solutions that Smart Wires has to offer. Each solution has the same technical effect on a transmission line: changing the reactive impedance of a transmission line(s) in an effort to influence the power flow on the overall system. Background knowledge of transmission line models is beneficial in understanding how and why this technology works.

Chapter 4 discusses Singular Perturbation and Time Scales (SPaTS). Methods for identifying and decoupling slow and fast subsystems are examined. These subsystems are used for Time Scale Synthesis which defines control laws capable of real-time implementation. These theories are used to form a model, state feedback, and optimal control for mitigating transients on a transmission line. The dynamics require a separate controller for the slow and fast subsystems. MATLAB is used as a tool to compare the

full order optimal controller to a control system that decouples the subsystems and uses two controllers in parallel.

Chapter 5 summarizes the results of this research and indicates the goals of future work.

## **Chapter 2**

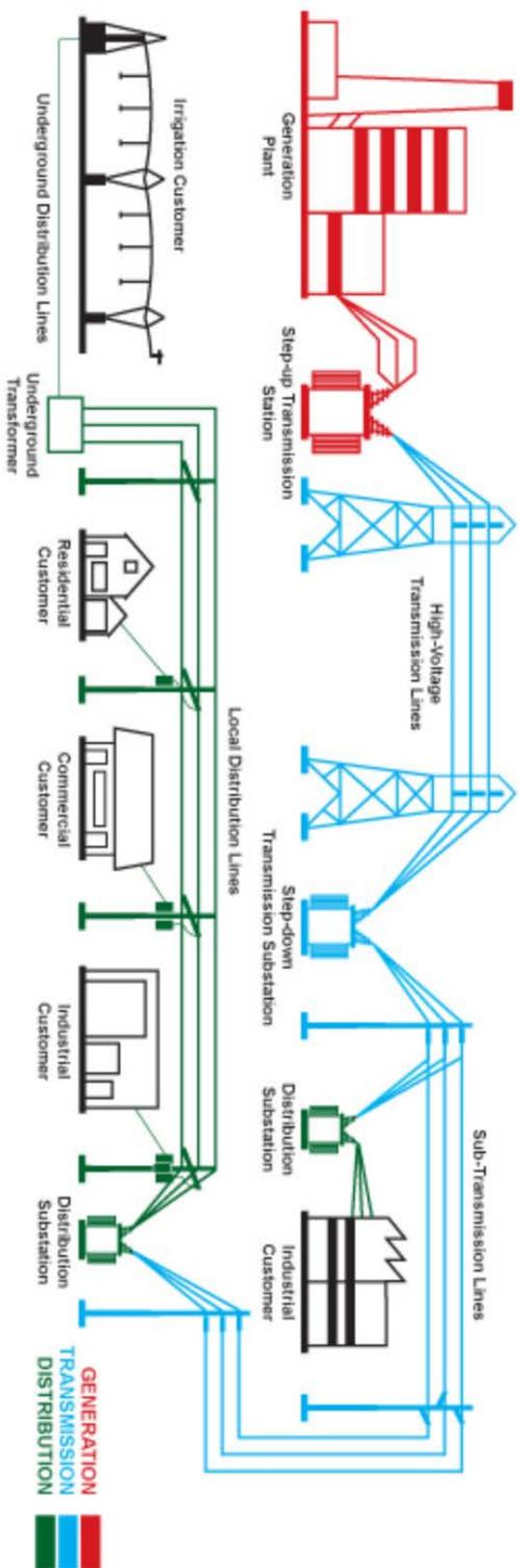
### **Power System Analysis**

This chapter presents the power systems background necessary for understanding substation configurations, fault analysis, transmission line models, and simulation software. Conceptual knowledge is necessary when analyzing contingencies and for mitigation planning in the event of overload conditions.

#### **2.1 From Power Generation to the Customer**

An electric utility uses overhead and underground transmission lines to provide its customers with reliable, uninterrupted electricity. Transmission lines can either be high voltage (69-765 kV) or local distribution (4-69 kV). Figure 2.1 from reference [4] demonstrates the dynamics of a power system. This thesis focuses primarily on overload conditions of high voltage overhead transmission lines.

# Power Supply From Generation to End-Use Customer



**Figure 21: Electric Power System [3]**

## **2.2 Subsystem Configuration**

This section defines six types of breaker arrangements that are commonly used in power system substations [5]:

1. Single Bus
2. Double Bus – Double Breaker
3. Main and Transfer (Inspection) Bus
4. Double Bus – Single Breaker
5. Ring Bus
6. Breaker – and – a – Half

### Single Bus Arrangement:

The single bus arrangement is the simplest configuration – a single bus is used for all transmission lines and transformers. This is the lowest cost configuration and also the least complicated to operate. One breaker switches one element – either a line or a transformer. Reliability is sacrificed for simplicity and low cost in a single bus arrangement. A significant portion of the substation will need to be de-energized for any required maintenance. A bus fault will result in a complete substation outage.

### Double Bus – Double Breaker:

The double bus – double breaker arrangement is often considered to be the most reliable, although more components increases the probability that one component will fail. One breaker out of service will not have an impact on the system because each incoming and outgoing circuit is fed by two breakers.

Cost and available space in the substation are significant factors in determining the practicality of a double bus – double breaker arrangement. A high degree of reliability and minimum interruption time are incentives for allocating more land and a larger budget for this configuration.

### Main and Transfer (Inspection) Bus:

The main and transfer bus allows restoration of service after an outage by connecting all circuits between the main bus and transfer bus. Failure of a bus section or breaker will cause a complete outage similar to the single bus scheme. This configuration is convenient for maintenance – selective switching can be used to avoid interruptions.

#### Double Bus – Single Breaker:

The double bus – single breaker arrangement has two buses with a tie breaker in between, and each circuit connects to both buses. When the tie breaker is operated normally closed, the switches allow any circuit to be supplied from either bus. When the tie breaker is operated normally open, the configuration is changed to a two single bus arrangement and the advantages of the system are eliminated.

System protection is more complicated for this arrangement with the flexibility of transferring each circuit to either bus. A bus tie breaker failure will cause an outage of the entire substation. Bus maintenance can be completed without interruption, but maintenance on the line circuit breakers will require additional switching and outages.

#### Ring Bus:

The ring bus arrangement is slightly more expensive than the single bus configuration, but has increased reliability and is more complicated to operate. An outage of one line or transformer can be isolated without loss of others.

The disadvantage of this arrangement is that the isolation of one element results in the entire current being carried by the elements remaining in service. Failure of a second circuit may split the ring into two separate buses. Additionally, as the number of incoming and the number of outgoing circuits become disparate, the reliability and benefits are further reduced.

If two source circuits are adjacent to each other, multiple outages could result in the elimination of all sources to the substation. To avoid this issue, a load circuit should always be next to a source circuit.

#### Breaker – and – a – Half:

In this scheme, all switching can be done with circuit breakers in order to isolate faults or to complete maintenance. The scheme is configured such that there are one – and – a – half breakers per circuit; there are two buses with each circuit being between two breakers in a three breaker line-up. As opposed to a ring bus, this arrangement does not cause a significant load increase on other elements in the event of one breaker outage. This arrangement increases flexibility and reliability, but can be complex due to the additional devices. This configuration is often the next development stage of a ring bus arrangement.

In Figure 1.1 shown in Chapter 1, Substation 3: 230kV is a ring bus configuration.

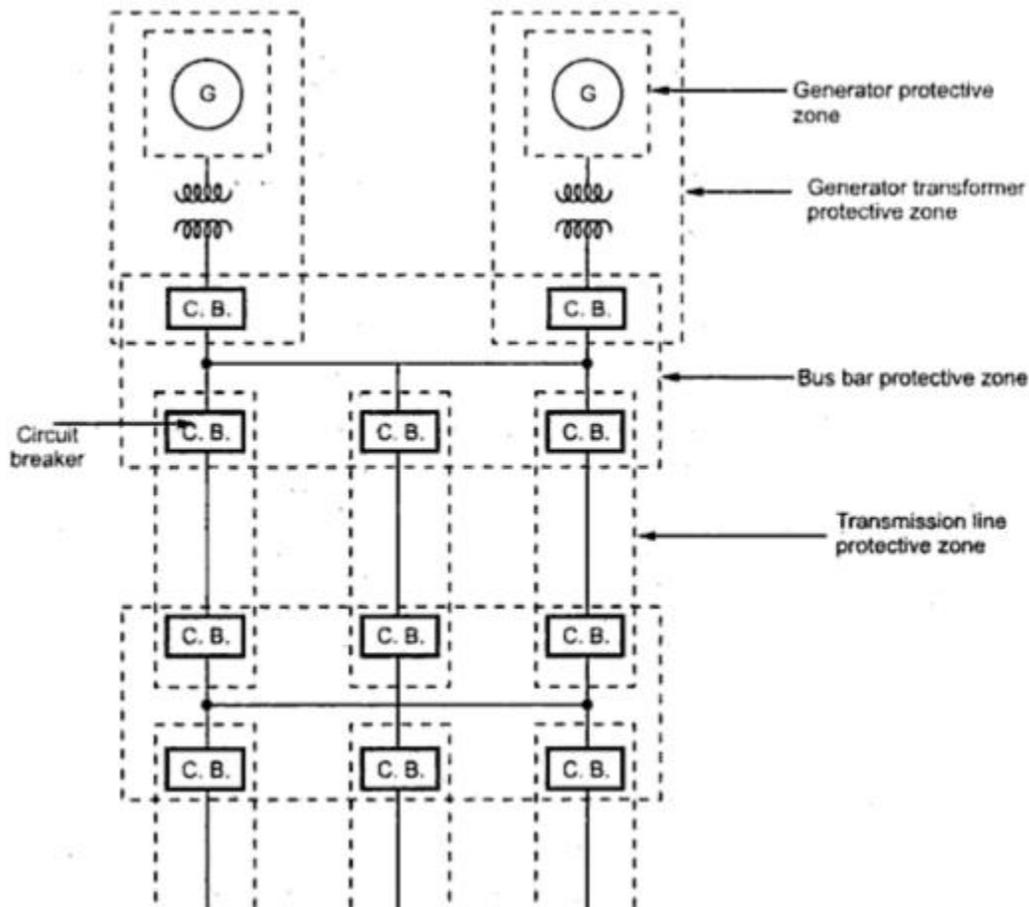
### **2.3 Fault Analysis**

Concerns for health, safety, and the functionality of equipment makes system protection a crucial component of power system studies, Fault currents on a power system would likely exceed the current ratings of surrounding equipment by significant margins. It is important to isolate the fault location to prevent catastrophic damage [6].

A fault occurs when a short circuit exists either between phases, or between phases and earth, or both. Faults are often the result of cable or transmission line insulation failure from a sudden overvoltage condition or from overstressing and degradation of the electrical insulation over time. A fault might also occur as the result of an open circuit [7].

The short circuits may be one-phase to earth, phase to phase, two-phase to earth, three-phase clear earth, or three-phase to earth. Three-phase faults are balanced, but all other types of faults are unbalanced. Lightning is a major contributor to system faults. If a tree falls on one phase of the transmission line, causing the conductor to make contact with ground, a one-phase fault occurs. If the conductor breaks and makes contact with earth as a result, there is a short circuit fault and an open circuit fault simultaneously. A small animal resting on top of substation equipment might inadvertently create a short circuit between two phases, causing a phase to phase fault [8].

Relays and circuit breakers prevent or limit damage during faults or overloads. Ideally, damage to equipment will be minimal, and at the very least the remainder of the system will remain intact. The system is divided into protective zones with each zone having protective relays that monitor for fault conditions [9]. The diagram shown in Figure 2.2 from reference [10] demonstrates the different zone protections in a power system.



**Figure 2.2: Protective Zones in Power Systems [10]**

Relays should operate within 3 or 4 cycles, and backup protection trips on a time delay. In a high-speed impedance relay, the impedance elements  $Z_1$ ,  $Z_2$ ,  $Z_3$ , and  $Z_4$  are set for different distances away from the relay. The  $Z_1$  element is set for the closest distance,  $Z_2$  is set a farther distance,  $Z_4$  is set the same distance as  $Z_2$  with a time delay, and  $Z_3$  is

used to block faults in the reverse direction [9]. The process for correctly setting the relays according to their perspective protective zones is called relay coordination.

A relay should only trip when there is a fault in its protection zone, and it should not trip when a fault is outside of that zone unless if on a time delay. A time delay on a relay is specifically intended to give the relay protection within the proper zone enough time to trip. System reliability and performance increases with demand, making it critical that protection equipment isolates a minimal portion of the system during fault conditions [11]. It is considered a misoperation if a relay overreaches its protective zone and trips in the absence of a fault or for a fault that is not within its protective zone. The North American Electric Reliability Corporation (NERC) requires that all relay operations be reported and that the cause of a misoperations be identified and corrected in its Standard PRC-004-5 [12].

In Figure 1.2 described in Section 1.2, an internal fault on BKR 3-1 forces BKR 3-2, BKR 3-3, BKR 4-1, BKR 4-2, BKR 5-1, and BKR 5-2 to open. Opening BKR 4-1 and BKR 4-2 results in the opening of Line 3-4 – removing a path from Substation 1 to Substation 3. The contingency illustrated in Figure 1.2 underscores the necessity for simulation software for both transmission planning and system protection. Knowing how the system will react to faults makes it possible to prepare for such conditions should they arise.

Relay engineers primarily use ASPEN One-Liner for short circuit studies and relay coordination. The simulation software enables an engineer to immediately see the impact when relay settings are changed and the network configuration is modified. The software also features relay curves, operation times, model equivalences, and more [13].

## **2.4 Transmission Line Models**

The main parameters that define the behavior of voltage,  $V$ , and current,  $I$ , signals as they travel via transmission line models are resistance  $R$ , inductance  $L$ , capacitance  $C$  and conductance  $G$ . Resistance and inductance define the series impedance,  $Z$ . Capacitance,

and conductance characterize the shunt admittance,  $Y$  [14]. Losses are negligible for short lines and therefore are not often represented in the transmission line model [15].

Transmission line models are classified based on the length of the lines:

Short line:  $0 < \text{length} < 80 \text{ km}$  ( $0 < 50 \text{ miles}$ )

Medium line:  $80 \text{ km} < \text{length} < 250 \text{ km}$  ( $50 \text{ miles} < \text{length} < 155 \text{ miles}$ )

Long lines:  $\text{length} > 250 \text{ km}$  ( $\text{length} > 155 \text{ miles}$ )

Electric power utilities include all parameters for medium to long transmission lines in power system models such as PSSE and ASPEN One-Liner. The transmission line described in the problem statement certainly requires consideration of all parameters. However, to gain a better understanding of how Smart Wires impacts a transmission line, let us consider the equivalent circuit of a short line as shown in Figure 2.4 from reference [15].

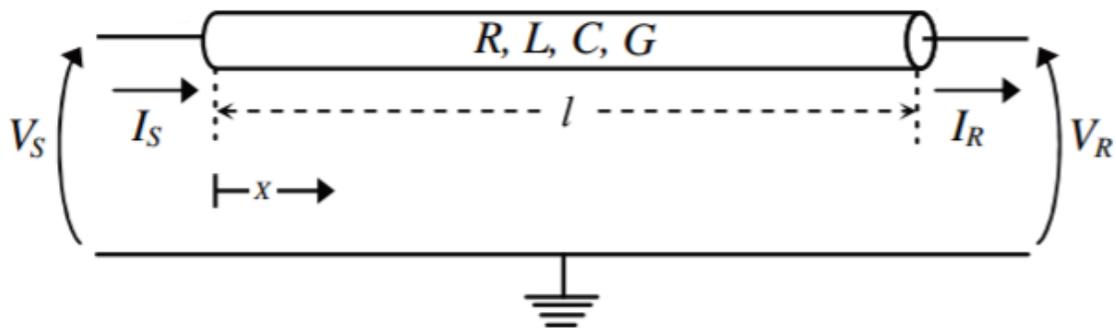


Figure 2.3: General Representation of a Transmission Line [15]

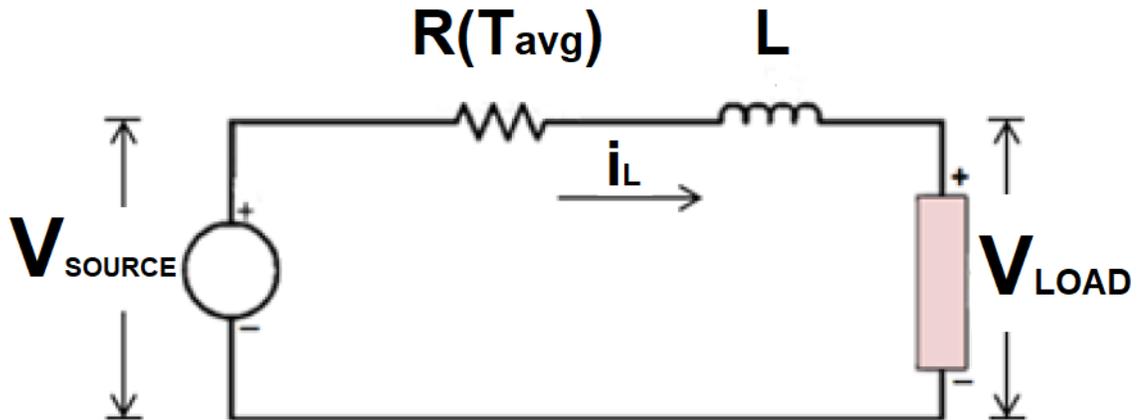


Figure 2.4: Equivalent Circuit of a Short Line [15]

The technologies offered by Smart Wires allow an electric utility to add or subtract reactive impedance from the transmission line in order to reroute the current and mitigate overload conditions and congestion [2]. When Smart Wires devices are introduced into the system, the equivalent circuit of the transmission line becomes as shown in Figure 2.5.

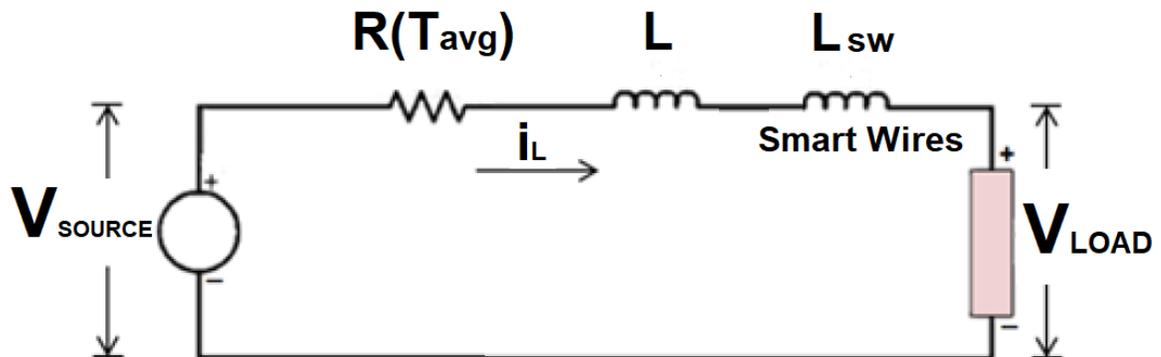


Figure 2.5: Equivalent Circuit of a Short Line with Smart Wires [15]

The inductance of the transmission line with Smart Wires implemented is the following:

$$L_{eq} = L + L_{sw} \quad (2.1)$$

$L_{sw}$  is zero if there are no Smart Wires devices injecting inductance onto the line.

The equivalent circuit makes it possible to create a system of equations to represent a transmission line. Kirchhoff's voltage and current laws define the line current dynamics, and the temperature dynamics are represented using the heat balance equation specified by the IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors.

The system of equations is shown:

$$\frac{di_L(t)}{dt} = -i_L(t) * \frac{R(T_{avg})}{L_{eq}} - i_L(t) * \frac{R_{load}}{L_{eq}} + \frac{V_{source}}{L_{eq}} \quad (2.2)$$

$$\frac{dT_{avg}(t)}{dt} = \frac{1}{mC_p} * (R(T_{avg})i_L^2(t) + q_s - q_c - q_r) \quad (2.3)$$

$i_L(t)$  is the line current,  $T_{avg}(t)$  is the average line temperature,  $q_s$  is solar heat gain,  $q_c$  is convection heat loss,  $q_r$  is radiation heat loss, and  $m$  is mass per unit length of the conductor.

Equation 2.4 represents how resistivity changes with temperature. [16]

$$R_T(T) = R_0[1 + \alpha(T-T_0)] \quad (2.4)$$

Resistivity increases nonlinearly as temperature rises, but can be considered linear if the temperature is within  $-40^\circ\text{C}$  to  $75^\circ\text{C}$  [17]. Depending on conductor type, many transmission lines have a  $100^\circ\text{C}$  operating temperature. The 4/0 copper described in the problem statement has a thermal rating of  $50^\circ\text{C}$  and can be upgraded, but only to  $75^\circ\text{C}$  [18].

