D-FACTS for Improved Reliability of

the Transmission System

during Contingencies

A Thesis

Presented in Partial Fulfillment of the Requirements for the

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by

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Authorization to Submit Thesis

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Abstract

This thesis reports on an investigation of the impact of a limited number of D-FACTS devices on typical power lines that utilities have within their grids. The D-FACTS devices do not require space in a substation and have reduced costs compared to rewiring an existing line or installing a new line. The device is designed to clamp onto existing power lines and therefore assist in power flow without the necessity of redesigning existing power delivery systems.

The lines are modeled appropriately with existing data from the WECC. Then D-FACTS devices are modeled and integrated with line models for appropriate simulation studies. This process uses commercial software for simulation. Applying these models to existing operating conditions yields predictions of device performance within the grid and identifies appropriate degrees of compensation. Finally, analysis of these results will be used to give some recommendations for modifying the specific system at hand using D-FACTS devices.

Acknowledgements

I thank my major professor, Dr. Herbert Hess for being my mentor and guide all through my Master's program. He has taken keen interest in supporting me at every stage of my research with prompt inspirations and timely suggestions, kindness and enthusiasm which helped me, to a great extent, in completing my thesis.

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Acronyms

CA – Contingency Analysis

CT – Current Transformer

D-FACTS – Distributed Flexible AC Transmission Systems

FACTS – Flexible Alternating Current Transmission Systems

kWh – Kilowatt hour

TXF – Transformer

SCADA – Supervisory control and data acquisition system

T&D – Transmission and Distribution

V – Volts

VAR – Volt-Ampere Reactive

W – Watts

WECC – Western Electricity Coordinating Council

1 Chapter 1: The grid

1.1 Introduction

The US power grid, which could be considered the largest interconnected system on earth, was mainly built after World War II. Its 7,000 power plants are connected by power lines with a combined total of more than 5 million miles, all managed by 3,300 utilities serving 150 million customers according to the Department of Energy. [1]

Such a complex system requires constant monitoring and investment. Possibly the most significant issue in terms of grid utilization is that of active power flow control. Utility customers purchase energy (kWh) in the form of real power (W), and not voltage (V) or reactive power (VAR). This means that having control of how and where real power flows on the network is of critical importance. Congested networks limit system reliability and constrain the ability of utilities to provide customers with lower costs for the power.

1.1.1 Long Term Declining Transmission Investment Leads to Decreased Stability

A recent increase in transmission investments has still not erased deficits from several decades of declining investments. This has resulted in an increased loading on the existing transmission lines, making the grid more vulnerable to disturbances.

1.1.2 High Cost of Building Transmission Lines

Over the recent years there has been increasing public sentiment against locating power lines close to their communities. Acronyms such as NIMBY (Not In My Backyard) and the more cynical BANANA (Build Absolutely Nothing Anywhere Near Anyone) have entered the vernacular. The long delays in siting and approving of new transmission lines make the process more expensive. This is especially true for urban areas where the cost of land is high.

1.1.3 Under Utilization of Existing Assets

In a meshed network, a fault results in the isolation of a single line segment with alternate paths maintaining power to customers. A major limitation of meshed networks is the inability to control the flow of power. The current always flows according to electrical laws of physics, which may result in an uneven loading of the network. The first line to reach its capacity limits the power transfer capacity of the system, even though majority of the system may be operating much below limits. Network reliability also demands that reserve margins be assigned to transmission lines to carry additional power so that no degradation of service occurs with an N-1 contingency. This further lowers the available transfer capacity of the transmission system.

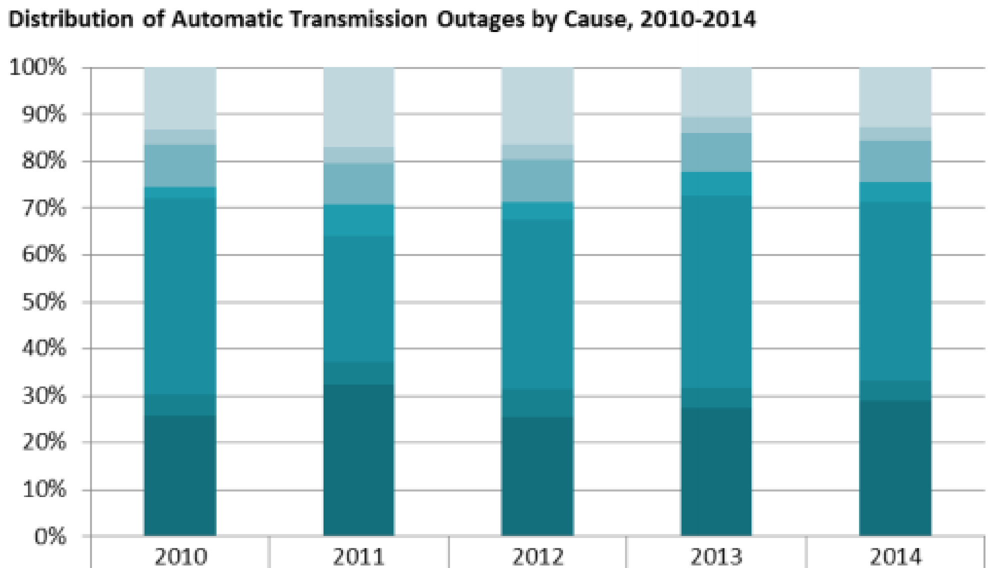
1.1.4 Contingencies

An electrical fault is a deviation of voltages and currents from nominal values or states. Under normal operating conditions, power system equipment or lines carry normal voltages and currents which results in a safe operation of the system.