## 2.5 Transmission Planning Tools

Transmission planning engineers use analysis tools such as PSSE to forecast contingency analysis, transient stability, voltage stability, power flow, short circuit, optimal power flow, and dynamics. PSSE is one of the leading transmission system tools in the world, and is considered the "industry standard" [19].

Vast automation and customization is possible through PSSE's Python-based APIs. Engineers utilize automation files to analyze the impacts of new generation, load growth, new industry, and other projects. A Python script allows an engineer to read in power flow, calculate a predicted load growth over time, and apply the predicted load growth to a base model of the system.

A single script can apply multiple different conditions to a model at the same time, allowing a base model to be modified and used without needing to save the model itself. These techniques are used in this thesis to determine how many Smart Wires devices are needed, to estimate the impact that the devices have on the transmission system, and to account for load growth in order to determine the longevity of the Smart Wires solution.

AC Contingency Calculation (ACCC) is a useful tool within PSSE that can be used to determine the contingencies that cause overload conditions and voltage violations. ACCC is also used to evaluate the performance of transmission planning solutions. When ACCC is run before mitigation of overload conditions is implemented, all power flow problems will be identified. When ACCC is used after overload mitigation is implemented, the analysis should demonstrate that the line is no longer overloading, and that the solution does not create additional problems, such as voltage violations and overload conditions, elsewhere on the system.

## **2.6 Chapter Conclusions**

This chapter provided the power systems background necessary in power systems to understand substation configurations, fault analysis, transmission line models, and simulation software. Conceptual knowledge is necessary when analyzing contingencies and for mitigation planning in the event of overload conditions.

## Chapter 3

### A Comparison of Traditional Methods and Smart Wires

This chapter examines several solutions to mitigate overload conditions, but focuses primarily on the efficiency, reliability, economics, longevity, and implementation of a Smart Wires solution. Background knowledge of transmission line models is beneficial for understanding how and why these solutions work. This chapter compares the traditional solutions against the technology offered by Smart Wires.

#### 3.1 Traditional Solutions for Overloading

##### **Line Upgrades:**

A common method to mitigate congestion and overload conditions of the transmission line is to increase the current capacity of the transmission line. Increasing the operating temperature of the line by upgrading the substation equipment or decreasing the sag of the transmission line are inexpensive methods of increasing current capacity on the line [20].

If the maximum temperature threshold cannot be increased, then increased capacity can only be achieved by upgrading to a conductor with a higher current capacity – this method is known as reconductoring. This method can be expensive and would require many hours of labor and outages. However, this method could serve as a long-term solution and would certainly be an effective method to mitigate the contingencies. The transmission line specified in the problem statement is of a length that makes upgrading the conductor uneconomical and impractical.

##### **Normal Open Transmission Line:**

Another possible solution is to normal open the transmission line. The normal open would only be required during the season overload conditions, and would redirect all of the current flow. Additional simulations are needed to ensure that the solution does not result in overload conditions or instability elsewhere on the system. The utility should use ACCC in PSSE to analyze the performance of the system with a normal open

transmission line. The ACCC report of the normal open solution should then be compared to the ACCC report before any solution was implemented; in doing this, it will be easy to determine if the solution has any negative consequences.

A normal open can have a negative effect on grid reliability, and the utility should take measures to limit customer outages. If transmission lines are opened due to maintenance or faults, the system would no longer be able to rely on Line 1-2 to service customers. The utility should prepare for unexpected conditions and ensure its customers have uninterrupted, reliable power. A normal open will also increase system losses, creating additional cost.

### **3.2 An Overview of a Smart Wires Solution**

Reconductoring is often expensive, and is a permanent solution. A permanent solution might not be needed if the system changes over time. Renewable energy is on the rise, and in March, 2017, 10 percent of all electricity generation in the U.S. was from wind and solar [21]. Utilities across the United States are shutting down coal plants [22], and are considering storage resources to “supplement and, in some cases, completely replace gas” [23]. Power utilities are changing the source of fuel and the location of generation, meaning that problems that exist today may or may not exist tomorrow.

Recently, Smart Wires Inc. [2] has offered an alternative solution to mitigate system contingencies by means of rerouting the power flow. Smart Wires argues that power flow control increases flexibility and decreases costs [24]. The method is known as Flexible Alternating Current Transmission System (FACTS), and for around two decades has been deployed on long, EHV transmission lines [25]. The method enables an electric utility to add or subtract impedance from the transmission line, rerouting the current and in order to mitigate overloading and congestion [3].

FACTS uses power electronics to control a series capacitor in parallel with a thyristor controlled reactor as demonstrated in Figure 3.1. In the early 2000s, Professor Deepak Divan introduced Distributed FACTS (D-FACTS) which uses modular controllers to provide the same effect as FACTS. The Distributed Series Reactor (DSR) uses D-FACTS

to increase line impedance. The DSR was the first D-FACTS device available on the market [25]. The first model of the DSR was the PowerLine Guardian and was installed concentrically around the transmission line as demonstrated in Figure 3.2.

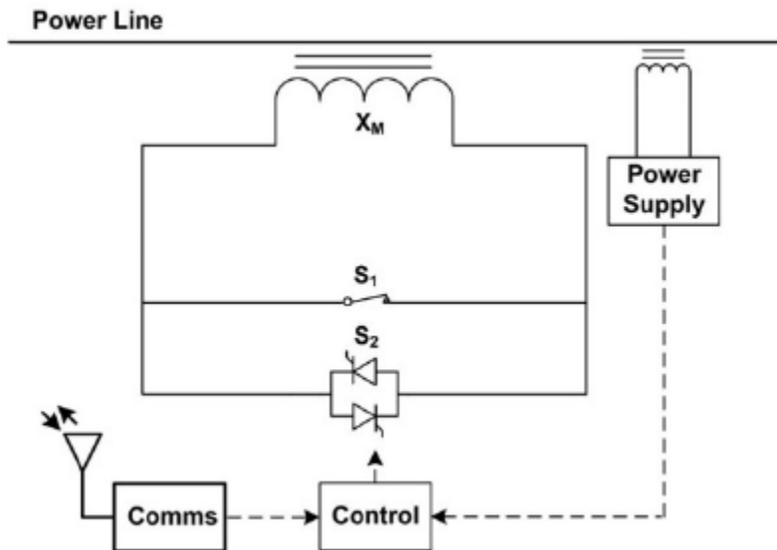


Figure 3.1 PowerLine Guardian Schematic [26]



Figure 3.2: PowerLine Guardian Installed Concentrically Around the Transmission Line [26]

More recently, the Power Guardian was introduced as a more capable DSR that provides much higher reactive impedance. The Power Guardian utilizes the same principles as the

PowerLine Guardian, but must be connected in series with the transmission line, as demonstrated in Figure 3.3 from reference [27].



**Figure 3.3: Power Guardian Connected in Series with a Transmission Line [27]**

The Power Router and Smart Valve are Static Synchronous Series Compensator-type (SSSC). The SSSC can act as a series reactor or as a series capacitor by coupling a leading or lagging  $90^\circ$  voltage onto the line [28]. The device imitates a series inductor when leading  $90^\circ$  voltage is injected and series capacitance when lagging  $90^\circ$  voltage is injected. A schematic of the Power Router and Smart Valve is demonstrated by Figure 3.4 from reference [29].

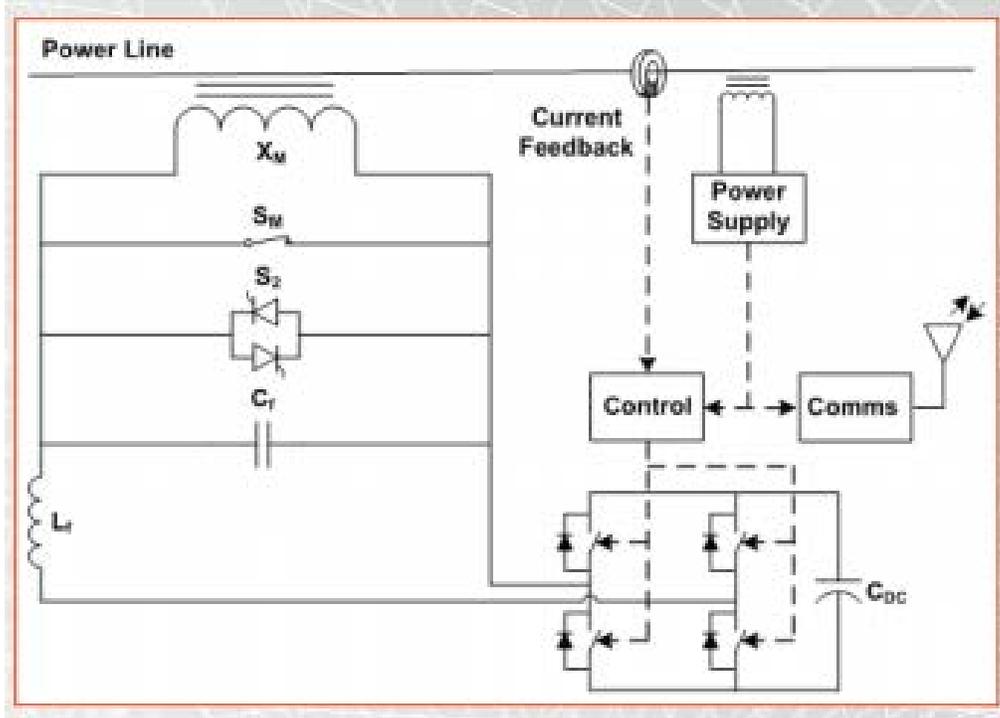


Figure 3.4: Power Router and Smart Valve Schematic [29]

The PowerLine Guardian, Power Guardian, Power Router, and Smart Valve offer more economical and deployable options. In 2016, Pacific Gas and Electric Company began implementation of Smart Wires technology as a portable and flexible solution [30]. The economics of a Smart Wires solution is compared to a traditional line upgrade in reference [31].

Smart Wires relies on the existence of multiple paths and/or sources to supply the load [26]. The diagram in Figure 1.1 is not a complete representation of the system. The diagrams in Figure 1.1 and Figure 1.2 are only meant to be used to assist in describing the contingency that results in significant overloading. There are other sources to supply the load and there are likely other paths from Substation 1 to Substation 3. The two paths from Substation 1 to Substation 3 are the most direct means of supplying the load. As discussed in the previous Section 3.1, a normal open transmission line for Line 1-2 is a satisfactory solution. The difference between Smart Wires and a normal open line is

Smart Wires redirects some of the current away from the line and a normal open line redirects all of the current away from the line.

One possible scenario is to use only Smart Valves. Since the Smart Valve is capable of both pushing power away from and pulling power onto a given transmission circuit, we have the option of either deploying the devices directly on the overloaded transmission line or on a parallel transmission line that has current capacity available.

Another possible scenario is to only use Power Guardians. Since the Power Guardian is only capable of pushing power away from a transmission circuit, we would need to deploy the devices directly on the overloaded line. Deploying the Guardians on the overloaded lines would effectively redirect the power flow to the transmission line with available current capacity.

A third possible scenario is to use a combination of Power Guardians and Smart Valves. This method would require a detailed analysis of the various different combinations of Guardians and Smart Valves that would result in the most cost-effective solution [27].

As previously discussed, there are only two direct paths from Substation 1 to Substation 3 when the system is intact. During the contingency with an internal fault on BKR 3-1, Line 1-2 is the only direct path. For this reason, it is most practical to have the devices directly on the overloaded line.

### **3.3 Calculating the number of Smart Wires Devices**

Determining the number of Smart Wires needed to mitigate overload conditions on a transmission line can be calculated through PSSE simulations and further calculations. Under post-contingency conditions, the engineer increases the reactive impedance of the line in the model until the loading is at or below the rating of the line. This process is automated in Appendix A.1. The automation script simulates the model under post-contingency conditions, reads the loading of the line in MVA, and increases the reactive impedance by the equivalence of one Smart Wires device. The automation script repeats this process until the line is no longer overloaded. It is important to note that this analysis uses the Power Guardian 390, while the new Power Guardian 700 [32] is much more

powerful. An easy conversion between the Power Guardian 390 and the Power Guardian 700 is to divide the number of Power Guardian 390s needed by 1.7.

The following equations define the number of Smart Wires devices needed [33]:

$$\frac{dS}{dX} \cong \frac{|S_{old} - S_{new}|}{I_{rated}^2 * X_{injected}} \quad (3.1)$$

$$X_{p.u.per\ device} = \frac{2\pi * f * L_{per\ device}}{Z_{base}} \quad (3.2)$$

$$Number\ of\ PG\ or\ PGL = 3 * \frac{X_{p.u.injection}}{X_{p.u.per\ device}} \quad (3.3)$$

$$Number\ of\ PG = 3 * \frac{X_{injection} * I_{device\ rating}^2}{S_{device\ rating}} \quad (3.4)$$

$$Number\ of\ Smart\ Valves = \frac{I_{rated} * X_{injection}}{V_{injection\ per\ device}} \quad (3.5)$$

### 3.4 Longevity of a Smart Wires Solution and Sensitivity Analysis

Solving an overloaded system is often more complicated than as discussed in Section 3.3. It is usually necessary to consider load growth over time, in addition to multiple different sensitivities. The data used in this section to derive the distribution factor and predict longevity was acquired through multiple PSSE simulations.

Line 1-2 was studied with various levels of Power Guardian deployments which reduce 2020 post-contingent overloading to below a targeted Line 1-2 conductor temperature rating. The base case model and sensitivities are applied and studied. For the existing 4/0 Cu at 50C, study results indicate that 186 Power Guardian units are needed to reduce worst case overloading to below the normal rating until 2028. As will be shown in the sensitivity analysis, worst case overloading occurs when both industrial loads are off.

There are a number of buses which when load is added at a bus, 4% or more of the added load flows on Line 1-2. The Python script scales 100 MW of additional load across these buses, while maintaining power factor. The “Scale Buses by 100 MW for Distribution Factor Calculation” scales the buses by 100 MW and is shown in Appendix A.2. The engineer documents the change in system wide MVA and the MVA on Line 1-2 after the 100 MW is added to the system. The distribution factor can be calculated using MVA increase of the system and of Line 1-2 and is shown in the equations below [18]:

$$Sys\_MVA\_Chng = \sqrt{Sys\_MW\_Chng^2 + Sys\_MVA\_Chng^2} \quad (3.6)$$

$$Line\_MVA\_Chng = New\_Line\_MVA - Old\_Line\_MVA \quad (3.7)$$

$$Distribution\ Factor = \frac{Line\_MVA\_Chng}{Sys\_MVA\_Chng} \quad (3.8)$$

A range of Power Guardians are simulated with and without the 100 MW of additional load. This process can be simplified by using an automation file as shown in Appendix A.3: “Read in MVA for a Range of Smart Wires Devices.” The automation file simulates the system model for a given number of Power Guardians, reads out the MVA on Line 1-2, increases the number of Power Guardians, and then repeats the process until the desired range of Power Guardians is simulated.

The data in Table 3.1 below shows the simulation results of a range of Power Guardian installed on Line 1-2.

<b>Line 1-2 Analysis: Overloading (MVA)</b>			
<b>Case</b>	<b>Base Case (MVA)</b>	<b>4% Line 1-2 DF Bus Load Scaled Up 100 MW (MVA)</b>	<b>Line 1-2 Distribution Factor with 4% 11L DF Bus Load Scaled Up 100 MW (%)</b>
159PGs	54.98	59.10	4.12%
162PGs	54.69	58.80	4.11%
165PGs	54.41	58.49	4.08%
168PGs	54.13	58.19	4.06%
171PGs	53.85	57.90	4.05%
174PGs	53.58	57.60	4.02%
177PGs	53.31	57.31	4.00%
180PGs	53.04	57.02	3.98%
183PGs	52.78	56.74	3.96%
186PGs	52.51	56.46	3.95%
189PGs	52.25	56.18	3.93%
192PGs	52.00	55.90	3.90%
195PGs	51.74	55.62	3.88%
198PGs	51.49	55.35	3.86%
201PGs	51.24	55.08	3.84%
204PGs	50.99	54.82	3.83%
207PGs	50.75	54.55	3.80%
210PGs	50.50	54.29	3.79%

**Table 3.1: Distribution Factor – PSSE Values**

The distribution factor can be used to predict future load on Line 1-2. An engineer can predict the longevity of the Smart Wires solution from the following equation [18]:

$$Load_{n+1} = Load_n + SysLoadGrowth * \frac{Dist.Factor}{100} \quad (3.9)$$

The data in Table 3.2 below is an example of how the distribution factor and load growth impacts the load on Line 1-2 over time.

0.005	2020	2021	2022	2023	2024	2025
0.5%/year	498.45	500.96	503.47	505.99	508.52	511.06
Incremental Load	-5.02	-2.52		2.51736	5.047307	7.589903
Line 1-2 Loading w/o PGs	80.5845	80.74	80.90	81.06	81.22	81.38
Line 1-2 Loading w/ 186 PGs	54.6282	54.72	54.82	54.92	55.01	55.11
Line 1-2 Loading w/ 189 PGs	54.3592	54.45	54.55	54.65	54.74	54.84
Line 1-2 Loading w/ 192 PGs	54.0902	54.18	54.28	54.38	54.47	54.57
Line 1-2 Loading w/ 195 PGs	53.8317	53.93	54.02	54.11	54.21	54.30
Line 1-2 Loading w/ 198 PGs	53.5622	53.66	53.75	53.84	53.94	54.03
Line 1-2 Loading w/ 201 PGs	53.3031	53.40	53.49	53.58	53.68	53.77
Line 1-2 Loading w/ 204 PGs	53.0431	53.14	53.23	53.32	53.42	53.51
Line 1-2 Loading w/ 207 PGs	52.7831	52.88	52.97	53.06	53.16	53.25
Line 1-2 Loading w/ 210 PGs	52.5331	52.63	52.72	52.81	52.91	53.00
Line 1-2 Loading w/ 213 PGs	52.2831	52.38	52.47	52.56	52.66	52.75
Line 1-2 Loading w/ 216 PGs	52.0331	52.13	52.22	52.31	52.41	52.50
Line 1-2 Loading w/ 219 PGs	51.7831	51.88	51.97	52.06	52.16	52.25

**Table 3.2: Longevity – PSSE Values**

The distribution factor should be calculated for a range of different conditions on the system in what is referred to as a sensitivity study. A sensitivity study is a useful tool for a utility, because it allows for flexibility in the face of uncertainty. New or evolving industrial load can make a significant impact on planning studies. When there is uncertainty, a transmission planning study should forecast for the worst-case overloading scenario, but it is still useful to examine all sensitivities in the event of change. Additionally, load growth is predicted based on past models and isn't a definitive future.

The following sensitivities are studied in the analysis:

- 1) Load 1 and Load 2 Online
- 2) No Load 1
- 3) No Load 2
- 4) Load 1 and Load 2 Offline

Each sensitivity condition is applied to the base case model, and load flow on Line 1-2 under post-contingency conditions was studied.

The system model in Figure 3.5 below is reproduced from Figure 1.2 in Chapter 1.