But when a fault occurs, excessively high currents flow which causes damage to equipment and devices. Fault detection and analysis is necessary to select or design settings for suitable switchgear equipment, protective relays, circuit breakers and other protection devices. [2]

Figure 1.1 shows the reported automatic transmission outages by cause in the period of 2010-2014.Those outages where located and reported by utilities inside the WECC system.

The three most common causes of outages are weather, equipment failure and unknown.



	2010	2011	2012	2013	2014
Equipment Failure	243	267	267	168	187
Foreign Interference	55	57	55	52	42
Human Caused	164	138	145	132	132
System Condition	44	107	64	79	62
Weather & Environment	765	422	592	643	558
Other	80	79	96	65	65
Unknown	471	511	417	432	425

Figure 1.1 WECC Reported Transmission Outages by Cause [1]

Line and equipment outages due to causes such as those shown in Figure 1.1 are referred to as contingencies. A more detailed explanation of them is described below.

Equipment failures: Internal failures in various electrical equipment like generators, motors, transformers, reactors, switching devices, etc. cause short circuit faults due to malfunctioning and insulation failure of cables and windings. These failures may cause high currents to flow through the devices or equipment at hand, further damaging it.

Human errors: Electrical faults are also caused due to human errors such as selecting improper rating of equipment or devices, forgetting to remove metallic or electrical conducting parts after servicing or maintenance, switching on the circuit while it is under servicing, etc.

External Attacks: There are two main types of attacks. The first one is physical and happens when somebody damages the equipment intentionally. That can be done by breaking the equipment, shooting at it, or any other means of causing physical damage. The second type of attack is cyber hacking. That happens when someone intercepts the communications and gains access to the computers running the system.

Cybersecurity and communications failures are a major concern because the grid is computer controlled. Just by modifying little things or shutting down equipment, a major blackout can occur. As of today there are not publicly reported thus making it difficult to study their impact.

Figure 1.2 shows that in the WECC system alone 36 vandalism and security attacks were reported in 2014. Out of those the most common one is vandalism with 26 instances but the critical one is sabotage. That accounts for only 3 security breaches but those can be major because the person causing them knows what they are doing and wants to cause as much damage as possible.

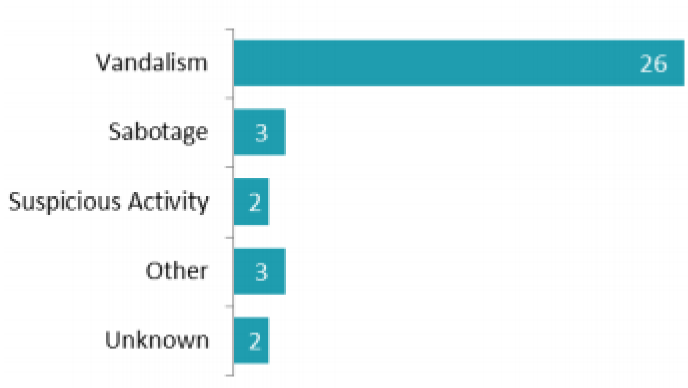


Figure 1.2 WECC Vandalism and Security Threats Reported in 2014 [1]

Weather conditions: These include lighting strikes, heavy rains, heavy winds, salt deposition on overhead lines and insulators, snow and ice accumulation on transmission lines, smoke, etc. These environmental conditions interrupt the power supply and may damage electrical installations. Ionization of air, due to smoke particles, surrounding the overhead lines results in arcing between the lines or between conductors to tower grounds. This contamination causes insulators to lose their insulating capacity due to high voltages.

The WECC disturbance events reported for 2014 are shown in Figure 1.3 and show that vandalism is the most common one followed by communications failures and loss of load. As mentioned earlier cyber hacking is not reported or the information is not publicly available.

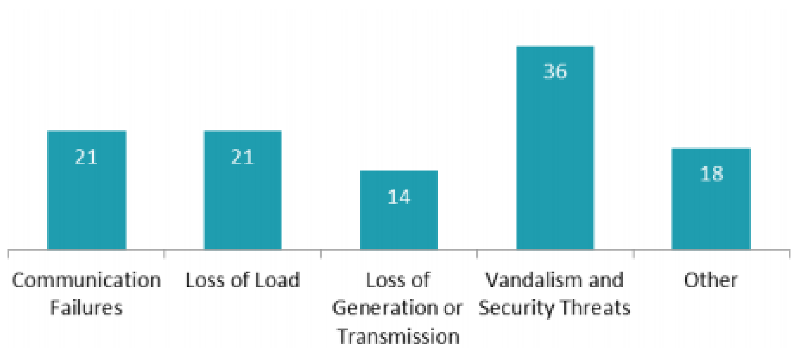


Figure 1.3 WECC Disturbance Events Reported in 2014 [1]

1.2 Objectives

The first objective of this thesis is to study the impact of a limited number of Distributed-Flexible AC Transmission Systems (D-FACTS) devices placed on transmission lines. Studies have found D-FACTS to be useful in order to increase capacity and reroute power flow, and this thesis looks to utilize this capability in order to maintain stability.

The second objective is to study the system improvements during contingencies using D-FACTS. This thesis focuses on the more favorable power flow that D-FACTS devices enable upon command.

The third objective is to develop a basis for optimal placement of the D-FACTS devices. The investigation will provide a set of questions that will help determine the optimal placement of D-FACTS devices within a given system. A line must meet certain requirement such as being a single conductor, not bundled conductors, or not having a maximum current of more than a 1,000 Amps.

The last objective is to compare the cost of installing an optimal number of D-FACTS devices to the cost of rewiring or installing a new line.

1.3 Outline of Chapters

In Chapter 2 the concept of FACTS and D-FACTS devices is explained as well as the expected benefits of using them. This chapter covers communications between the D-FACTS devices themselves and between the D-FACTS and the control room. Also the technical information of the commercial devices used for this thesis is explained.

Chapter 3 describes the simulation tools used for this thesis. The software used is PowerWorld® Simulator 19. This software tool allows for a quick study of D-FACTS on large systems. The chapter explains how to set up the software and use it for better performance and more accurate results. Chapter three explains why the WECC full model is used for the simulations in this thesis.

Chapter 4 develops the different contingency scenarios studied. Some examples of each type of contingency are developed and explained. Those three different contingency scenarios are: N-1 contingency, N-2contingency, and N-1 contingency at a neighbor's system.

Chapter 5 discusses all the results that have been found out during the project. This validates the case that D-FACTS devices are actually a good solution for some contingencies and grid topologies. Positive and negative aspects of D-FACTS are discussed, topics for future work are presented.

2 Chapter 2: D-FACTS

2.1 FACTS

The term FACTS (Flexible Alternating Current Transmission System) refers to a family of power electronics-based devices able to enhance AC system controllability and stability and increase power transfer capability. [Ref]

The design of different schemes and configurations of FACTS devices is based on the combination of traditional power system components (such as transformers, reactors, switches, and capacitors) with power electronics elements (various types of transistors and thyristors). Over the last few years, the current ratings of power electronic devices has grown substantialy, making power electronics available for high power applications of tens, hundreds and thousands of MW.

FACTS devices, thanks to their speed and flexibility, are able to provide the transmission system with several advantages such as: transmission capacity enhancement, power flow control, transient stability improvement, power oscillation damping, and voltage stability and control. Depending on the type and rating of the selected device and on the specific voltage level and local network conditions, a real power transmission capacity enhancement of up to 40-50% may be achieved by installing a FACTS element. [3] In comparison to traditional mechanically-driven devices, FACTS controllers are not subject to wear and require lower maintenance. [3]

Costs, complexity, and reliability issues represent the main barriers to the integration of these promising technologies. Further FACTS penetration will depend on the technology providers' ability to overcome these barriers, thanks to more standardization, interoperability and economies of scale. [3]

2.2 D-FACTS

Distributed Flexible AC Transmission Systems.

D-FACTS devices are designed to provide the functionality of FACTS but with a smaller size and at lower cost and high reliability. This is achieved by:

- Series VAR injection controls effective line impedance and real power flow
- Large numbers of modules float electrically and mechanically on the line
- Incrementally deployable to provide controllable power flow
- Standard low-cost mass-manufactured modules
- Redundancy gives high reliability and availability

With all those advantages D-FACTS devices are becoming more and more an option to increase system capacity and reliability. Although few have been deployed at the time this thesis was written. Being manufactured on an economy of scale could allow utilities to purchase a set amount of devices now and then more in the future if needed with a lower cost than a specific solution for each line. Also as they are attached directly to the lines, no extra space would be required in substations or other points of the system.

The savings compared to rewiring a line or adding a new line are substantial. For the lines examined in this thesis, each mile of a new line has a cost of around one million US dollars. That is the same as a hundred D-FACTS devices, each one of them having a price of $10,000, including the cost of purchase and installation. Just by using the cost of a new twenty miles line, 2000 D-FACTS devices could be installed around the system in order to increase capacity and reliability of the whole system and not just one new path.