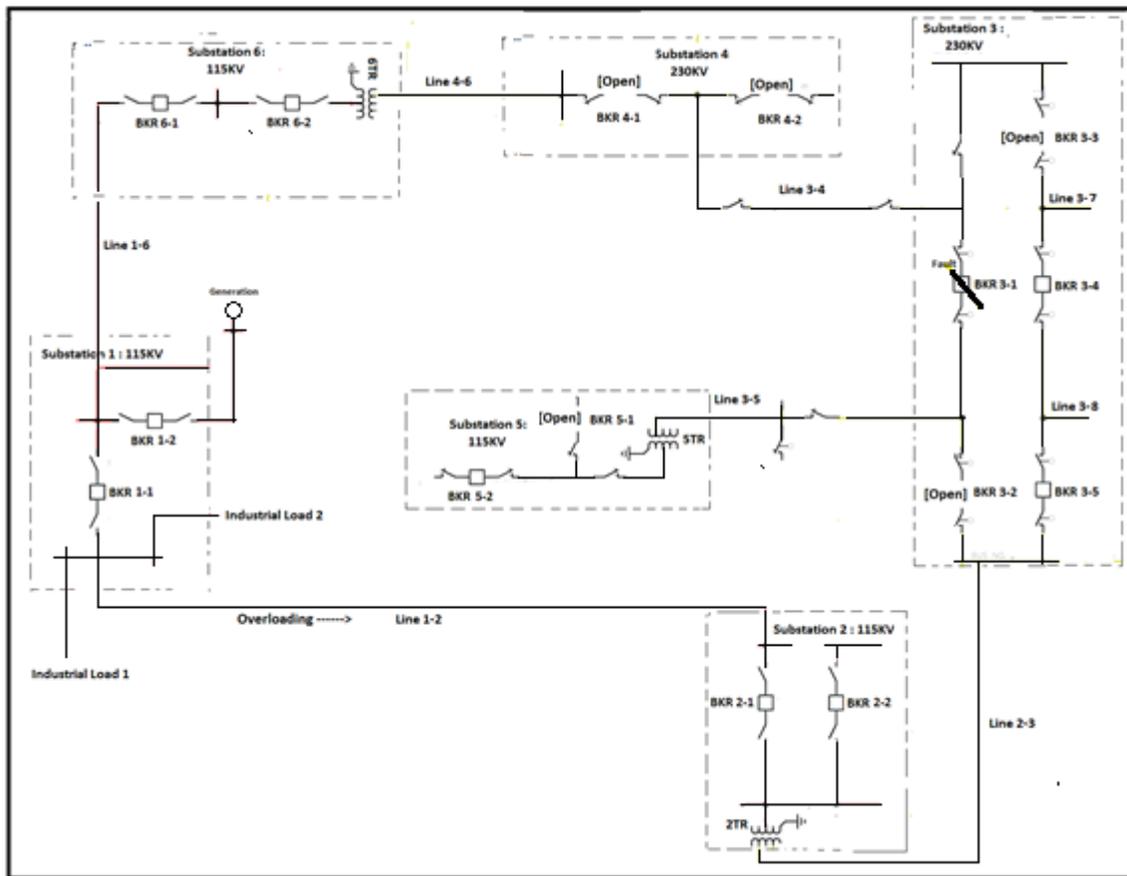


Figure 3.5: Fault on BKR 3-1 - System Overloading, Reproduced from Figure 1.2

### ***3.4.1 Load 1 and Load 2 Online***

The “Load 1 and Load 2 Online” thermal overloads on Line 1-2 are listed in Appendix A.4. These overload values are for 100 MW of additional load scaled across targeted bus loads with Smart Wires devices off.

### ***3.4.2 No Load 1***

The “No Load 1” thermal overloads on Line 1-2 are listed in Appendix A.4. These overload values are for 110 MW of Load 1 disconnected at Substation 1 with Smart Wires devices off.

### ***3.4.3 No Load 2***

The “No Load 2” thermal overloads on Line 1-2 are listed in Appendix A.4. These overload values are for 92 MW of Load 2 disconnected at Substation 1 with Smart Wires devices off.

### ***3.4.4 Load 1 and Load 2 Offline***

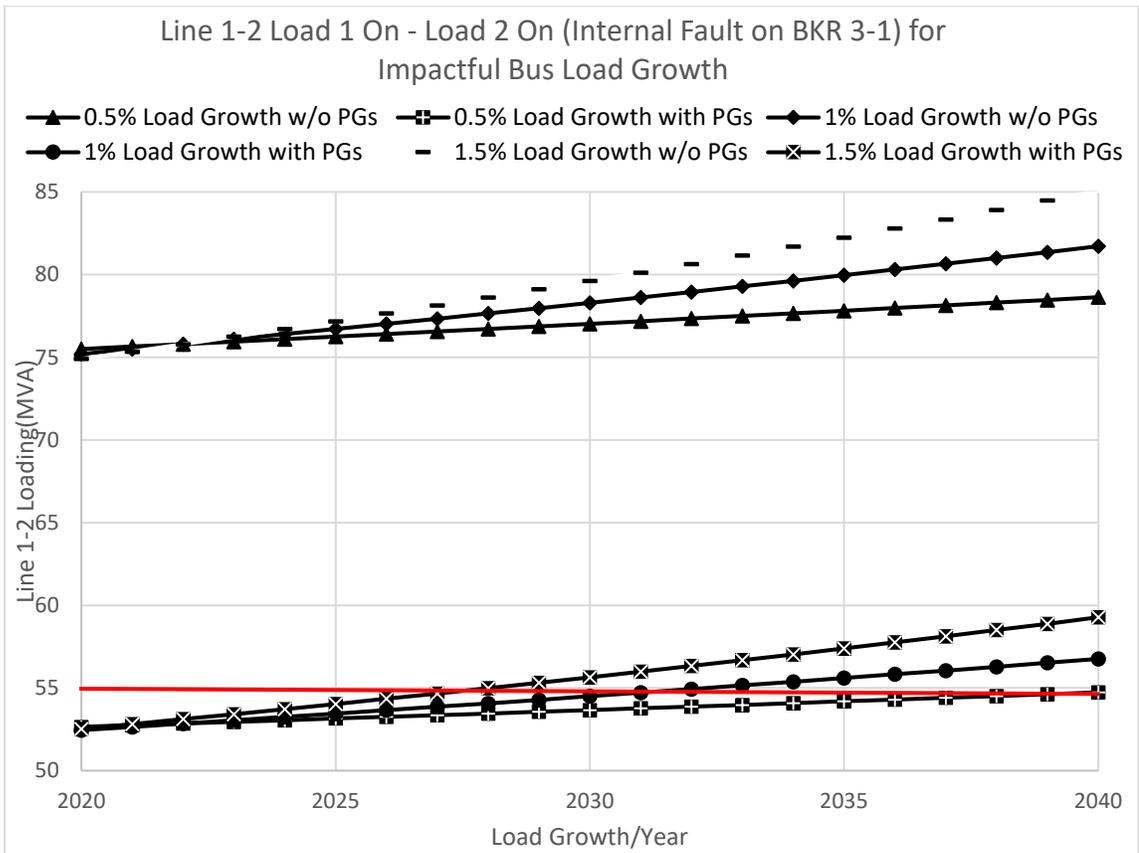
The “No Load 1, Load 2” thermal overloads on Line 1-2 are listed in Appendix A.4. These overload values are for 202 MW of Load 1 and Load 2 disconnected at Substation 1 with Smart Wires devices off. Simulation results should demonstrate that worst case overloading occurs when both industrial loads are off.

## **3.5 Power Guardian Units on Line 1-2 Longevity Forecast**

This section is intended to show how long a Smart Wires solution is likely to last given a range or different conditions. The future load of a power system isn’t always definite, and it is therefore important to consider all possibilities in order to have a successful solution that ensures reliable service to the utility’s customers.

**3.5.1 Load 1 and Load 2 Online**

Figure 3.6 demonstrates the impact of choosing a 0.5%, 1.0%, or 1.5% Impactful Bus load growth assumption with 0.5% being a typical conservative assumption used. After 5 years, the difference in the load growth assumptions is about a 1.5 MVA increase for every 0.5%. This is the case for 162 Power Guardians added to Line 1-2. The graph demonstrates the impact that load growth has on the system over time. Without Power Guardians, a simulation of the system shows significant overloading on Line 1-2. By the year 2040, loading will increase by 4.84% for a load growth of 0.5%, 8.97% for a load growth of 1%, and 13.33% for a load growth of 1.5%.



**Figure 3.6: Impactful Bus Load Growth Assumption - Load 1 and Load 2 Online in PSSE**

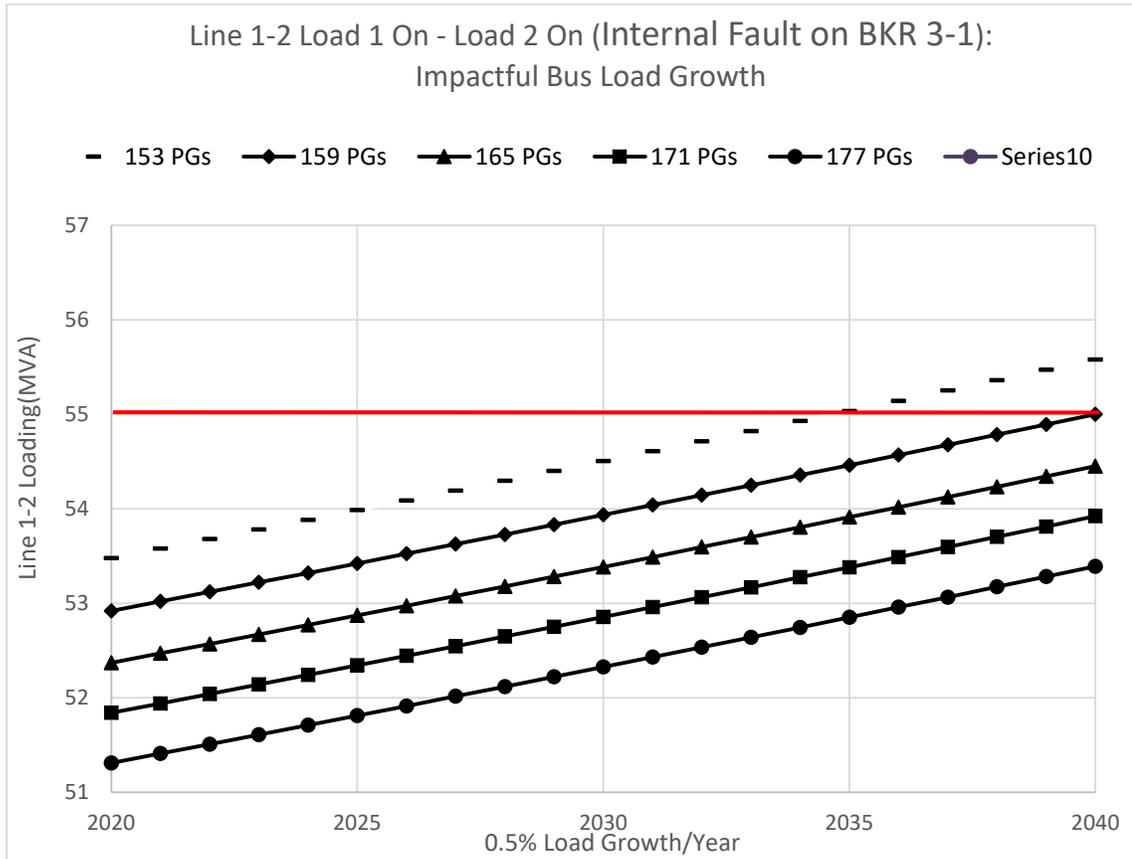
The graph in Figure 3.6 shows that 162 Power Guardians are sufficient to mitigate overloading in both the near-term and long term if a 0.5% load growth is assumed. Under

all three load growth assumptions, 0 to 1.5%, 162 Power Guardians are capable of solving the overloaded system until the year 2028.

A load growth of 0.5% is the most reasonable assumption, and 162 Power Guardians can therefore be used as an acceptable long-term solution. Annual power flow studies should be performed in order to ensure the longevity of the solution. If future power flow studies show a load growth that is higher than 0.5%, the number of Power Guardians on the transmission line will need to increase in order to ensure that the load on the line is below its rated capacity.

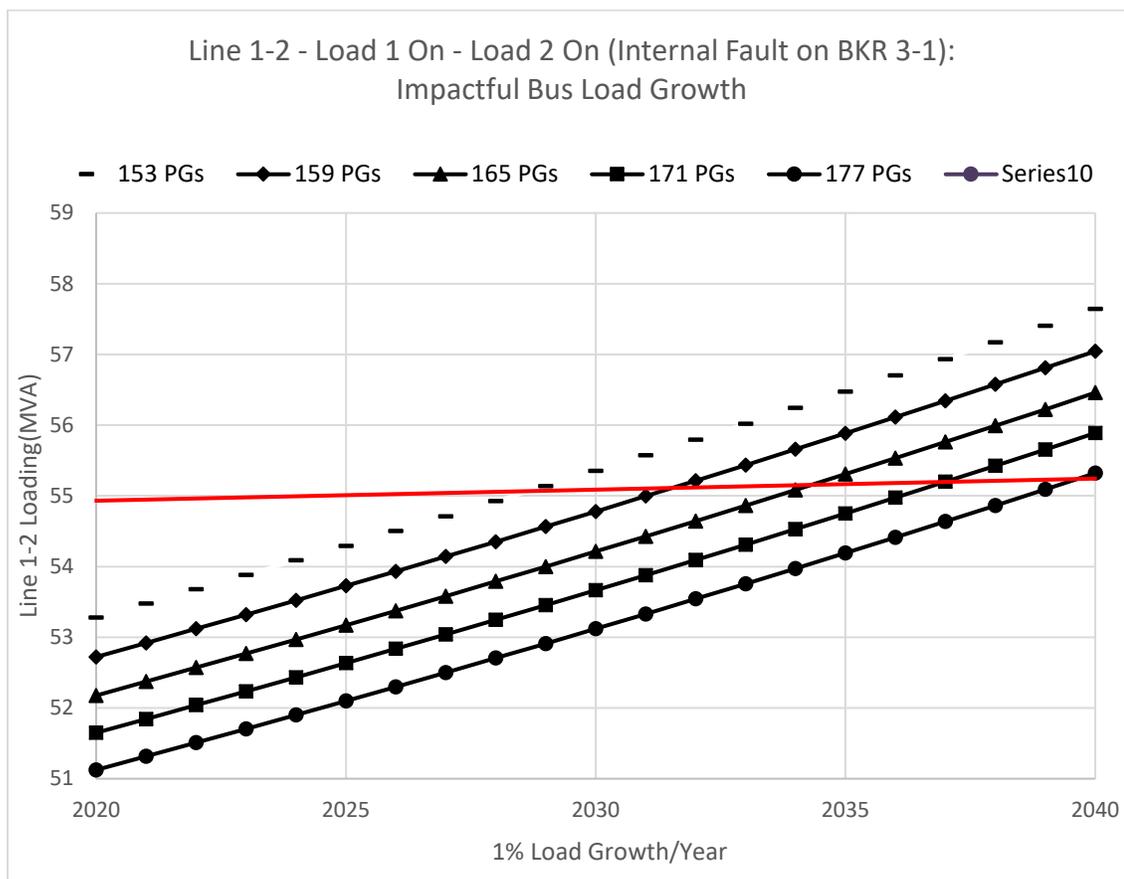
Figure 3.7 demonstrates Line 1-2 base case loading at 0.5% load growth per year for various levels of Power Guardian deployments for an internal fault on BKR 3-1. The graph reiterates that 162 Power Guardians are sufficient to mitigate overloading on Line 1-2 when assuming a load growth of 0.5%.

Assuming a 20 year lifespan of a Smart Wires device, it isn't practical to consider the solution beyond 2040. If both Load 1 and Load 2 are online, it would be unnecessary to install more than 162 Power Guardians. If one or both of the industrial loads are offline, a long-term solution that mitigates overloading until 2040 will, of course, require more than 162 Power Guardians.



**Figure 3.7: Different Levels of Power Guardians at 0.5% Load Growth - Load 1 and Load 2 Online in PSSE**

Figure 3.8 demonstrates Line 1-2 base case loading at 1% load growth per year with various levels of Power Guardian deployments for an internal fault on the BKR 3-1. The graph demonstrates that 177 Power Guardians are sufficient to mitigate overload conditions on Line 1-2 until 2040 when assuming a load growth of 1%. It isn't likely that load growth will be as high as 1%, but it is important to consider the possibility of higher load growth. If a later study shows that load is increasing at a higher rate than initially anticipated, this analysis can be used to determine how many more devices are needed to mitigate overload conditions on the line.



**Figure 3.8: Different Levels of Power Guardians at 1% Load Growth - Load 1 and Load 2 Online in PSSE**

### 3.5.2 No Load 1

Figure 3.9 demonstrates the impact of choosing a 0.5%, 1.0%, or 1.5% Impactful Bus load growth assumption with 0.5% being a typical conservative assumption used. After 5 years, the difference in the load growth assumptions is about a 1.5 MVA increase for every 0.5%. This is the case for 180 Power Guardians added to Line 1-2. The graph demonstrates the impact that load growth has on the system over time. Without Power Guardians, a simulation of the system shows significant overloading on Line 1-2. By the year 2040, loading will increase by 3.03% for a load growth of 0.5%, 5.35% for a load growth of 1%, and 7.75% for a load growth of 1.5%.

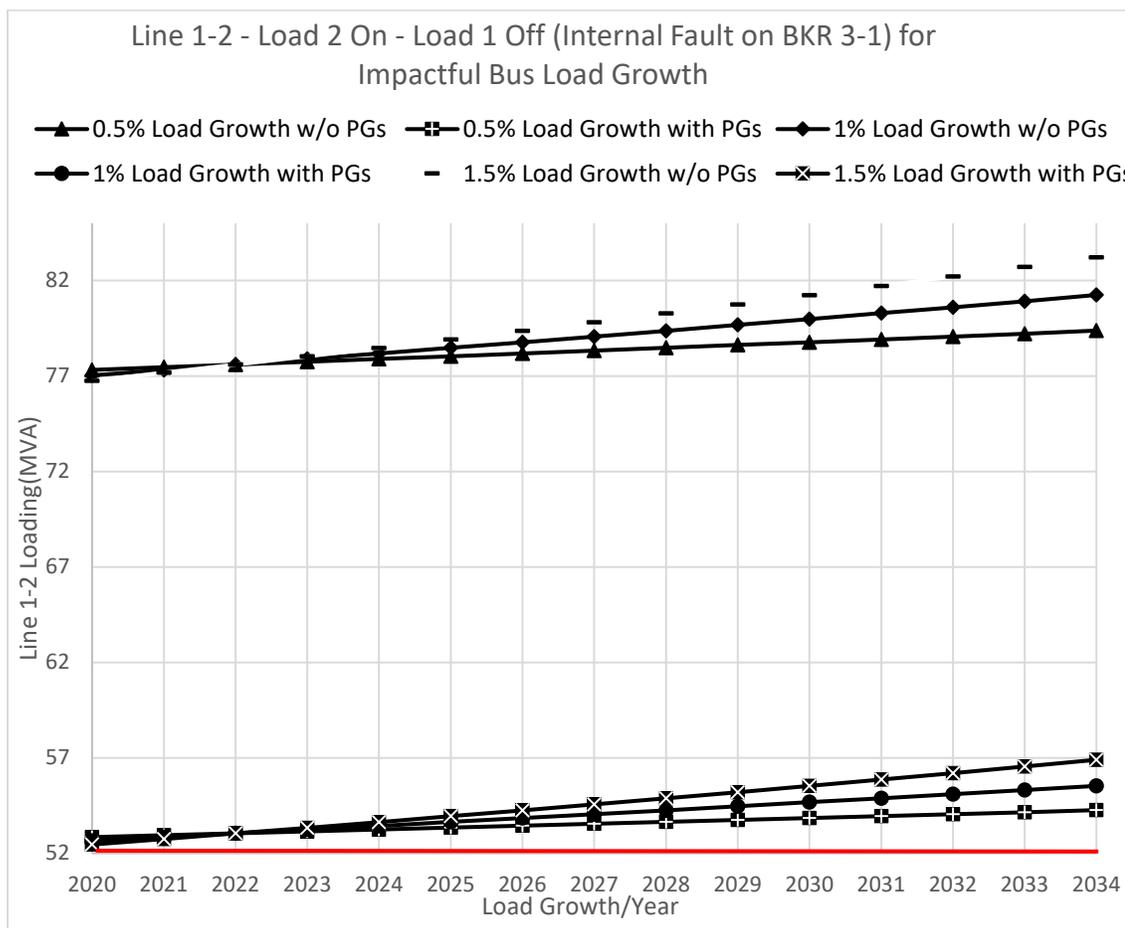
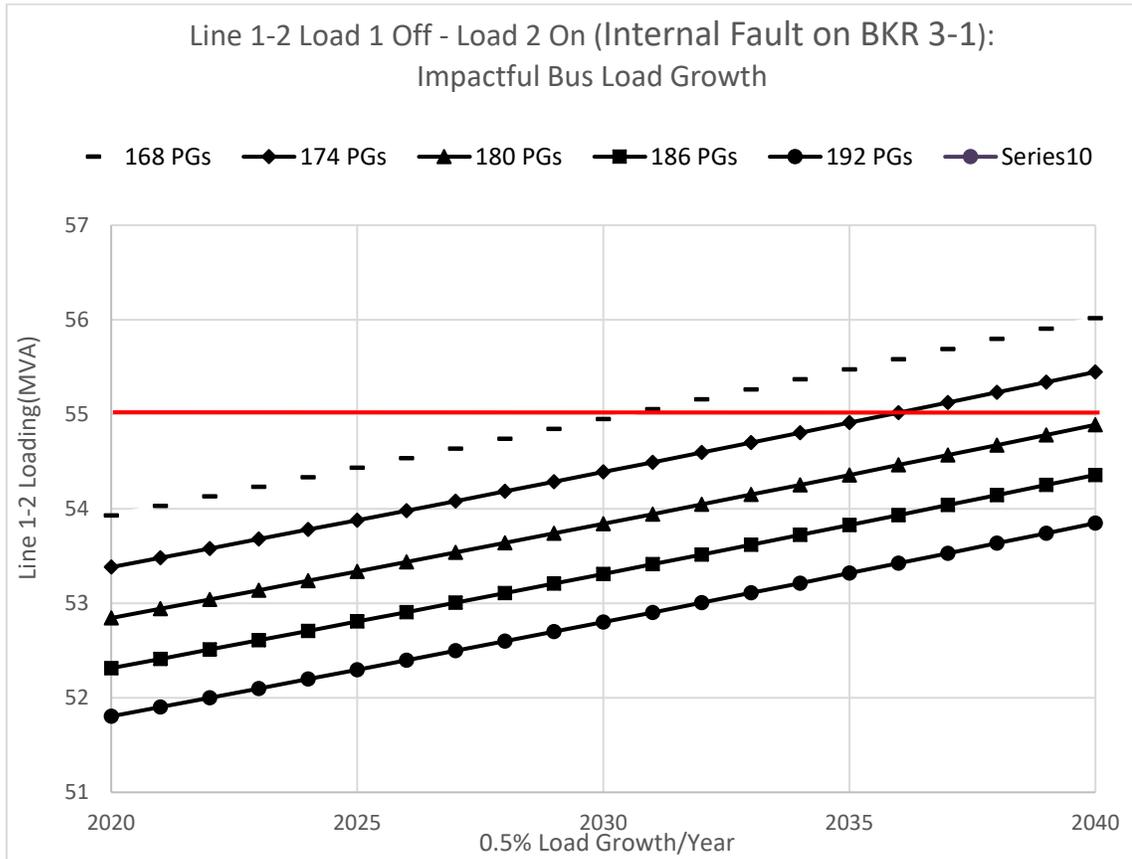


Figure 3.9: Impactful Bus Load Growth Assumption - No Load 1 in PSSE

Figure 3.10 demonstrates Line 1-2 base case loading at 0.5% load growth per year with various levels of Power Guardian deployments for an internal fault on the BKR 3-1. If Load 1 is offline and Load 2 is online, it would be unnecessary to install more than 180 Power Guardians. If both of the industrial loads are offline, a long-term solution that mitigates overload conditions until 2040 will, of course, require more than 180 Power Guardians.