With such a big difference in costs and the advantage of being re-deployable makes the D-FACTS devices a competitive solution.

2.2.1 Power Flow

Power flow control is the ability to change the effective impedance of the network or the sending or receiving voltages to influence the path of current flowing through the transmission grid. This enables the ability to keep power on a transmission line at a certain level or direction. Current follows the path of least resistance (or lowest impedance), and the result of changing the pathways of the grid is to change the way that power flows through the transmission system. Specifically, power flow control can be used to remove congestion, respond to contingency events (e.g. loss of a generator or transmission line), and mitigate power quality issues.

Power flow is difficult to control because the control is nonlinear. To change the way power flows in the system it is necessary to be able to change line impedance, voltage magnitude, or angle differences as shown in Figure 2.1. In these case of D-FACTS devices, the line impedance is the selected control parameter because they only add inductance to the line.

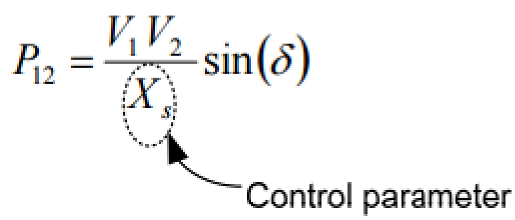


Figure 2.1 Power Flow Equation

By increasing the line reactance of a given line, D-FACTS devices can decrease the power flow in the line and reroute that flow to parallel paths. D-FACTS devices increase the line reactance and can be connected in steps to achieve a progressive increase according to the system needs.

The main benefits of having power flow control are:

- Relieve overloaded lines
- Reduce transmission and distribution losses
- Maintain acceptable voltages
- Improve stability
- Greater utilization of existing system

The main obstacles to obtaining power flow control are:

- Cost of additional equipment
- Large equipment that requires extra space in substations

Power flow control can increase reliability and resiliency, optimize transmission asset efficiency, and help prioritize new transmission construction by increasing the capacity of the transmission grid. [B6]

2.2.2 Increased Capacity

An advantage of D-FACTS devices is the increase in capacity of the system. The system capacity can be increased in a decentralized fashion by routing the power the most efficient way and increasing line efficiency. The rerouting of power is achieved through decentralized power flow control using D-FACTS devices.

Studies done by D. Divan, R. Haley and J. Harjeet show that even for a simple system, such as the one in Figure 2.2, application of D-FACTS devices can result in a noticeable increase in transfer capacity. [4]

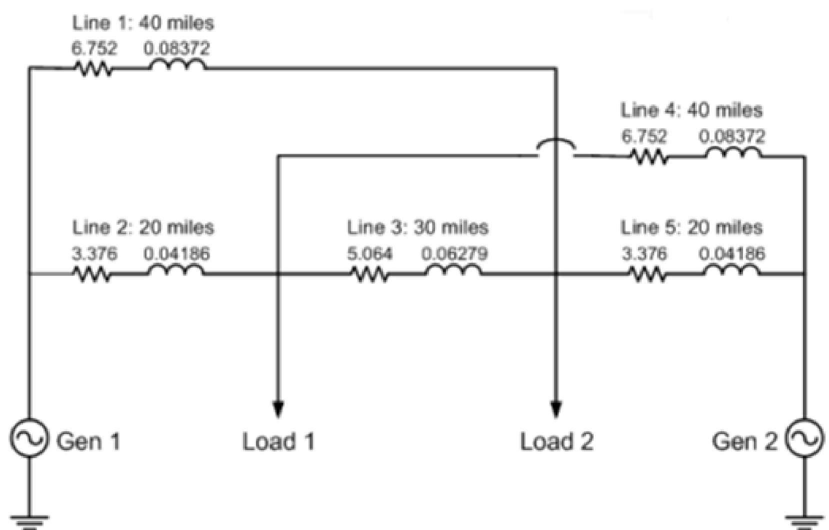


Figure 2.2 Detailed schematic of the 4 bus system [4]

Figure 2.3 shows the increase in transfer capacity of the system by adding 15 D-FACTS devices of 4.1 mH on each line. That means that both loads 1 and 2 can be bigger which translates into more customers being supplied with the same infrastructure.

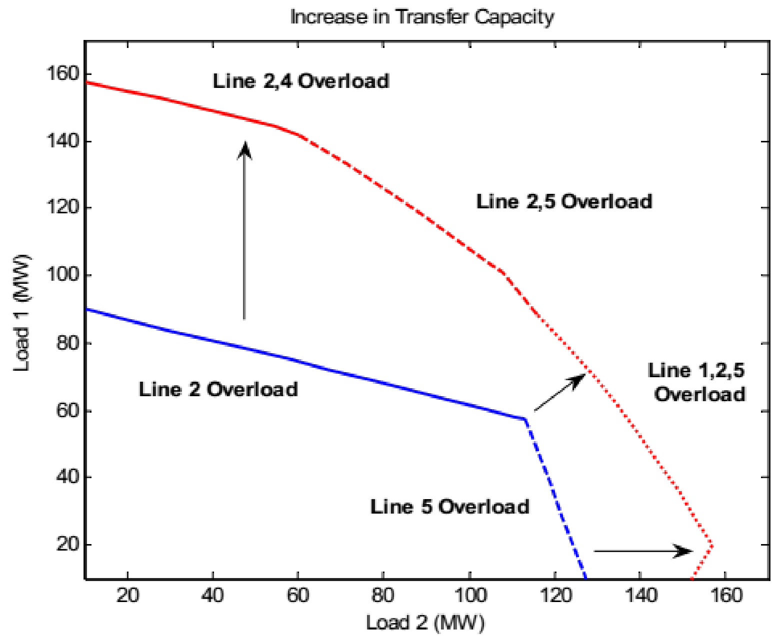


Figure 2.3 Increase in ATC with injected MVARs [4]

Another example of an increase in capacity is shown by studying a standard version of the IEEE 39 bus system shown in Figure 2.4. This model serves to show the impact of D-FACTS devices on improving system capacity and reliability. [4]

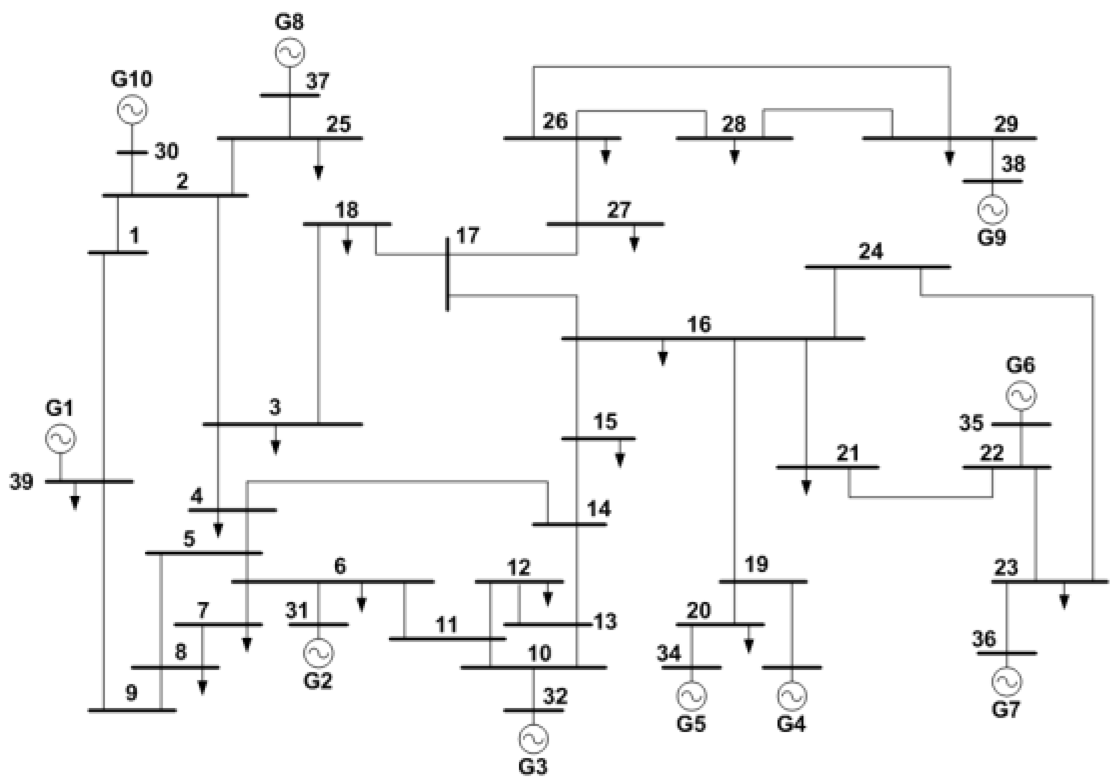


Figure 2.4 IEEE 39 bus system [4]

On a three phase basis, the maximum capacity of the IEEE 39 bus system was obtained to be 1904 MW.[4] A set of 14 power lines were identified as the most critical to the system and most likely to suffer congestion. The utilization of these lines at the maximum system capacity are highlighted in Figure 2.5.