**Figure 3.10: Different Levels of Power Guardians at 0.5% Load Growth - No Load 1 in PSSE**

Figure 3.11 demonstrates Line 1-2 base case loading at 1% load growth per year with various levels of Power Guardian deployments for an internal fault on the BKR 3-1. The graph demonstrates that 198 Power Guardians are sufficient to mitigate overload conditions on Line 1-2 until 2040 when assuming a load growth of 1%. It isn't likely that load growth will be as high as 1%, but it is important to consider the possibility of higher load growth. If a later study shows that load is increasing at a higher rate than initially anticipated, this analysis can be used to determine how many more devices are needed to mitigate overload conditions on the line.

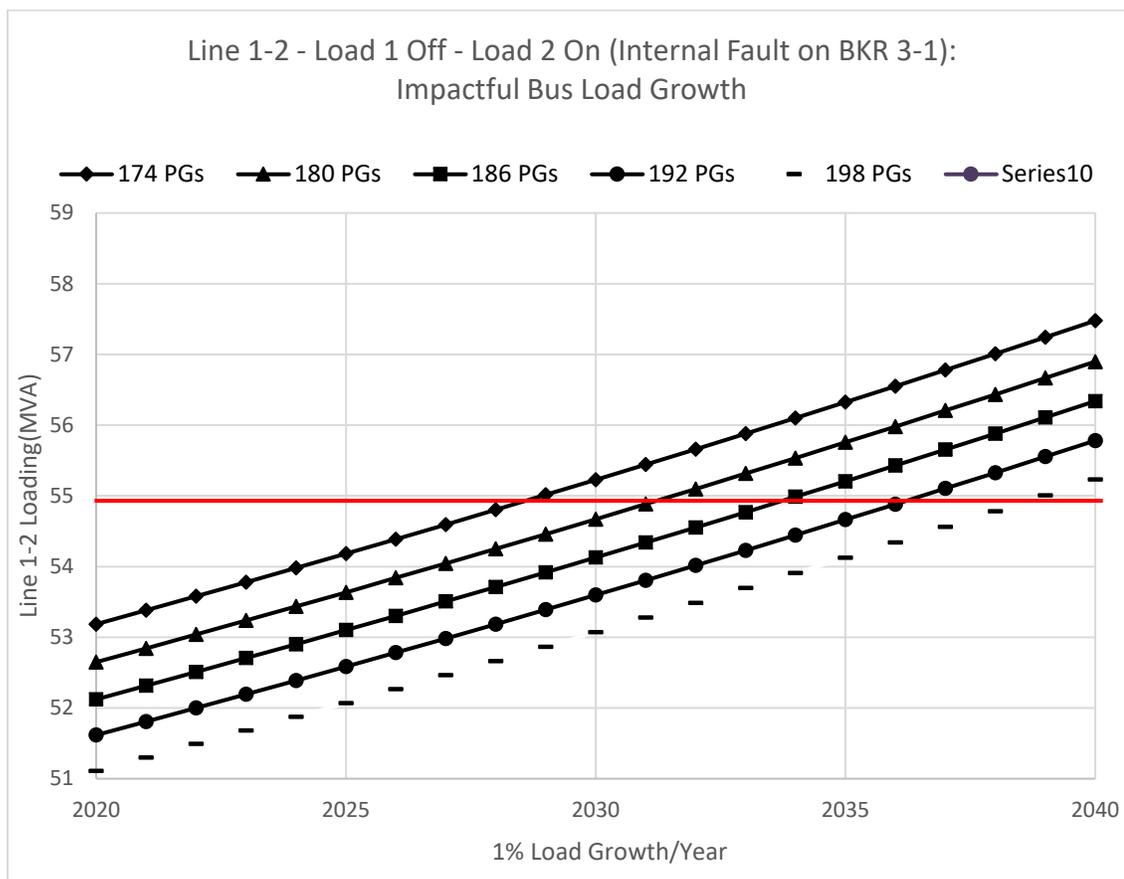


Figure 3.11: Different Levels of Power Guardians at 1% Load Growth - No Load 1 in PSSE

### 3.5.3 No Load 2

Figure 3.12 demonstrates the impact of choosing a 0.5%, 1.0%, or 1.5% Impactful Bus load growth assumption with 0.5% being a typical conservative assumption used. After 5 years, the difference in the load growth assumptions is about a 1.5 MVA increase for every 0.5%. This is the case for 183 Power Guardians added to Line 1-2. The graph demonstrates the impact that load growth has on the system over time. Without Power Guardians, a simulation of the system shows significant overloading on Line 1-2. By the year 2040, loading will increase by 3.66% for a load growth of 0.5%, 5.97% for a load growth of 1%, and 8.35% for a load growth of 1.5%.

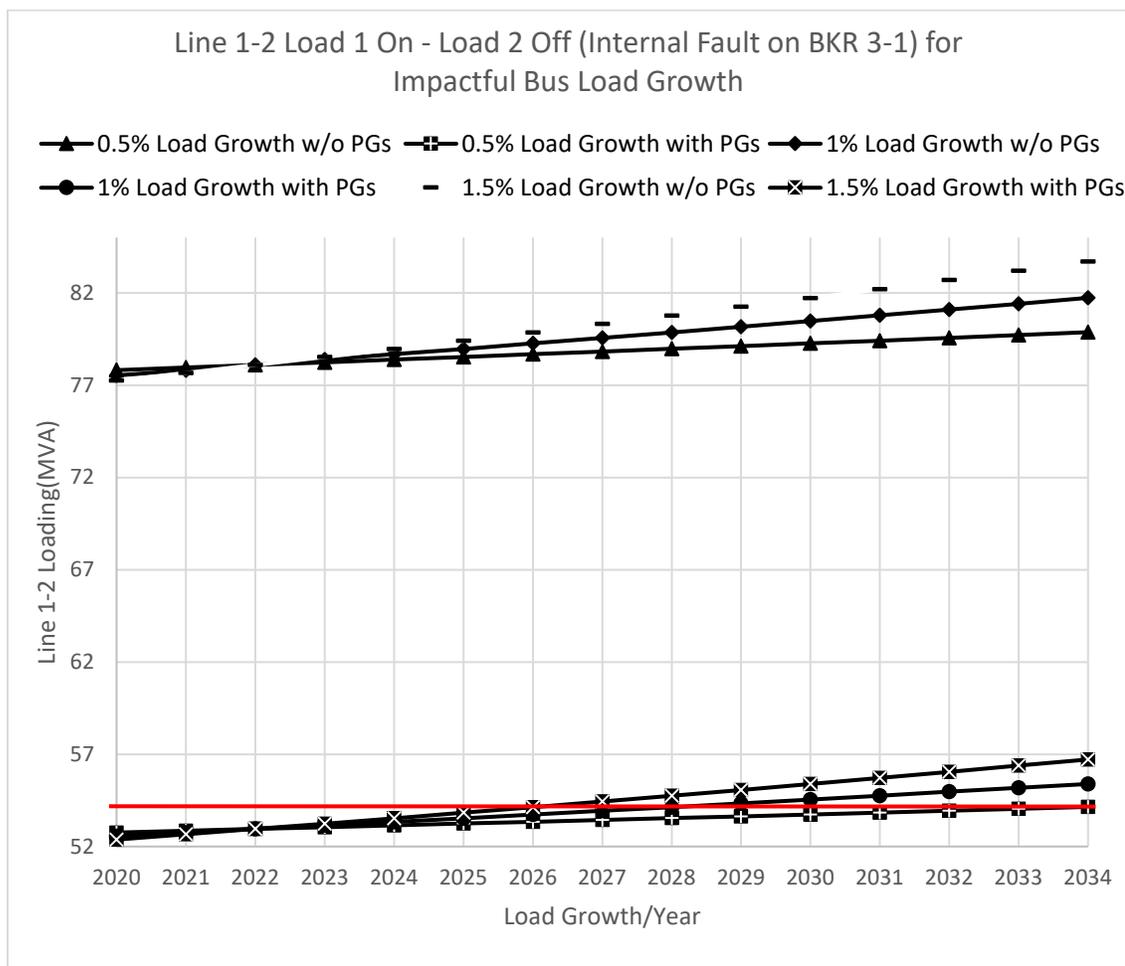
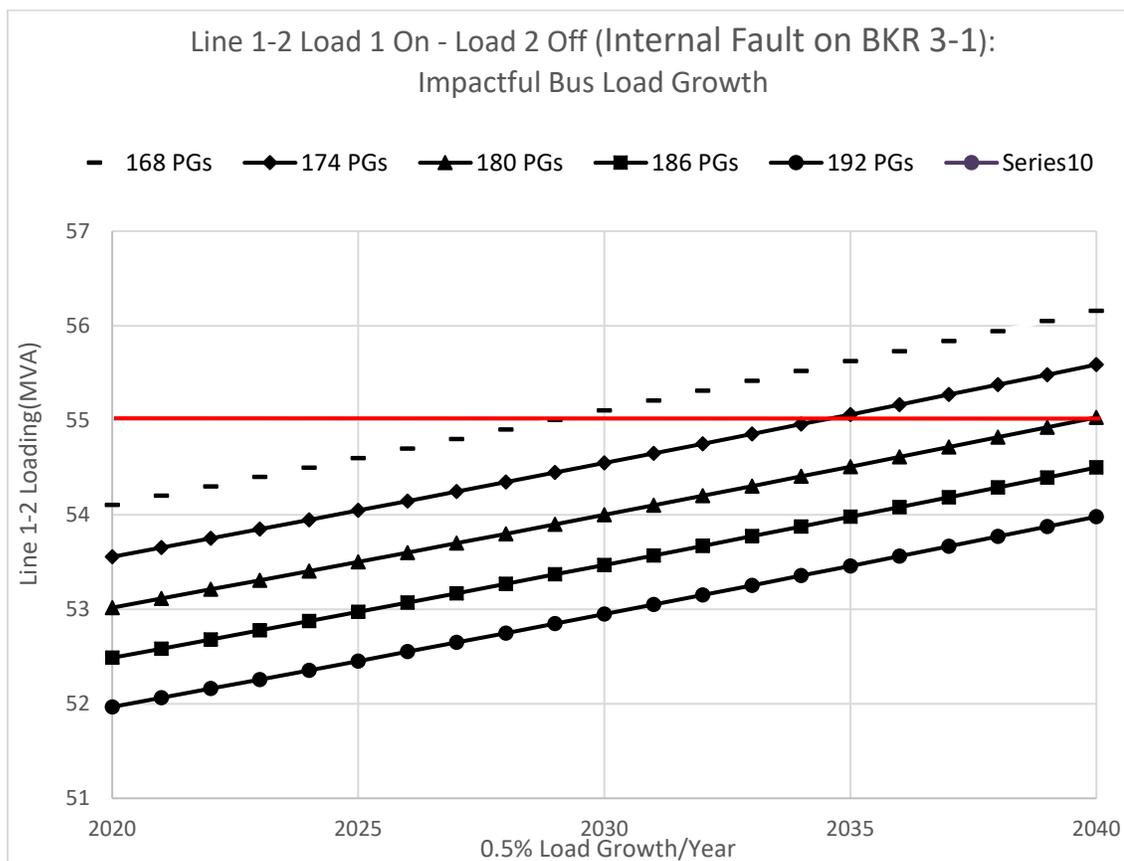


Figure 3.12: Impactful Bus Load Growth Assumption - No Load 2 in PSSE

Figure 3.13 demonstrates Line 1-2 base case loading at 0.5% load growth per year with various levels of Power Guardian deployments for an internal fault on the BKR 3-1. If Load 1 is online and Load 2 is offline, it would be unnecessary to install more than 183 Power Guardians. If both of the industrial loads are offline, a long-term solution that mitigates overload conditions until 2040 will, of course, require more than 183 Power Guardians



**Figure 3.13: Different Levels of Power Guardians at 0.5% Load Growth - No Load 2 in PSSE**

Figure 3.14 demonstrates Line 1-2 base case loading at 1% load growth per year with various levels of Power Guardian deployments for an internal fault on the BKR 3-1. The graph demonstrates that more than 198 Power Guardians are sufficient to mitigate overload conditions on Line 1-2 until 2040 when assuming a load growth of 1%. It isn't likely that load growth will be as high as 1%, but it is important to consider the possibility of higher load growth. If a later study shows that load is increasing at a higher rate than initially anticipated, this analysis can be used to determine how many more devices are needed to mitigate overload conditions on the line.

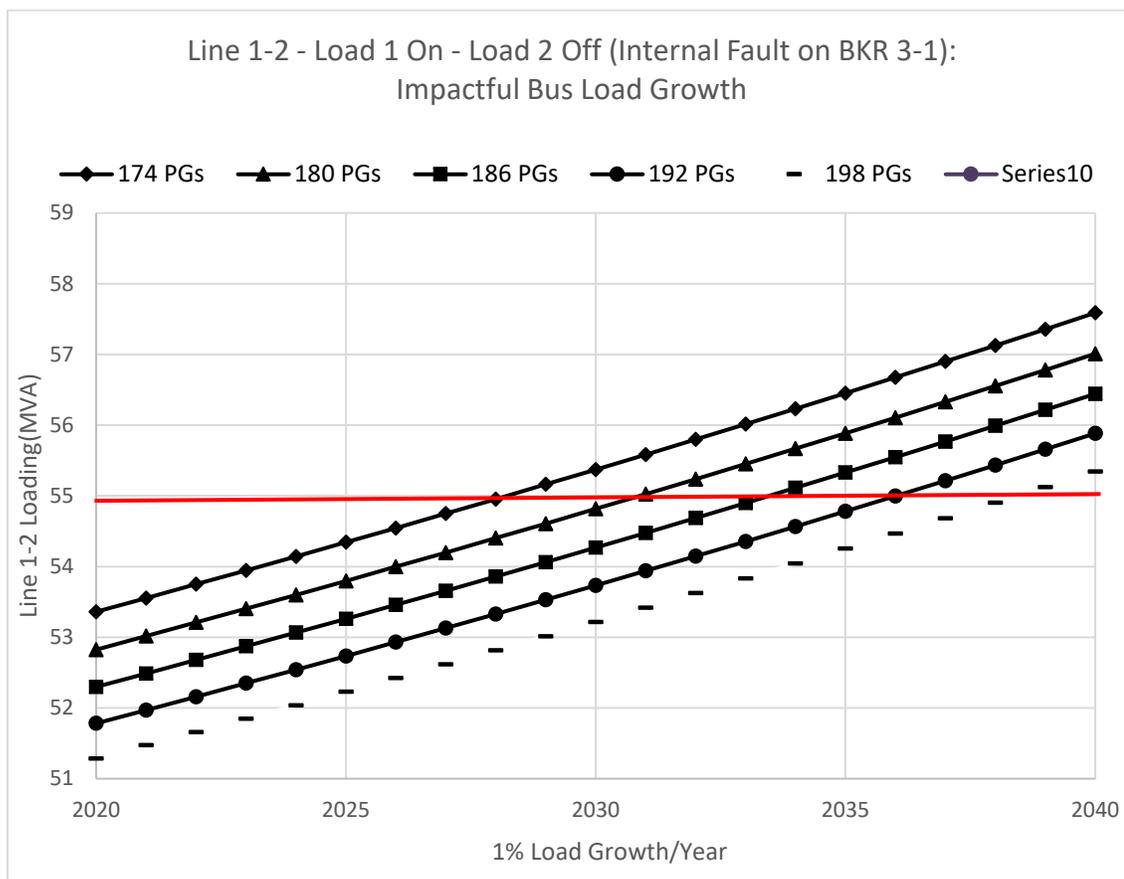
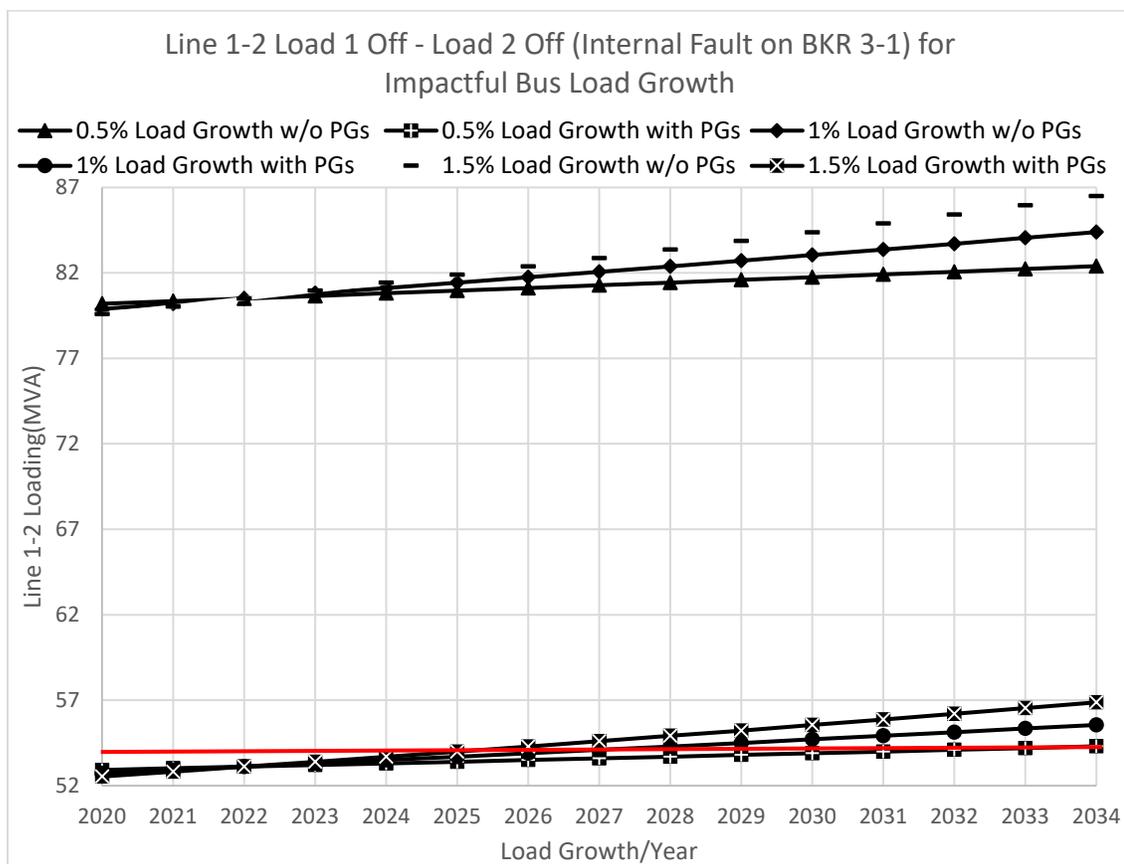


Figure 3.14: Different Levels of Power Guardians at 1% Load Growth - No Load 2 in PSSE