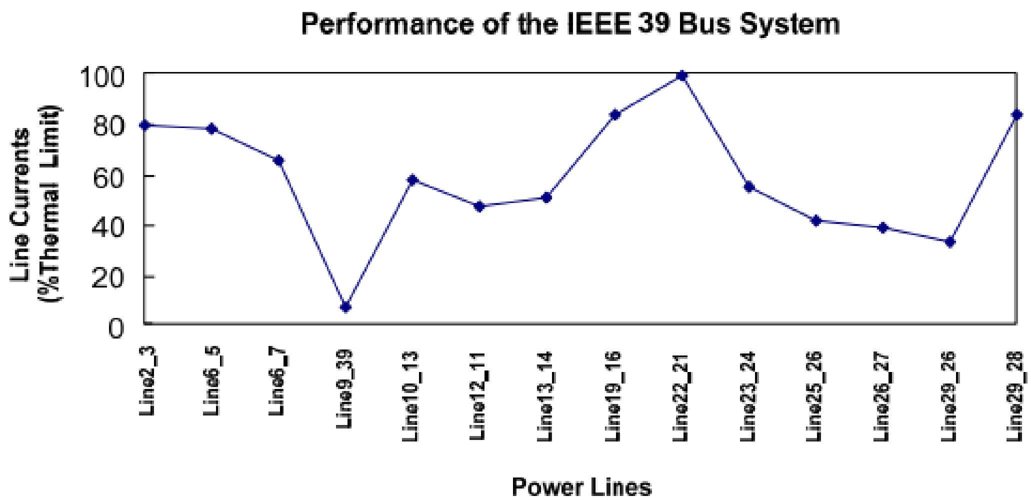


Figure 2.5 Network utilization when the first line reaches thermal limit [4]

D-FACTS devices are inserted in the 9 lines shown in Figure 2.6 which provides the maximum increase in capacity. Those lines have ten 51 µH D-FACTS installed in each of them. The critical point in the system for increasing capacity is the line that reaches maximum loading first. Which in this IEEE 39 Bus system is Line 21-22 as seen in Figure 2.5.

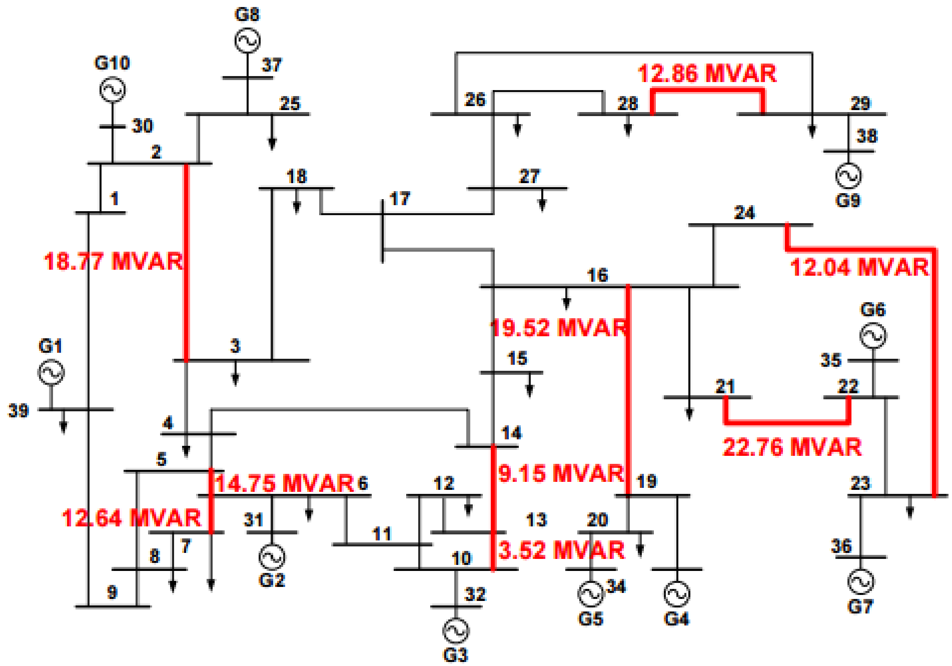


Figure 2.6 Critical lines of IEEE 39 bus system [5]

The system capacity was seen to improve significantly, around 33.5% just by adding the D-FACTS devices. Figure 2.7 illustrates that increase in line usage from 59% to 93.3% that can be realized from a redistribution of the current through the network, as the system load is increased. The blue lines show the original loading of the system and the pink one the increased loading capacity after introducing the D-FACTS devices. This increase in utilization was obtained without addition of new lines, and while ensuring that all lines operate within their thermal limit. [4]

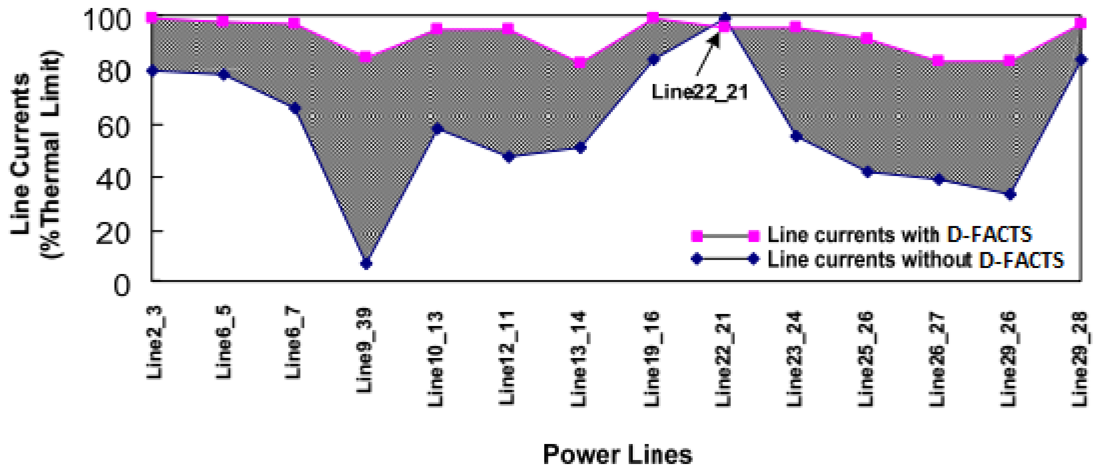


Figure 2.7 Network performance with D-FACTS [5]

2.2.3 Increased Reliability

The same studies conducted by D. Divan, R. Haley and J. Harjeet show that an increase in reliability is achieved by installing D-FACTS devices on the system. This increase in reliability is achieved by an increase in system capacity.

Contingency conditions constraints requires that system operators reserve extra margin on critical lines, so that a secure and stable system operation is guaranteed at any time. This further reduces the available transfer capacity of the system and requires extra effort to identify critical paths.

The study done in [4] shows that the efficiency of D-FACTS is topology-dependent. They prove that D-FACTS can improve the performance of the system under contingency conditions. Table 2.2-1 shows how the capacity is increased on the IEEE 39 bus system when the most critical N-1 contingency occurs. The system capacity increases substantially by strategically pacing D-FACTS devices. The increase in capacity of the system, 600 MW in nominal conditions, is even more apparent when the N-1 contingency happens. Then the system capacity is increased by almost a 1000 MW.

Table 2.1 Summary of results on the IEEE 39 bus system

System Capacity	Nominal Conditions	Worst Case (N-1) Contingency
No D-FACTS	1904 MW	1469 MW
With D-FACTS	2542 MW	2339 MW

2.2.4 Smart Wires

As of today, the only commercially available D-FACTS products are those manufactured by the SmartWires Company.

The commercial product that is evaluated in this thesis is the PowerLine Guardian unit. [6]. Out of the different models available as of today the 500-SD5 and 1000-SD5 are the ones chosen. As seen on Table 2.4 they are selected for their inductance range and current ratings of the conductors they can be connected to. The selected models have the highest inductance range possible, 105.7 µh for the 500 A and 53.7µH for the 1000A. This optimizes the cost of the devices by choosing the most capable ones.

Figure 2.8 Smart Wires - PowerLine Guardian Unit

Table 2.2 Specifications of PowreLine Guardian

Specification	Model 500-SD4	Model 500-SD5	Model 1000-SD5	Model 1000-LD5
Continuous Current Rating	500 A	500 A	1000 A	1000 A
Inductance at Rated Current	85.2 µH (0.0321 Ω)	105.7 µH (0.0398 Ω)	53.7 µH (0.0203 Ω)	44.9 µH (0.0169 Ω)
Weight	206 lbs	256 lbs	256 lbs	235 lbs
Length	56"	66"	66"	66"
Corona Free Voltage (L-L RMS)	≤550 kV	≤362 kV	≤362 kV	≤362 kV
Conductor Size Capacity	4/0 AWG – 795 kcmil	4/0 AWG – 795 kcmil	4/0 AWG – 795 kcmil	4/0 AWG – 1272 kcmil
Fault Current Rating	63 kA for 30 cycles			
Fault Current Response	Automatically switches out of injection mode in < 50 µs			
Life	20 + years			
Communication Protocol	As specified by Owner			

PowerLine Guardians function as distributed series reactors installed along the transmission line and are attached directly to the conductor. The modules have been tested under a variety of conditions, including high fault levels, field contingencies, and are expected to operate continuously for more than twenty years with no maintenance. PowerLine Guardians are currently operational on three high voltage transmission lines. [6]

The D-FACTS devices offer a quick installation and other sensors, as shown in Figure 2.9. For the quick installation the company claims that typical PowerLine Guardian installations can be completed in less than one month. [6]

The other benefits delivered by the PowerLine Guardian include power flow control and monitoring. In addition, the devices have the potential to provide the following: [6]

- Overload Mitigation
- RAS/SPS Simplification
- Congestion/Uplift Reduction

- Phase Balancing
- Construction and Maintenance Support
- Circular/Inadvertent/Unscheduled Flow Mitigation
- Geomagnetically Induced Current Flow Detection and Mitigation
- Increase in Grid Resiliency
- Grid Monitoring