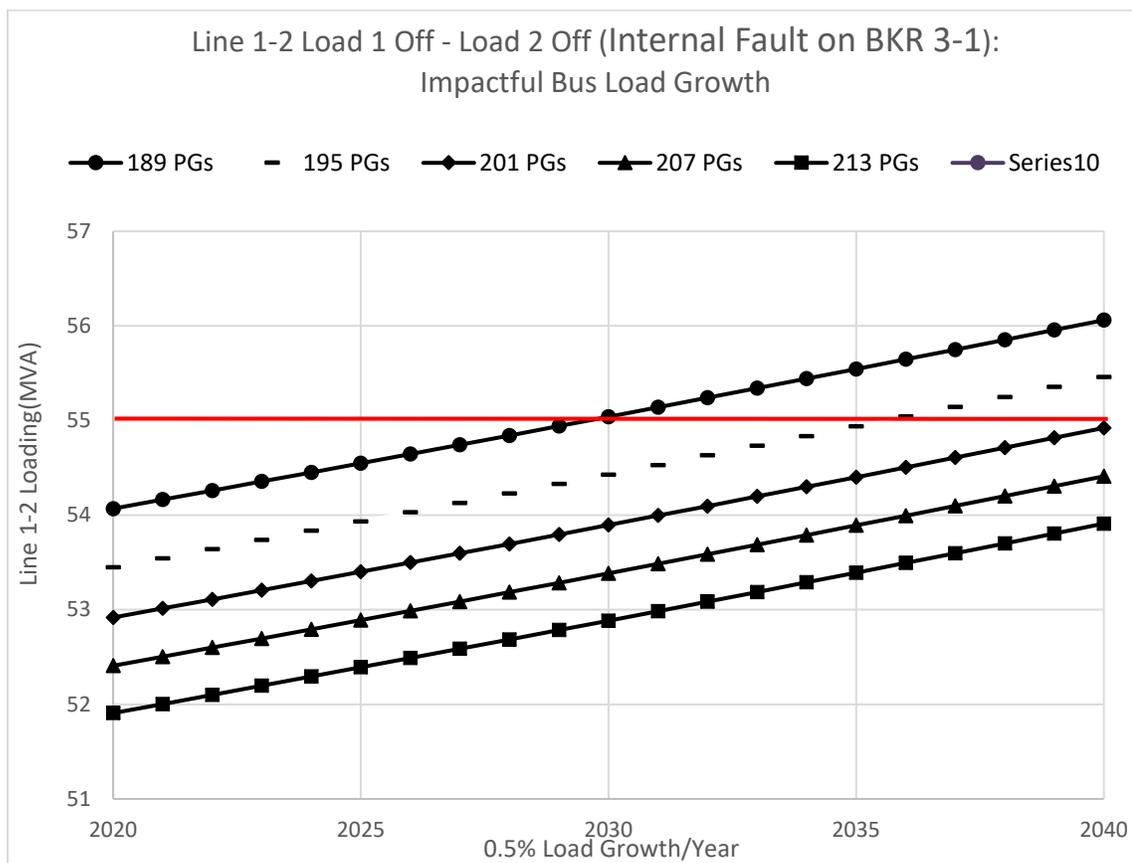
### 3.5.4 Load 1 and Load 2 Offline

Figure 3.15 demonstrates the impact of choosing a 0.5%, 1.0%, or 1.5% Impactful Bus load growth assumption with 0.5% being a typical conservative assumption used. After 5 years, the difference in the load growth assumptions is about a 1.5 MVA increase for every 0.5%. This is the case for 201 Power Guardians added to Line 1-2. The graph demonstrates the impact that load growth has on the system over time. Without Power Guardians, a simulation of the system shows significant overloading on Line 1-2. By the year 2040, loading will increase by 3.46% for a load growth of 0.5%, 5.85% for a load growth of 1%, and 8.32% for a load growth of 1.5%. The data shows that overloading is greatest when both Load 1 and Load 2 are off, requiring a stronger solution.



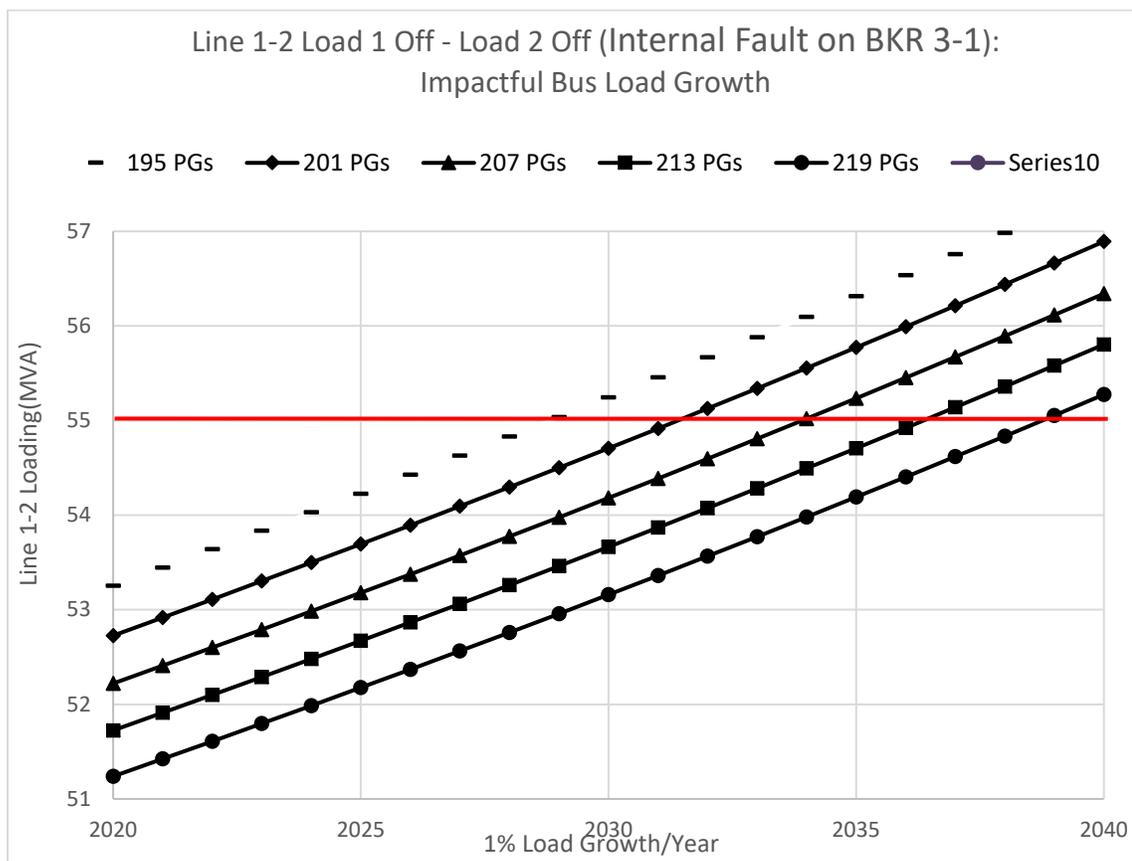
**Figure 3.15: Impactful Bus Load Growth Assumption - Load 1 and Load 2 Offline in PSSE**

Figure 3.16 demonstrates Line 1-2 base case loading at 0.5% load growth per year with various levels of Power Guardian deployments for an internal fault on BKR 3-1. If both Load 1 and Load 2 are offline, it would be unnecessary to install more than 201 Power Guardians.



**Figure 3.16: Different Levels of Power Guardians at 0.5% Load Growth - Load 1 and Load 2 Offline in PSSE**

Figure 3.17 demonstrates Line 1-2 base case loading at 1% load growth per year with various levels of Power Guardian deployments for an internal fault on the BKR 3-1. The graph demonstrates that 219 Power Guardians are sufficient to mitigate overload conditions on Line 1-2 until 2040 when assuming a load growth of 1%. It isn't likely that load growth will be as high as 1%, but it is important to consider the possibility of higher load growth. If a later study shows that load is increasing at a higher rate than initially anticipated, this analysis can be used to determine how many more devices are needed to mitigate overload conditions on the line.



**Figure 3.17: Different Levels of Power Guardian at 1% Load Growth - Load 1 and Load 2 Offline in PSSE**

The utility should plan for the worst case scenario, with both industrial loads are off and overloading at its highest. Figure 3.18 demonstrates that 186 Power Guardians are a sufficient solution until 2028. A Smart Wires solution might include 186 Power Guardians and a re-evaluation of the PSSE model before additional devices are purchase. If both industrial loads are offline and load growth is at or below 0.5%, then more devices can be purchased using Figure 3.18 as a guide

If both industrial loads are online and load growth is at or below 0.5%, then the solution is complete requires no additional devices. According to the graphs, 159 Power Guardians are required for a solution lasting until 2040 when assuming 0.5% load growth. If both industrial loads are online, there would be an additional 27 Power Guardians that could be redeployed elsewhere on the power system.

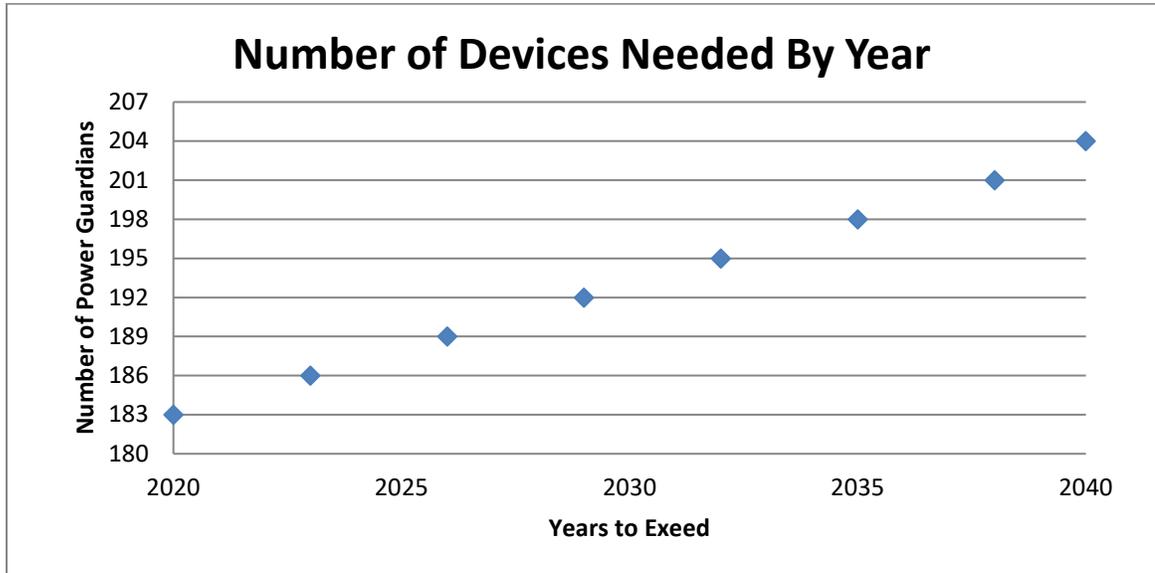


Figure 3.18: Number of Devices Needed at 0.5% Load Growth - Load 1 and Load 2 Off in PSSE

### 3.6 Power Guardians or Smart Valves

In Section 3.2, it was determined that it is most effective to put the Smart Wires devices directly onto Line 1-2. In this section, we will consider the option of Smart Valves to determine the most efficient solution. The equation below is reproduced from Equation 3.5.

$$\text{Number of Smart Valves} = \frac{I_{\text{rated}} * X_{\text{injection}}}{V_{\text{injection per device}}} \quad (3.10)$$

Let us consider the same conditions where 186 Power Guardians are required:

Where  $I_{\text{rated}} = 276 \text{ A}$   $X_{\text{injection}} = 33.48 \text{ } \Omega$  per phase  $V_{\text{injection per device}} = 566 \text{ V}$

Given these conditions, 17 devices are needed for each phase in order to mitigate overload conditions on Line 1-2 until 2028. Given that this is a 3-Phase system, 51 devices are need.

Smart Valves are slightly smaller and significantly lighter than Power Guardians. Power Guardians are 3600 pounds [34], while Smart Valves are just 500 pounds [35]. The smaller weight and size of Smart Valves makes installment easier and reduces the amount of space required in the substation.

The smaller and lighter Smart Valve is the best solution in this case given that only 51 devices are required as opposed to 186 devices that would be required if the larger and heavier Power Guardian is used. The Smart Valve is also expected to be the more economical solution – the Smart Valve is slightly more expensive per device than the Power Guardian, but 51 Smart Valves are still significantly cheaper than 186 Power Guardians.

While the Smart Valve is the best solution for Line 1-2, it isn't necessarily the best device for every situation. The Power Guardian adds a fixed reactive impedance to the line, while the Smart Valve is dependent on the operating current. If the operating current is low, as it is in this particular line, then the Smart Valve is likely the best option. If the operating current is as high as 600 amps, then it is likely that the Power Guardian is a more effective solution. The graph from [29] in Figure 3.19 shows how the reactive impedance changes with operating current.

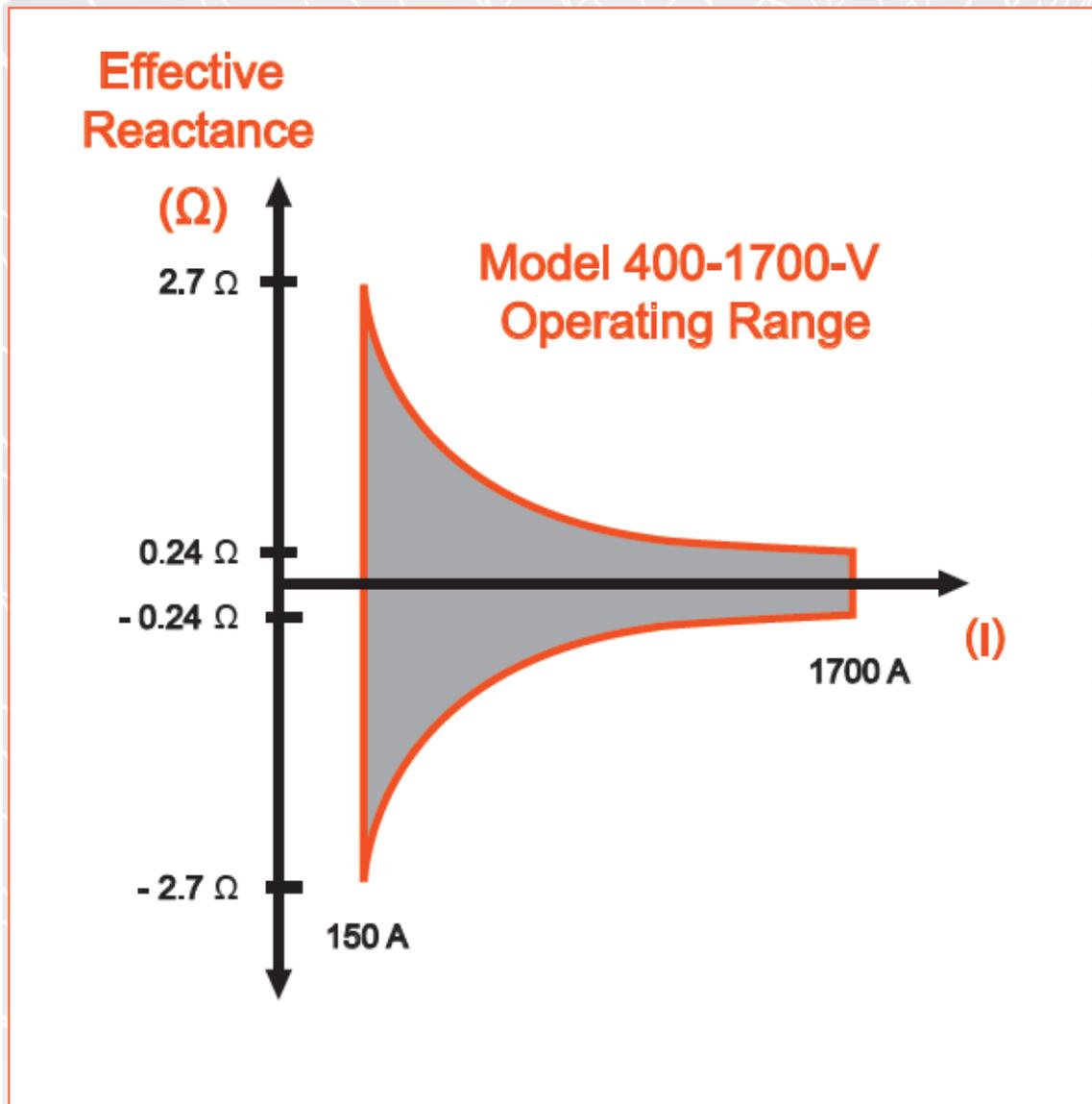


Figure 3.19: How the Reactive Impedance Changes With Current - Power Router and Smart Valve [29]

### 3.7 Ensuring Equal Usage of the Smart Wires Devices

Smart Wires devices can be turned to non-injecting mode when they are not needed. If only a portion of the devices are needed, the ones that are in non-injecting mode and the ones in injecting mode should be alternated in order to ensure equal use of each device.

In order to ensure equal usage of each device, consider the reactive power of each device. Consider the following equation for Vars:

$$Q = I^2 * X \quad (3.11)$$

Where X is the impedance of the device and Q is reactive Power.

Equation 3.11 gives us the reactive power of the Smart Wires device in Vars. This equation by itself is not enough. We must also consider the time,  $t_{injection}$ , the device is in injection mode.

$$Q = I^2 * X * t_{injection} \quad (3.12)$$

Equation 3.12 is in Var-hours, which makes it easier to manage the devices put into injection mode. Operators should alternate the devices in a way that each device has an equal number of Var-hours.

### 3.8 Smart Wires and Fault Conditions

The Smart Valve can operate in conjunction with the Smart Bypass to transition into bypass mode during fault conditions. Alternatively, the device is rated for fault current up to 63 kA RMS for one second, 164 kA peak for the first cycle, and 4 kA RMS continuous. [36]. The Smart Bypass is an improvement from the internal bypass functions offered in previous Smart Wires options. The Power Router automatically switches to bypass mode for a fault current of 3 kA RMS or 1 kA RMS continuous [37].

The data sheets and academic papers presented by Smart Wires give the option to bypass on fault or to remain in injection mode for the duration of 1 second. If fault simulators such as ASPEN One-Liner show conditions within the fault current ratings specified by Smart Wires documentation, it may be ideal to remain in injection mode. Relay protection often isolates the fault within several cycles and at most 24 cycles, which is well under the 1 second rating of the Smart Wires device.

Relay settings and simulation software relies on accurate line impedance values in order to operate correctly. Since Smart Wires changes the reactive impedance of the line, this would make previous relay settings invalid and fault detection uncertain. Added reactive impedance could also change the current flow during a fault on a different line or element other than Line 1-2. If the Smart Valves are left in injection mode, the relay settings could be adjusted to reflect the new parameters. In doing this, the relays would be able detect and trip for faults, but fault location would no longer be accurate. Relays would be unable to differentiate between the impedances of the conductor and the reactive impedances added by Smart Wires devices.

The Smart Wires devices are only needed when there is an internal fault on BKR 3-1, which results in overload conditions on the Line 1-2. Switching the device to bypass mode during fault conditions could extend the lifetime of the device, but could also create uncertainty with relay settings if bypass mode fails. The relays allow for multiple groups of settings, so it might be possible to have the Smart Wires devices communicate to the relevant relays when they are in bypass mode and when they are in injection mode. The disadvantage with this method is that it restricts the flexibility of the Smart Wires devices in that we would only want two conditions: all devices in bypass mode or all devices in injection mode.

Having only two conditions would make it easier when programming the relay, but takes away the advantage being able to choose how many of the devices go into injection mode. As an example, a utility might have 100 devices on any given transmission line, but only requires half of them to switch to injection mode in order to mitigate overload conditions on the line. Under the conditions specified, the devices only have two options: all on or all off.

If the Smart Valve unexpectedly switches from injection mode or injects more reactive impedance than originally planned, then it should communicate to the relay that there has been a change and to switch groups.

### **3.9 Chapter Conclusions**

This chapter examined several solutions for solving overload conditions, focusing primarily on the efficiency, reliability, longevity, and implementation of a Smart Wires solution. Background knowledge of transmission line models proved beneficial for understanding how and why these solutions work. This chapter explained why line upgrades are often more expensive and more permanent than what is offered by Smart Wires.

There were some concerns with how relay coordination would be affected by transmission lines whose impedance does not always remain the same. This chapter considered the Smart Wires the option of adjusting the relay settings and adding multiple groups of settings in order to accommodate the additional reactive impedance, but the solution does not work without some level of certainty.

Additional analysis from running ACCC showed that Smart Wires mitigated the overload conditions without creating any additional overload conditions or voltage violations. However, ACCC also showed that a normal open on Line 1-2 does not create any additional overload conditions or voltage violations. A Smart Wires solution would redirect some of the current away from Line 1-2, but normal open would redirect all of the current flow. With a normal open, the system would no longer be able to rely on Line 1-2 to service customers. The utility should prepare for unexpected conditions and ensure its customers have uninterrupted, reliable power. Smart Wires is a more affordable option than a line upgrade, but it might be more expensive than a normal open solution. A normal open line is more complicated than simply leaving the transmission line open – some reconfiguration of the system would be required in order to ensure reliability. Additional analysis is needed to determine the costs of a normal open solution. Both Smart Wires and a normal open solution will redirect current flow which increases system losses, creating additional cost. A normal open redirects all the current on Line 1-2 and would result in higher system losses than a Smart Wires solution.

## **Chapter 4**

### **Time Scale Analysis and Optimal Control**

Flexible solutions are difficult to achieve due to the complexity of real-time line monitoring – which plays an important role in understanding the true ampacity of a transmission line. The computations of the system are “stiff” due to the simultaneous presence of fast electrical dynamics and slow thermal dynamics that interact with each other.

This chapter examines a nonlinear state-space model of a transmission line where the dynamics of the line current and temperature are defined. When a step change is introduced, both the temperature and current responses to the step change will be observed in simulations. This step change corresponds to perturbations caused by lightning strikes or an abrupt change in source voltage. The goal is to see how Smart Wires devices impact this control response. Control room operators need to deal with perturbations on the grid – this chapter looks at a method to automatically bring the perturbations to zero. Additionally, the concepts developed in this chapter can be used to mitigate perturbations common to wind generation [38].

We will define methods for identifying and decoupling slow and fast subsystems. These subsystems are used for Time Scale Synthesis which defines control laws capable of real-time implementation. A model, state feedback, and optimal control for mitigating transients on a transmission line are formed by using the defined control laws. The controller, a Linear Quadratic Regulator (LQR), is separated into slow and fast subsystems. MATLAB is used as a tool to compare the full order optimal controller to a control system that decouples the subsystems and uses two controllers in parallel. This chapter also determines whether or not Smart Wires devices affect the response of the LQR controllers.

#### **4.1 Modeling**

For convenience, some of the following information is reproduced from Chapter 2:

The main parameters that define the behavior of voltage,  $V$ , and current,  $I$ , signals as they travel via transmission line models are resistance  $R$ , inductance  $L$ , capacitance  $C$  and conductance  $G$ . Resistance and inductance define the series impedance,  $Z$ . Capacitance, and conductance characterize the shunt admittance,  $Y$  [14]. Losses are negligible for short lines and therefore are not often represented in the transmission line model [15].

The transmission line described in the problem statement certainly requires consideration of all parameters when modeled in PSSE and ASPEN One-Liner. However, for simplicity, conductance and shunt capacitance was ignored for all MATLAB simulations. Additionally, all MATLAB simulations assumed a constant load with zero reactance. Therefore, the model of the system in MATLAB is not equivalent to the model of the system in PSSE and ASPEN One-Liner

The technologies offered by Smart Wires allow an electric utility to add or subtract reactive impedance from the transmission line in order to reroute the current and mitigate overload conditions and congestion [2]. When Smart Wires devices are introduced into the system, the equivalent circuit of the short transmission line becomes as shown in Figure 4.1 [15].

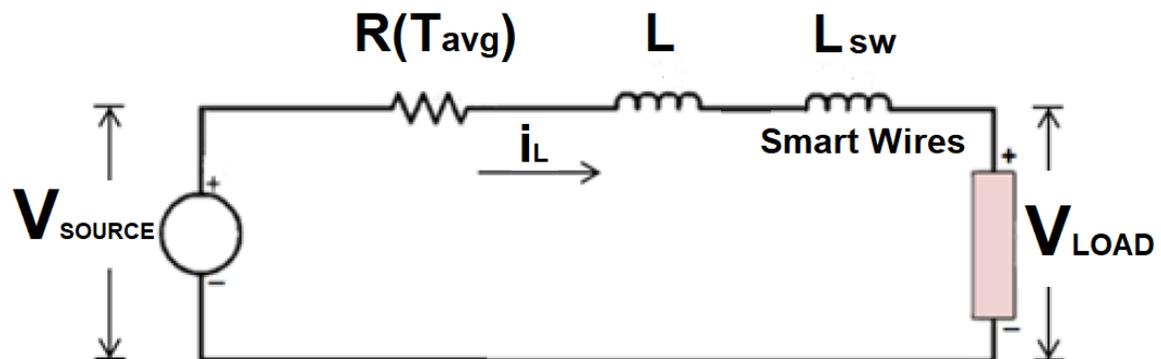


Figure 4.1: A Reproduced Model from Figure 2.4 - Equivalent Circuit of a Short line with Smart Wires [15]

The inductance of the transmission line with Smart Wires implemented is the following:

$$L_{eq} = L + L_{sw} \quad (4.1)$$

$L_{sw}$  is zero if there are no Smart Wires devices injecting inductance onto the line.

The equivalent circuit makes it possible to create a system of equations to represent a transmission line. Kirchhoff's voltage and current laws define the line current dynamics, and the temperature dynamics are represented using the heat balance equation specified by the IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors.

The system of equations shown below is reproduced from Chapter 2:

$$\frac{di_L(t)}{dt} = -i_L(t) * \frac{R(T_{avg})}{L_{eq}} - i_L(t) * \frac{R_{load}}{L_{eq}} + \frac{V_{source}}{L_{eq}} \quad (4.2)$$

$$\frac{dT_{avg}(t)}{dt} = \frac{1}{mC_p} * (R(T_{avg})i_L^2(t) + q_s - q_c - q_r) \quad (4.3)$$

$i_L(t)$  is the line current,  $T_{avg}(t)$  is the average line temperature,  $q_s$  is solar heat gain,  $q_c$  is convection heat loss,  $q_r$  is radiation heat loss, and  $m$  is mass per unit length of the conductor.

Equation 4.4, reproduced from Chapter 2, represents how resistivity changes with temperature. [16]

$$RT(T) = R_0[1 + \alpha(T-T_0)] \quad (4.4)$$

The state vector,  $x$ , is defined as:

$$x = \begin{bmatrix} i_L \\ T_{avg} \end{bmatrix} \quad (4.5)$$

The input vector,  $u$ , is defined as:

$$u = [V_{source}] \quad (4.6)$$

The system has electrical dynamics which operate at a faster time scale, and thermal dynamics which operate at a slower time scale. Because of this, it is evident that the real part of the fast dynamics eigenvalues is at least 5 times away from the real part of the slow dynamics eigenvalues in the group [39]. This is shown in Figure 4.2.

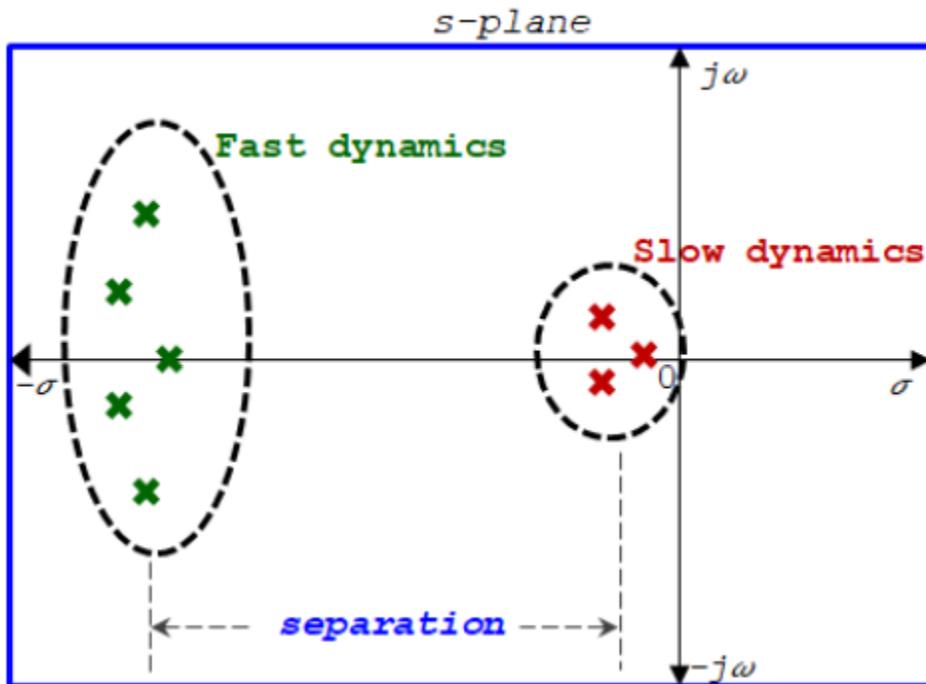
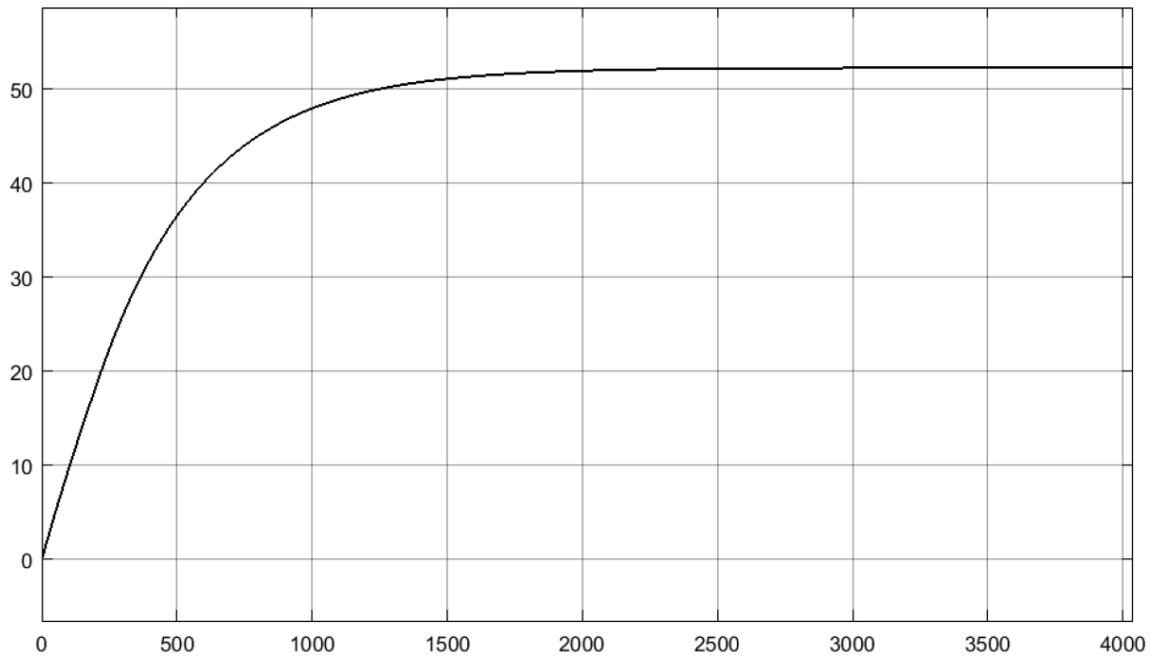


Figure 4.2: Eigenvalues - Fast and Slow Dynamics [15]

The slow and fast dynamics of the system interact with each other, making computations difficult, and thus complicating closed loop control schemes. When given a step input, the current responds much faster than the average temperature. The response of the slow dynamics is shown in Figure 4.3.



**Figure 4.3: Temperature, Time – seconds**

When comparing the slow dynamics to the fast dynamics, it is easier to consider the response to a step input in logarithmic scale; Figure 4.4 shows a logarithmic plot of the current and temperature on the same graph.

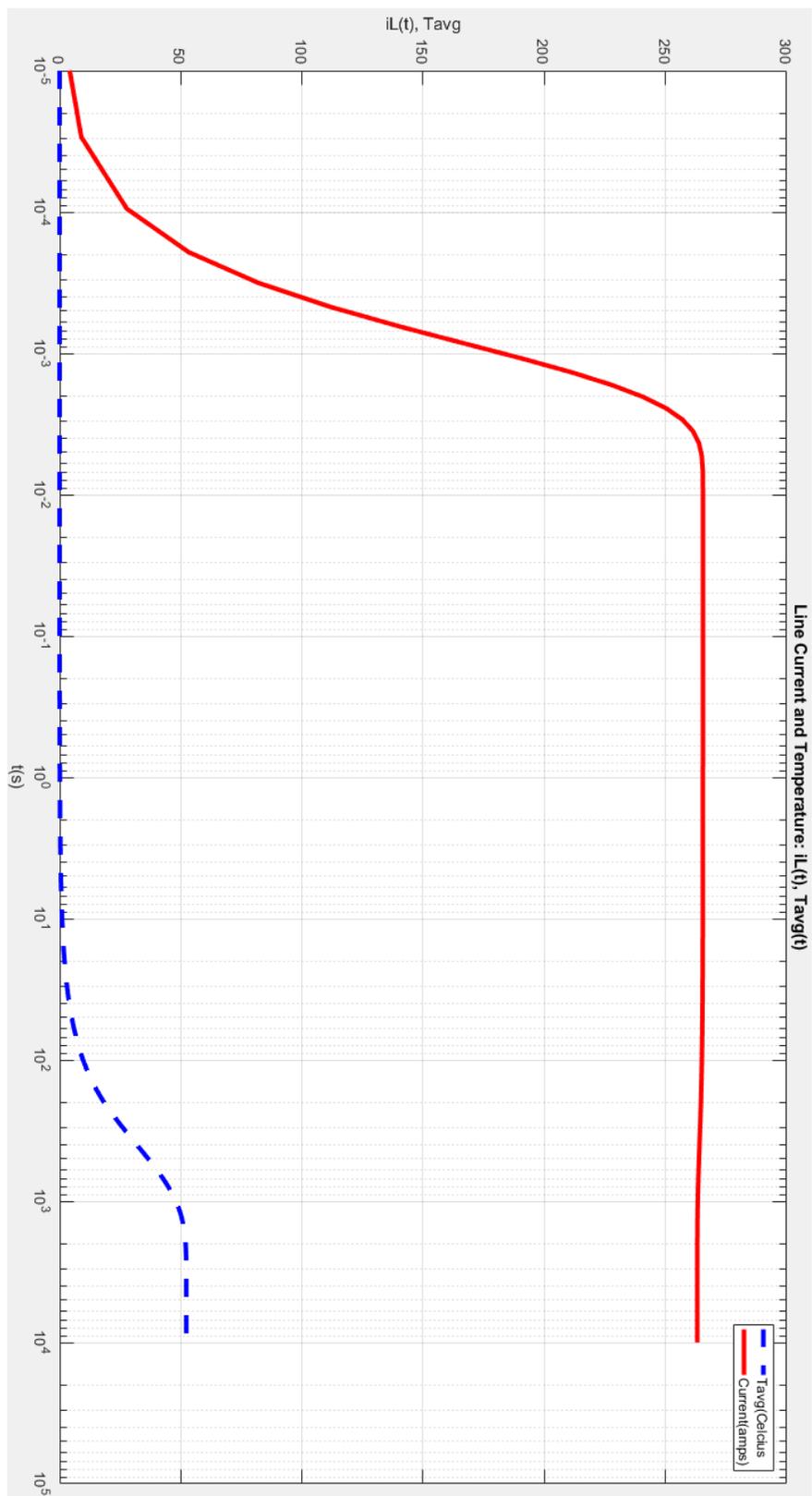


Figure 4.4: Temperature and Current Response Comparison, Logarithmic Timeline

## 4.2 DECOUPLING THE FAST AND SLOW DYNAMICS

Linearized about a nominal operating point of the system Equations 4.2 and 4.3, the transmission line system is obtained as the following:

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dT_{avg}(t)}{dt} \end{bmatrix} = \begin{bmatrix} -587.1616 & -0.0015 \\ 1.96 * 10^{-9} & -0.000286 \end{bmatrix} \begin{bmatrix} i_L(t) \\ T_{avg}(t) \end{bmatrix} + \begin{bmatrix} 5.87 \\ 0 \end{bmatrix} V_{source} \quad (4.7)$$

Where:

$Length = 109226$  meters

$i_L = 394$  amps

$t_{avg} = 62.08$

$R_{load} = 416.16 \Omega$

$L_{eq} = 0.1703$  h

$R_{T\_Low} = 0.00016556 \Omega$

$T_{Low} = 20^\circ C$

$T_{high} = 50^\circ C$

With Smart Wires, the system can be obtained as the following:

$$\begin{bmatrix} \frac{di_L(t)}{dt} \\ \frac{dT_{avg}(t)}{dt} \end{bmatrix} = \begin{bmatrix} -268.6169 & -0.000708 \\ 1.96 * 10^{-9} & -0.000286 \end{bmatrix} \begin{bmatrix} i_L(t) \\ T_{avg}(t) \end{bmatrix} + \begin{bmatrix} 2.69 \\ 0 \end{bmatrix} V_{source} \quad (4.8)$$

Where:

$Length = 109226$  meters

$i_L = 394$  amps

$t_{avg} = 62.08$

$R_{load} = 416.16 \Omega$

$L_{eq} = 0.3723$  h

$R_{T\_Low} = 0.00016556 \Omega$

$T_{Low} = 20^\circ C$

$T_{high} = 50^\circ C$

Since it is computationally difficult to design a controller for the full order system, a different approach is to decouple the fast and slow dynamics and to design an optimal control system for the fast system and for the slow system.

The slow and fast systems will be defined by the equations [40]:

$$\frac{dx_s}{dt} = A_s x_s(t) + B_s u(t) \quad (4.9)$$

$$\frac{dx_f}{dt} = A_f x_f(t) + B_f u(t) \quad (4.10)$$

We can solve for  $A_s$ ,  $B_s$ ,  $A_f$ , and  $B_f$  using the following equations:

$$A_s = A_{11} - A_{12}L \quad (4.11)$$

$$B_s = B_{11} - MLB_{11} - MB_{12} \quad (4.12)$$

$$A_f = A_{22} + LA_{12} \quad (4.13)$$

$$B_f = B_{12} + LB_{11} \quad (4.14)$$

$$LA_{11} + A_{21} + LA_{12}L - A_{22}L = 0 \quad (4.15)$$

$$(A_{11} - A_{12}L)M - M((A_{22} + LA_{12}) + A_{12}) = 0 \quad (4.16)$$

$L$  and  $M$  are solved iteratively using the Newton method [41]. Convergence of Newton's algorithm is demonstrated in reference [42]. From these equations, we can decouple the slow and fast dynamics of the system. The system can now be defined as such:

$$A_s = [-587.16] \quad A_f = [-0.0002859]$$

$$B_s = [5.8716] \quad B_f = [-0.000040278]$$

With Smart Wires, the system can be obtained as such:

$$A_s = [-268.62] \quad A_f = [-0.0002859]$$

$$B_s = [2.6862] \quad B_f = [-0.000018427]$$

### 4.3 Designing the LQR

The Performance index for the slow subsystem is as follows [40]:

$$J_s = \frac{1}{2} \int_{t_p}^{\infty} [X_s^T(t) Q_s X_s(t) + u_s^T(t) R_s u_s(t)] dt \quad (4.17)$$

Where  $Q_s$  and  $R_s$  are the weighting matrices for the slow subsystem. The control signal,  $u_s^*$ , and the slow algebraic Riccati equation, respectively, are [40]:

$$u_s^*(t) = -K_s X_s(t) = -R_s^{-1} B_s^T P_s X_s(t) \quad (4.18)$$

$$P_s A_s + A_s^T P_s + Q_s - P_s B_s R_s^{-1} B_s^T P_s = 0 \quad (4.19)$$

The Performance index for the fast subsystem is as follows:

$$J_f = \frac{1}{2} \int_{t_p}^{\infty} [X_f^T(t) Q_f X_f(t) + u_f^T(t) R_f u_f(t)] dt \quad (4.20)$$

Where  $Q_f$  and  $R_f$  are the weighting matrices for the fast subsystem. The control signal,  $u_f^*$ , and the slow algebraic Riccati equation, respectively, are:

$$u_f^*(t) = -K_f X_f(t) = -R_f^{-1} B_f^T P_f X_f(t) \quad (4.21)$$

$$P_f A_f + A_f^T P_f + Q_f - P_f B_f R_f^{-1} B_f^T P_f = 0 \quad (4.22)$$

The weighting matrices are chosen as follows:

$$R_s = 10, Q_s = 10000, R_f = 0.9, Q_f = 2$$

These matrices were chosen such that the states get to zero in the least amount of time.

The gains of the slow and fast subsystems are:

$$K_s = 41.4223 \text{ and } K_f = 0.1548$$

With Smart Wires, the gains of the slow and fast subsystems are:

$$K_s = 41.4222 \text{ and } K_f = 0.0714$$

The LQR control designs for the fast and slow subsystems work in parallel to bring any perturbations on the system to zero. The diagram for the LQR control design is shown in figure 6 below.

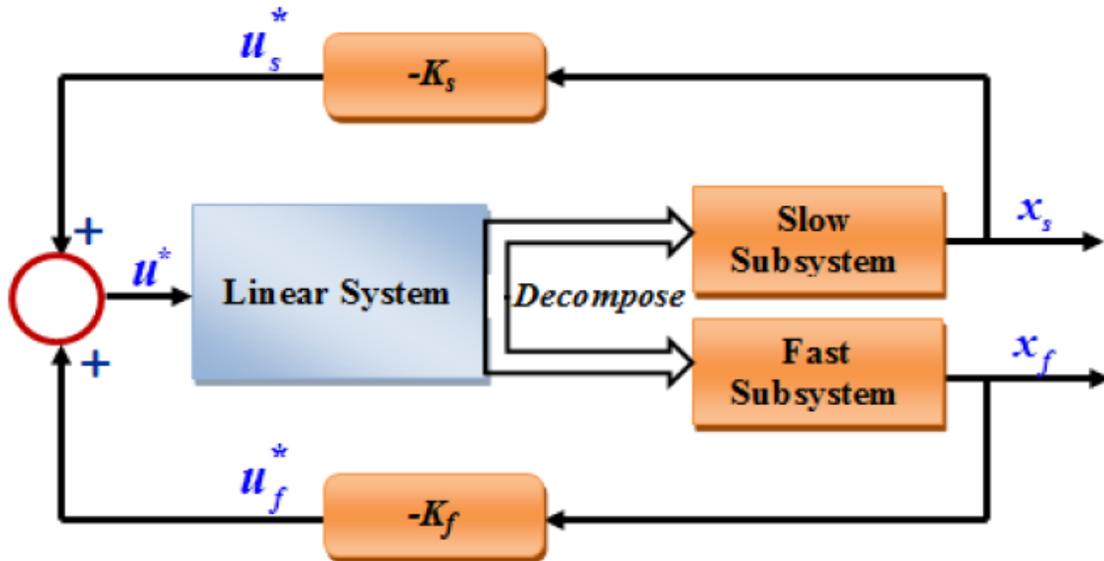
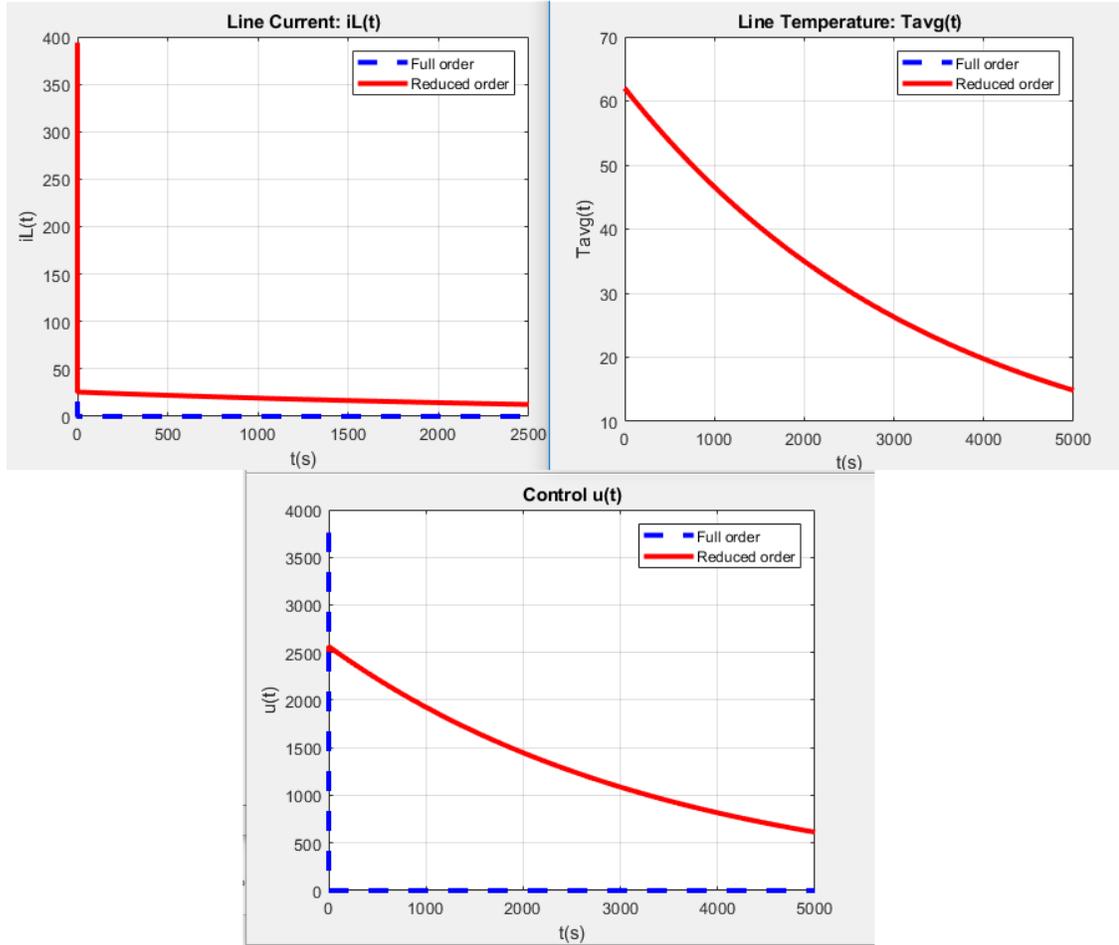


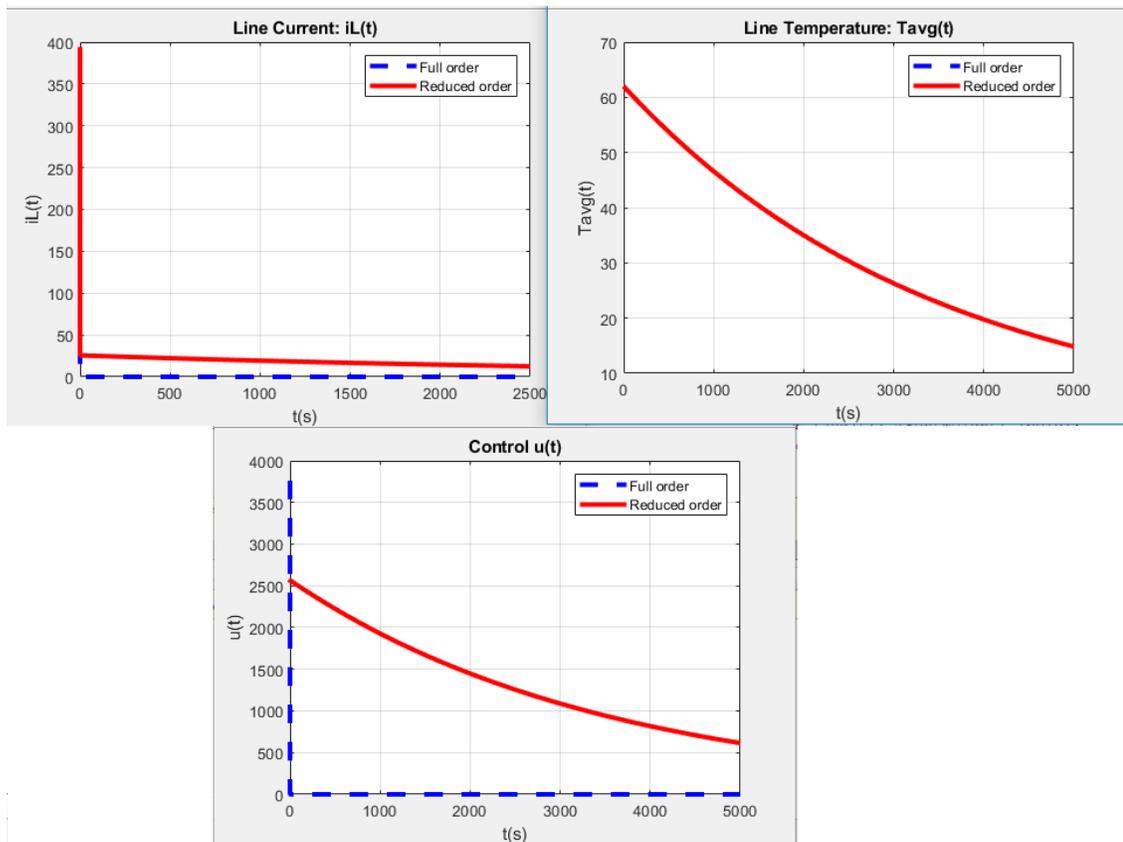
Figure 4.5: Diagram For LQR Control Design [15]

The LQR control design for a decoupled system works fairly well. In traditional LQR designs, the slow and fast dynamics are not separated. The full order system is compared with the decoupled system in the graphs in Figure 4.6. Figure 4.6 shows the control system responses to a step input when there are no Smart Wires devices on the transmission line.



**Figure 4.6: Comparison of Full Order and Reduced Order LQR – No Smart Wires**

The LQR control design for a decoupled system works fairly well. In traditional LQR designs, the slow and fast dynamics are not separated. The full order system is compared with the decoupled system in Figure 4.7. Figure 4.7 shows the control system responses to a step input shown when there are 168 Smart Wires devices on the transmission line. The devices are modeled in MATLAB by changing the inductance parameter to reflect the total inductance injected onto the line as shown in Equation 4.1.



**Figure 4.7: Comparison of Full Order and Reduced Order LQR – With Smart Wires**

The LQR is insensitive to change in line reactance introduced by Smart Wires devices on a radial line with constant load. This analysis proves that the design would work under different conditions.

The response of the LQR controller for the reduced order system is slightly slower than that of the full order system, but the lower order controllers are less computationally expensive and could offer a cheaper method than that of traditional methods.

Decoupling the system makes the computations much less difficult – which can reduce cost. Most LQR designs do not separate the slow and fast dynamics. An LQR design that separates the slow and fast dynamics is just as effective as the full order system in bringing the perturbations to zero, but is slightly slower in bringing the input,  $u(t)$ , to zero. The line current is not immediately brought to zero as shown in Figures 4.6 and 4.7, but is very close to doing so;  $R_s$ ,  $Q_s$ ,  $R_f$ , and  $Q_f$  can be adjusted to account for this error.

Control room operators might be concerned with an LQR control design that is slower than the standard full order control design. More research should be done in order to improve the response of the reduced order design. It is possible that this can be achieved by adjusting the weighting matrices.

This type of control design would also be useful in a hypothetical cyber-attack that renders one of the LQR controllers useless. Since this control design has two controllers – one for the slow subsystem and one for the fast subsystem – the system would still have one controller left after a successful cyber-attack. However, it is unlikely that the system would be survivable if the fast controller was lost.

#### **4.4 Chapter Conclusions**

This chapter examined a time domain modeling approach that defined the electrical and thermal dynamics of transmission line. This method allows real-time line monitoring of transmission lines, which is important in determining true ampacity.

Overall, the controller design is an innovative method of bringing perturbations on a transmission line to zero. Although still in the research phase, this design has potential for implementation on a real system. The simulations show that the LQR is insensitive to change in line reactance introduced by Smart Wires devices on a radial line with constant load. This analysis proves that the design would work under different conditions. This controller is similar to a Remedial Action Scheme (RAS), and could be used to adjust

generation during normal load conditions. This scheme could be used in a similar function as Smart Wires: rolling back generation when line overloading occurs.

Most power utilities would be hesitant to abandon protective relaying that has consistently proven to isolate and bring perturbations to zero, but it is possible that the controller designs discussed in this chapter will be used on a much smaller systems such as microgrids. Schweitzer Engineering Laboratories (SEL) offers microgrid controllers [43], and a comparison to the controller designed in this chapter and the one offered by SEL would be a beneficial study for application and design. The controller designs discussed in this chapter would have applications in mitigating transient behavior seen in existing wind turbines. Traditional relay applications are unable to mitigate sub-harmonic current oscillations seen in wind turbine models, but ERLPhase Power Technologies Ltd offers protection against these instabilities [44]; Smart Wires could also be used to mitigate sub-harmonic current oscillations.

## Chapter 5 Summary and Future Research

This thesis addressed a problem shown in a power flow study that revealed overload conditions due to changes in power generation. Smart Wires was presented as an effective means to mitigate the overload conditions, and the Smart Valve was the best product available when considering weight and number of devices.

Automation files were used to determine the number of Smart Wires devices needed and assisted with longevity analysis. Longevity is primarily influenced by load growth, and this thesis gave graphical evidence for a solution lasting up to 20 years. This thesis addressed the challenges that arise from a transmission line whose reactive impedance varies depending on settings. It was determined that traditional solutions are more permanent solutions than what is offered by Smart Wires. Future work might look into the advantages of being able to redeploy the Smart Wires devices, and also look into the transportation methods mentioned in reference [45]

Additionally, the problem of time scale analysis and synthesis of the transmission line, with and without Smart Wires, was addressed. The decoupled controller design is an innovative method of bringing perturbations on a transmission line to zero. Although still in the research phase, this design has potential for implementation on a real system. Most power utilities would be hesitant to abandon protective relaying that has consistently proven to isolate and bring perturbations to zero, but it is possible that the controller designs discussed in this chapter will be used on smaller systems such as microgrids. More research should be done in order to improve the response of the reduced order design. It is possible that this can be achieved by adjusting the weighting matrices. In future research, it might be worthwhile to examine the methods discussed in reference [46] in order to adjust the weighting matrices and optimize the response of the controllers.

Smart Wires devices could possibly be used for Real-time Dynamic Thermal Rating (RDTR) according to reference [47]. RDTR is important, because 10-30% of line

capacity is not being utilized for 90-98% of the time due to the restrictions imposed by current operational techniques [48].

Perhaps the biggest question that remains is how protective relay coordination would be affected by a Smart Wires solution. Impedance based relays would present challenges, and other relay schemes would need to be investigated in order to ensure proper system protection. Smart Wires devices would need to communicate to the protective relays how much, if any, inductance or capacitance is being injected into the transmission line.

The simulation results in this limited case study showed no negative impacts of Smart Wires. It would be beneficial to complete a more comprehensive study to determine if a significant increase of reactive impedance could lead to voltage violations. Power electronics devices called Static Synchronous Compensator (STATCOMS) are made up of capacitors and inductors and can be connected in series or in parallel with the lines. The STATCOM shown in Figure 5 would act as a capacitor generating reactive power when the secondary voltage is lower than the bus voltage. It would serve as an inductor when the secondary voltage is higher than the bus voltage, absorbing reactive power from the bus [49].

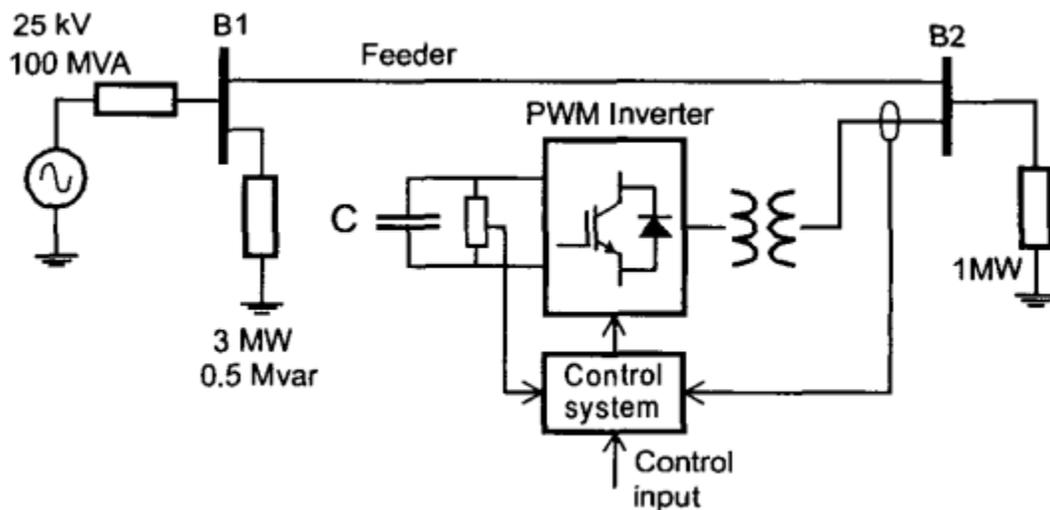


Figure 5.1: Static Synchronous Compensator (STATCOM) [49]

A STATCOM can improve efficiency, increase transmission capacity, and reduce the risk of blackouts and voltage collapse [50]. Future research should study the overall impact that Smart Wires devices can have on line voltage to determine if they can stabilize line voltage.

Smart Wires offers an affordable and innovative solution that would allow a power utility to mitigate overload conditions on a transmission line without the downsides of huge capital costs and years of planning. Smart Wires would also create obstacles for engineers to overcome, but the benefit of a dynamically controlled system is that the utility would be better positioned to deal with intermittent resources and the transition away from traditional fossil resources. A clean and responsible future is worth the challenges we face.

## Bibliography

- [1] IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors (738-2012), US: IEEE, 2013.
- [2] <https://www.smartwires.com/>.
- [3] R. Zavadil, "Comparative Performance of Smart Wires SmartValve with EHV Series Capacitor: Implications for Sub-Synchronous Resonance," 2018.
- [4] "Nebraska Public Power District," [Online]. Available: [http://www.nppd.com/assets/image15\\_large.jpg](http://www.nppd.com/assets/image15_large.jpg).
- [5] J. D. McDonald, *Electric Power Substations Engineering*, CRC Press, 2012.
- [6] C. R. Mason, *The Art and Science of Protective Relaying*, 1956.
- [7] N. Tleis, *Power Systems Modelling and Fault Analysis*, Elsevier Ltd, 2008.
- [8] M. M. Saha, J. Izykowski and E. Rosolowski, *Fault Location on Power Networks*, Springer, 2010.
- [9] ABB, "Electrical Transmission and Distribution Reference Book," pp. 342-378, 1997.
- [10] "Protective Zones in Power Systems," [Online]: <http://www.studyelectrical.com/2016/09/protective-zones-in-power-systems.html>.
- [11] EATON BUSSMANN SERIES, "Overcurrent Protection Fundamentals," 2017.
- [12] NERC, "Standard PRC-004-5 — Protection System Misoperation Identification and Correction," Effective Date: 2005, Revision: 2015.
- [13] ASPEN, "OneLiner: The leading short circuit and relay coordination system," [Online]: <https://www.aspeninc.com/web/software/oneliner>.
- [14] L. Andrade, H. Leite and M. Leao, "Time-domain distributed parameters transmission line model for transient analysis," *Progress In Electromagnetics Research*, vol. 53, pp. 25-46,

2013.

- [15] S. Jaison, "Time Scale Analysis and Synthesis in Electrical Energy and Life Sciences," Idaho State University, 2017.
- [16] J. H. Dellinger, "THE TEMPERATURE COEFFICIENT OF RESISTANCE OF COPPER," *Bulletin of the Bureau of Standards*, vol. 7, 1910.
- [17] M. Farzaneh, S. Farokhi and W. Chisholm, *Electrical Design of Overhead Power Transmission Lines*, McGraw-Hill Companies Inc., 2012.
- [18] Minnesota Power - Transmission Planning Group, "Conductor Ratings, Distribution Factor, Sensitivity and Longevity Analysis," 2017.
- [19] Siemens AG, "High-performance Transmission Planning and Operations Software for the Power Industry," 2017.
- [20] W. Min Byong, M. Choi and A. Deb, "Line Rating System Boosts Economical Energy Transfer," *IEEE*, vol. 10, no. 4, pp. 36-39, 1997.
- [21] "Electric Power Monthly," U.S. Energy Information Administration, [Online]. Available: <https://www.eia.gov/todayinenergy/detail.php?id=31632#>., 2017.
- [22] S. Marcacci, "Utilities Closed Dozens Of Coal Plants In 2017. Here Are The 6 Most Important.," [Online] Forbes, <https://www.forbes.com/sites/energyinnovation/2017/12/18/utilities-closed-dozens-of-coal-plants-in-2017-here-are-the-6-most-important/#2ff3c98d5aca>, 2017.
- [23] J. Lin, "Optimizing natural gas generation with energy storage," [Online] Utility Dive, <https://www.utilitydive.com/news/optimizing-natural-gas-generation-with-energy-storage/540401/>, 2018.
- [24] J. C. S. RAMSAY, C. T. J. MELCHER and F. KREIKEBAUM, "Deploying Power Flow Control to Improve the Flexibility of Utilities Subject to Rate Freezes and Other Regulatory Restrictions," *Cigre*, 2013.
- [25] F. Kreikebaum, A. Wang and S. Broad, "Integration of Series FACTS into Interconnect-scale Production Cost and Long-term Planning Tools," *Cigre*, 2016.
- [26] L. Grant, J. Shultz, S. Omran, J. Couillard, F. Kreikebaum and R. Broadwater, "Initial Field Trials of Distributed Series Reactors and Implications for Future Applications," *Cigre*, 2014.

- [27] Smart Wires Inc, "A Flexible Future: Addressing Uncertainty in the Grid with Innovative Power Flow Control Technology," [Online] <https://www.smartwires.com/papers/>, San Francisco, 2017.
- [28] O. Pohl, A. Kubis and D. Kirsten, "Advancements in Distributed Power Flow Control," [Online]<https://www.smartwires.com/papers/>.
- [29] Smart Wires Inc., "Smart Wires Power Router," 2016.
- [30] Pacific Gas and Electric Company, "PG&E - EPIC Final Report," [Online] <https://www.smartwires.com/papers/>, 2016.
- [31] P. Jennings, F. Kreikebaum and J. Ham, "Flexibility in Wind Power Interconnection Utilizing Scalable Power Flow Control," *Cigre*, 2015.
- [32] Smart Wires, "Power Guardian 700, Version 180208," [Online]: <https://www.smartwires.com/guardian/>, San Francisco, 2018.
- [33] Smart Wires Inc., "Equations, Company Information," 2017.
- [34] Smart Wires Inc, "Power Guardian, Version 170426," [Online] <https://www.smartwires.com/guardian/>, San Francisco, 2017.
- [35] Smart Wires Inc, "Smart Valves 500-900, Version 180504," [Online] <https://www.smartwires.com/smartvalve/>, San Francisco, 2018.
- [36] Smart Wires Inc., "Smart Bypass 400, Version 180507," San Francisco, 2018.
- [37] R. Zavadil, "COMPARATIVE PERFORMANCE OF SMART WIRES POWER ROUTER WITH EHV SERIES CAPACITOR: IMPLICATIONS FOR SUB-SYNCHRONOUS RESONANCE (SSR)," *EnerNex*, 2016.
- [38] S. Jaison, D. Naidu and D. Zydek, "Time Scale Analysis and Synthesis of Deterministic and Stochastic Wind Energy Conversion Systems," *WSEAS Transactions*, vol. 9, pp. 189-198, 2014.
- [39] D. Naidu, "Singular perturbations and Time Scales in Control Theory and Applications: An Overview," *Dynamics of Continuous, Discrete and Impulsive Systems Series*, vol. 9, pp. 233-278, 2002.
- [40] D. Naidu, *Optimal Control Systems*, CRC Press, 2003.

- [41] Z. Gajic and M. Lim, *Optimal control of singularly perturbed linear systems and applications- High accuracy techniques*, New York: Marcel Dekker, Inc, 2001.
- [42] T. Grodt and Z. Gajic, "The Recursive Reduced-Order Numerical Solution of the Singularly Perturbed Matrix Differential Riccati Equation," *IEEE Transactions on Automatic Control*, vol. 33, no. 8, pp. 751-754, 1988.
- [43] Schweitzer Engineering Laboratories, "2017 Catalog," pp. 40-41.
- [44] ERL, "Sub-Harmonic Protection Relay, S-PRO 4000, Model 4001".
- [45] Smart Wires Inc., "Mobile Deployment," [Online]:  
<https://www.smartwires.com/mobile/#tab-id-1>, 2018.
- [46] T. Chibanga, "Applications of the Inverse LQR Problem to a Wind Energy Conversion System," University of Minnesota, Duluth, 2016.
- [47] F. Kreikebaum, D. Das, Y. Yang, F. Lambert and D. Divan, "Smart Wires – A Distributed, Low-Cost Solution for Controlling Power Flows and Monitoring Transmission Lines," [Online]:  
[http://www.smartwires.com/wp-content/uploads/2015/01/Smart\\_Wire\\_3.pdf](http://www.smartwires.com/wp-content/uploads/2015/01/Smart_Wire_3.pdf).
- [48] J. Lilien, "Ampacimon as a Tool for Transmission Line Assets," University of Liège, [Online]:  
[www.ampacimon.com](http://www.ampacimon.com) , 2008.
- [49] P. Giroux, G. Sybille and H. Le-Huy, "Modeling and simulation of a distribution STATCOM using Simulink's Power System Blockset," *IEEE*, 2001.
- [50] ABB, "SVC Light® For electrical transmission grids," 2014.

## Appendices

### A.1: Calculating the Number of Smart Wires Devices Needed

Python Code:

---



---

```

#"Number_of_Devices_Needed_MVA-Target"
import math
#p.u. injection
puinjection=.004083
numofdevices=0
old_impedance=.107012
new_impedance=numofdevices*puinjection+old_impedance

#overloaded branch
devicesonbus1=608740#Substation 1 Bus #
devicesonbus2=618009#Substation 2 Bus #
psspy.branch_chng(devicesonbus1,devicesonbus2,r""1"",[_i,_i,_i,_i,_i,
_i],[_f, new_impedance,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
psspy.fdns([1,0,0,1,1,0,0,0])
#target rating
target=55*1
#MVA Arrays
MVA_FROM_BUS_NUM = [608740]#Substation 1 Bus #
MVA_TO_BUS_NUM = [618009]#Substation 2 Bus #
MVA_FROM_BUS_NAME = ['Substation 1 115.00']
MVA_TO_BUS_NAME = ['Substation 2 115.00']

#MVA Data
MVA_LINES_MW = []
MVA_TEMP_MW = 0.0
#Retrieve, Calculate, Store, Display MVA Levels
for i in range(len(MVA_FROM_BUS_NUM)):
    MVA_LINES_MW.append(i)
for i in range(len(MVA_FROM_BUS_NUM)):
    ierr, MVA_TEMP_MW = psspy.brnmsc(MVA_FROM_BUS_NUM[i],
MVA_TO_BUS_NUM[i], r""1"", "MVA")
    if ierr != 0:
        MVA_LINES_MW[i] = 0.0
        FLOW_STRING = 'MVA: Line from ' + repr(MVA_FROM_BUS_NAME[i]) +
' to ' + repr(MVA_TO_BUS_NAME[i]) + ' does not exist in this model.'
        print FLOW_STRING
    elif ierr == 0:
        MVA_LINES_MW[i] = MVA_TEMP_MW
    else:
        FLOW_STRING = 'MVA ERROR'
        print FLOW_STRING

```

```

MVA_INTERFACE_STRING = 'Modeled ll flow is ' +
repr(round(sum(MVA_LINES_MW), 2)) + ' MVA. \n'
print MVA_INTERFACE_STRING

MW_REP=round(sum(MVA_LINES_MW), 2)
while (MW_REP >= target):
    numofdevices=numofdevices+1
    new_impedance=numofdevices*puinjection+old_impedance
    psspy.branch_chng(608740,618009,r""1"",[_i,_i,_i,_i,_i,_i],[_f,
new_impedance,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
    psspy.fdns([1,0,0,1,1,0,0,0])
    for i in range(len(MVA_FROM_BUS_NUM)):
        MVA_LINES_MW.append(i)
    for i in range(len(MVA_FROM_BUS_NUM)):
        ierr, MVA_TEMP_MW = psspy.brnmsc(MVA_FROM_BUS_NUM[i],
MVA_TO_BUS_NUM[i], r""1"", "MVA")
        if ierr != 0:
            MVA_LINES_MW[i] = 0.0
            FLOW_STRING = 'MVA: Line from ' +
repr(MVA_FROM_BUS_NAME[i]) + ' to ' + repr(MVA_TO_BUS_NAME[i]) + ' does
not exist in this model.'
            print FLOW_STRING
        elif ierr == 0:
            MVA_LINES_MW[i] = MVA_TEMP_MW
        else:
            FLOW_STRING = 'MVA ERROR'
            print FLOW_STRING
    MW_REP=round(sum(MVA_LINES_MW), 2)
MVA_INTERFACE_STRING = 'Modeled Current Level is ' +
repr(round(sum(MVA_LINES_MW), 2)) + ' MVA. \n'
print MVA_INTERFACE_STRING
NUM_OF_DEV_STRING = 'We need ' + repr(3*(numofdevices)) + ' guardians'
print NUM_OF_DEV_STRING

```

---

---

## A.2: Scale Buses by 100 MW for Distribution Factor Calculation

```
# Reads in specific buses and scales up by 100 MW while maintaining
#power factor

psspy.bsys(1,0,[0.0,0.0],0,[],146,[

#{INSERT LIST OF BUSES THAT INCREASE LOADING ON LINE 1-2 BY 4% #WHEN
#100 MW IS ADDED}

],0,[],0,[])

psspy.scal_2(1,0,1,[0,0,0,0,0],[0.0,0.0,0.0,0.0,0.0,0.0,0.0])

psspy.scal_2(0,1,2,[_i,1,0,1,0],[ 681.04, 26.4,0.0,-.0,0.0,-.0,
132.18])
```

---

---

---



---

### A.3: Read in MVA for a Range of Smart Wires Devices

```

Longevity Analysis - MVA_53-70_Devices
import math
# File:"C:\Users\abekkala\Downloads\smartwires.py", generated on MON,
NOV 06 2017 13:49, release 33.05.02
#Contingencies
#lineoutbus1=608612
#lineoutbus2=608625
#psspy.fdns([1,0,1,1,1,0,99,0])
#psspy.fdns([1,0,0,1,1,0,99,0])
#psspy.branch_chng(lineoutbus1,lineoutbus2,r""1"",[0,_i,_i,_i,_i,_i],
[_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])

#p.u. injection
#zbase=132.25
puinjection=.004083
numofdevices=53

old_impedance=.107012
new_impedance=numofdevices*puinjection+old_impedance

#overloaded branch
devicesonbus1=608740 #Substation 1 Bus #
devicesonbus2=618009 #Substation 2 Bus #
psspy.branch_chng(devicesonbus1,devicesonbus2,r""1"",[_i,_i,_i,_i,_i,
_i],[_f,new_impedance,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
psspy.fdns([1,0,0,1,1,0,0,0])

#target rating
PF=1
#target=276*PF*1.0
target=55
#MVA Arrays
MVA_FROM_BUS_NUM = [608740] #Substation 1 Bus #
MVA_TO_BUS_NUM   = [618009] #Substation 2 Bus #
MVA_FROM_BUS_NAME = ['Substation 1    115.00']
MVA_TO_BUS_NAME   = ['Substation 2    115.00']
devices_array     =
[53.,54.,55.,56.,57.,58.,59.,60.,61.,62.,63.,64.,65.,66.,67.,68.,69.,70
.]
#MVA Data
MVA_LINES_MVA     = []
MVA_TEMP_MVA      = 0.0
MVA_Array         = []

for j in range(len(devices_array)):
    MVA_Array.append(j)

```

```

for j in range(len(devices_array)):

    #numofdevices=numofdevices+1
    new_impedance=(devices_array[j])*puinjection+old_impedance

#psspy.branch_chng(devicesonbus1,devicesonbus2,r""1"",[_i,_i,_i,_i,_i
,_i],[_f, new_impedance,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
    psspy.branch_chng(608740,618009,r""1"",[_i,_i,_i,_i,_i,_i],[_f,
new_impedance,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f,_f])
    psspy.fdns([1,0,0,1,1,0,0,0])
    for i in range(len(MVA_FROM_BUS_NUM)):
        MVA_LINES_MVA.append(i)

    for i in range(len(MVA_FROM_BUS_NUM)):
        ierr, MVA_TEMP_MVA = psspy.brnmsc(MVA_FROM_BUS_NUM[i],
MVA_TO_BUS_NUM[i], r""1"", "MVA")
        if ierr != 0:
            MVA_LINES_MVA[i] = 0.0
            FLOW_STRING = 'MVA: Line from ' +
repr(MVA_FROM_BUS_NAME[i]) + ' to ' + repr(MVA_TO_BUS_NAME[i]) + ' does
not exist in this model.'
            print FLOW_STRING
        elif ierr == 0:
            MVA_LINES_MVA[i] = MVA_TEMP_MVA
            #FLOW_STRING = 'MVA: Line from ' +
repr(MVA_FROM_BUS_NAME[i]) + ' to ' + repr(MVA_TO_BUS_NAME[i]) + '
exists in this model with flow at ' + repr(round(MVA_TEMP_MVA, 2)) + '
MVA.'
            #print FLOW_STRING
        else:
            FLOW_STRING = 'MVA ERROR'
            print FLOW_STRING

    MVA_REP=round(sum(MVA_LINES_MVA), 2)
    MVA_Array[j]=MVA_REP
    #psspy.fdns([1,0,0,1,1,0,99,0])

devices_array_new = []
for j in range(len(devices_array)):
    devices_array_new.append(j)
for j in range(len(devices_array)):
    devices_array_new[j]=3*devices_array[j]
print devices_array_new
print MVA_Array
#MVA_INTERFACE_STRING = 'Modeled Current Level is ' +
repr(round(sum(MVA_LINES_MVA), 2)) + ' MVA. \n'
#print MVA_INTERFACE_STRING
#NUM_OF_DEV_STRING = 'We need ' + repr(3*(numofdevices)) + ' guardians'
#print NUM_OF_DEV_STRING

```

---



---

**A.4 Overloading on Line 1-2**

Loads ON/OFF	Load (MVA)	Rating (MVA)	% Loading
Indust. Load 1 OFF, Indust. Load 2 OFF	78.6	55	142.91
Indust. Load 1 OFF, Indust. Load 2 ON	75.9	55	138.00
Indust. Load 1 ON, Indust. Load 2 OFF	75.9	55	138.00
Indust. Load 1 ON, Indust. Load 2 ON	73.1	55	132.91

**Table A.1: Overloading Given Different Industrial Load**

## A.5 MATLAB: Parameters for Simulink – With Smart Wires

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% File Name: parameters_for_simulink_with_smart_wires.m
% Date: 08/21/2018
% Authors: Allan Bekkala, Shaleena Jaison
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
clc

%% Initial conditions
% i_ic = 1138;
% Tavg_ic = 112.7916;
% i_ic = 0;
% Tavg_ic = 0;
i_ic = 0%265.4;
Tavg_ic = 0%52;

%% Line length
len = 67.87*1609.34; % meters

%% qs value - calculation
alpha = 0.8; % solar absorptivity
Lat = 47.24; % Latitude, degNorth
N = 161; % Day of the year for June 10 (sample calc.)
delta = 23.46*sind(360*(284+N)/365); % solar declination,deg
omega = -15; % hour angle for 11:00 a.m., degrees
Hc = asind( cosd(Lat)*cosd(delta)*cosd(omega) + sind(Lat)*sind(delta)
);% Solar Altitude, deg
Qs_inp_args = [Hc, -42.2391, 63.8044, -1.9220, 3.4692e-2, -3.6111e-4,
1.9431e-6, -4.07608e-9];
Qs = calcQs(Qs_inp_args);% Total heat flux density, W/m^2

He = 0; % line elevation, m
Ksolar = 1 + 1.148e-4*He + (-1.108e-8)*He^2;
Qse = Ksolar*Qs;
psi_ang = sind(omega)/(sind(Lat)*cosd(omega) - cosd(Lat)*tand(delta)
);
% Constant C_azm -> lookup table
if (-180<=omega)&& (omega<0)
    disp('step1')
    if(psi_ang>=0)
        C_azm = 0;
        sprintf('C = %d',C_azm);
    else
        C_azm = 180;
        sprintf('C = %d',C_azm);
    end
elseif(0<=omega)&& (omega<180)
    disp('step2')
    if(psi_ang>=0)
        C_azm = 180;

```



```
%L=1.56*10e-06*len
%% R(Tavg) calc
Tlow = 20; % degC
Thigh = 50; % degC
%.03151
R_Tlow = 0.00016556 % (ohm/m)

%R_THigh = 0.00016556*(1+.00387*(50-20))
%R_Tlow = 7.283e-5; % ohm/m
R_Thigh = 1.8563e-04; % ohm/m

% load('Ks')
% load('Kf')
```

## A.6 MATLAB: System\_of\_Equations\_Equiv\_Circuit

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% File Name: System_of_Equations_Equiv_Circuit
% Date: 11/8/2018
% Authors: Allan Bekkala
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

syms M
p_air=1.225
i_avg=394;
t_avg=62.08;
%qr=(17.8*D0*epsilon*(((t_avg+273)/100)^4)-((Ta+273)/100)^4))*60000
qr=(17.8*D0*epsilon*(((t_avg+273)/100)^3)/100)*60*1000
qc=3.645*(p_air^.5)*(D0^.75)*60*1000%*(t_avg-Ta)^1.25
A1=-(1/L)*((R_Thigh-R_Tlow)/(Thigh-Tlow)*(111.79-25)+R_Tlow+100)
A2=-i_avg*(1/L)*(R_Thigh-R_Tlow)/(Thigh-Tlow);
A3=(1/mCp)*(i_avg*(R_Thigh-R_Tlow)/(Thigh-Tlow)*(111.79-25)+R_Tlow)
A4=(1/mCp)*((i_avg)^2*(R_Thigh-R_Tlow)/(Thigh-Tlow))-qr-qc)
%A4=(1/mCp)*((i_avg)^2*485.3*L-qr-qc)
Bu=1/L
%A3=0.0001684;
%A4=-0.001462;
%L=6*10^-8

Eq1=L*A1+A3-L*A2*L-A4*L
Eq2=(A1-A2*L)*M-M*(A4+L*A2)+A2
A=[A1 A2; A3 A4];
%plot(L,Eq1)
%[C,D] = equationsToMatrix([Eq1, Eq2], [L, M])

```

## A.7 MATLAB: Data for the LQR Controller

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% File Name: data_TSA_lqr_linear_txnline.m
% Date: 04/23/2015
% Author: Allan Bekkala, Shaleena Jaison
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
clc
close all
%With Smart Wires
A = [-268.6169 -7.0803E-04; 1.9615e-09 -2.8594e-04]
B = [2.6862;0];
C = [1 0;0 1];
D = [0;0];

%Without Smart Wires
%A = [-587.1616 -.0015; 1.9615e-09 -2.8594e-04]
%B = [5.8716;0];
%C = [1 0;0 1];
%D = [0;0];

% Computing the row norms of A matrix
display('Row norms of A matrix')
fprintf('%f\n%f\n%f\n',norm(A(1,:)),norm(A(2,:)))

% PERMUTATION of A matrix
% Defining the elementary column vector
e1 = [1;0];
e2 = [0;1];

% Defining the permutation matrix P
P = [e1 e2]; % no permutation
% P = [e2 e1];

Ap = P*A*P^-1;

% Computing the row norms of Ap matrix
display('Row norms of Ap matrix')
sprintf('%f\n%f\n%f\n',norm(Ap(1,:)),norm(Ap(2,:)))
%

% A11 = Ap(1,1)      % 1x1
% A12 = Ap(1,2:3)   % 1x2
% A21 = Ap(2:3,1)   % 2x1
% A22 = Ap(2:3,2:3) % 2x2

A11 = Ap(1,1);      % 1x1
A12 = Ap(1,2);      % 1x1
A21 = Ap(2,1);      % 1x1

```

```

A22 = Ap(2,2);      % 1x1

% Permuted B matrix:
Bp = P*B
B1 = Bp(1,:);
B2 = Bp(2,:);

epsilon=1;

[Ln,Mn,k] = Hoa_Newton(A11,A12,A21,A22,epsilon,10^-4);
As = A11 - A12*Ln;
Af = A22 + Ln*A12;
Bs = B1 - Mn*Ln*B1 - Mn*B2;
Bf = B2 + Ln*B1;

Po = eig(Ap)
Ps = eig(As)
Pf = eig(Af)

%% Design of LQR controllers

Q = [1000 0; 0 1];

R = .5*eye(1);

[K,S,e] = lqr(A,B,Q,R);
K

% LQR controller for the slow subsystem
Qs_lqr = 10000*eye(1);

Rs = 10*eye(1);

[Ks,Ss,es] = lqr(As,Bs,Qs_lqr,Rs);
% Ks = lqr(As,Bs,Qs,Rs)
Ks

% LQR controller for the fast subsystem
Qf_lqr = 2*eye(1);
Rf = .90*eye(1);

[Kf,Sf,ef] = lqr(Af,Bf,Qf_lqr,Rf);
% Kf = lqr(Af,Bf,Qf,Rf)
Kf

%% System Response Plots

t = 0:0.05:10;
tfinal = 10000;

```

```
BIN = [0;0];  
% X0= [1140;115];  
X0= [0.1;1];  
% [Y,X,t]=initial(A-B*K,BIN, C,D, X0,tfinal);  
  
[Y,X,t]=initial(A-B*K,BIN, C,D, X0,tfinal);
```