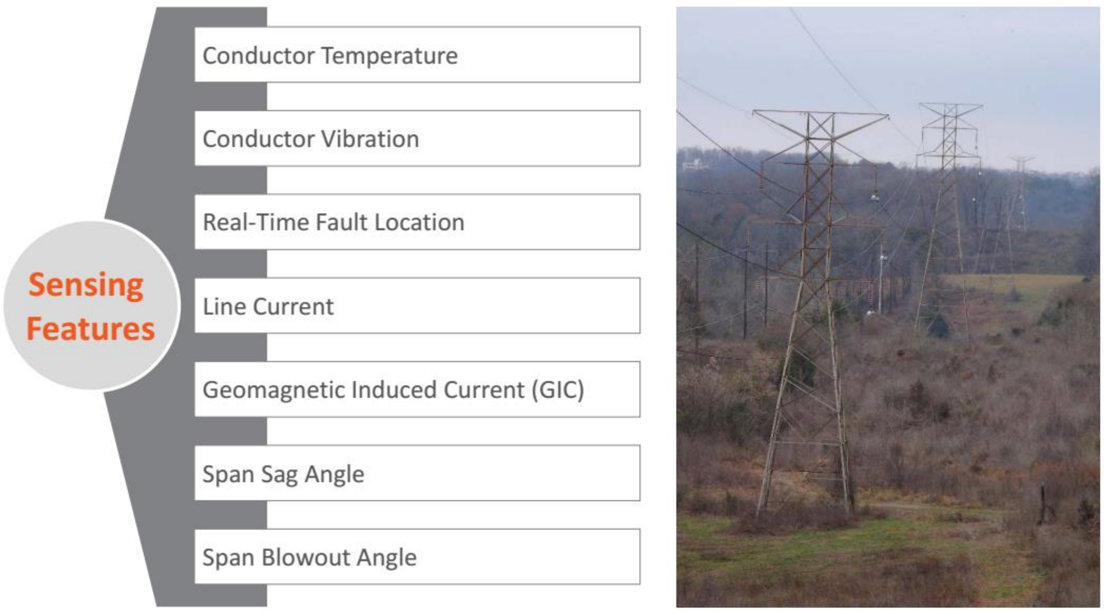


Figure 2.9 SmartWires - D-FACTS Extra Features [6]

As shown in Figure 2.9 the Smart Wires Company claims that the D-FACTS devices can provide much more information monitoring capability beyond just adjusting line impedance. That extra information can be relevant for other studies and for continuous monitoring the state of the line and the system.

2.2.5 Communications

New vulnerabilities in critical infrastructure continue to emerge, and cyber adversaries are becoming more technically capable and sophisticated in their determination to attack critical infrastructure in North America. As cyber incidents increase in number and consequence globally, adversaries are reinvesting their gains to develop more complex attacks. Policy makers and industry leaders across North America are concerned about the impact that emerging cyber threats might have on the stability, resilience, and reliability of the BPS. [7]

With all that in mind the security of D-FACTS devices communications need to be taken seriously. The devices use wireless communications as seen on Figure 2.10. That means that communications are easier to intercept than the cabled ones.

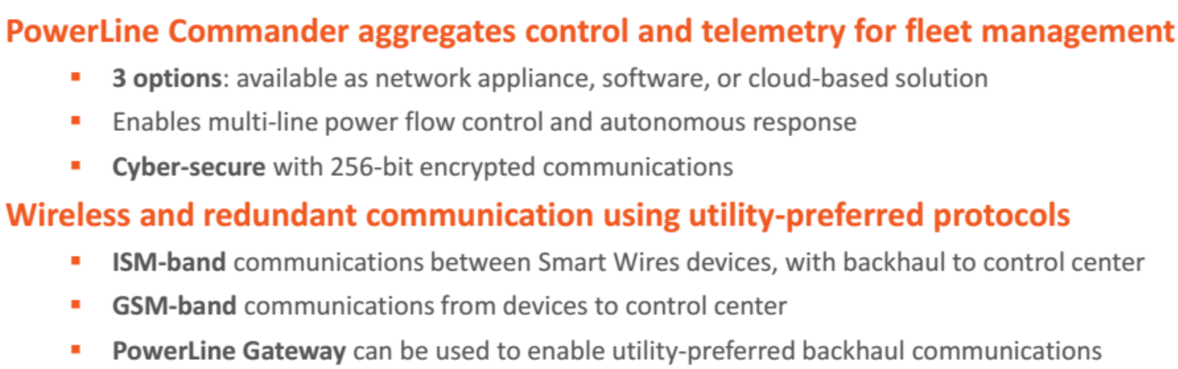


Figure 2.10 SmartWires Communications [6]

Figure 2.10 shows the communications protocol used by the devices is based on the one used by the utility that owns them. That can translate into a major security issue if someone is able to hack the D-FACTS devices and gain access to the whole utility system through them. In order to avoid cyber hacking, communications are encrypted using a 256-bit protocol.

Looking at the communications between devices and the control room there are two different wireless systems used. Wi-Fi for short range communications and GSM for long distance. The advantage of using communications between devices is that the main GSM channel is not overloaded. There are one or two devices per tower with capability to send GSM data collected from all the other devices nearby as shown in Figure 2.11.

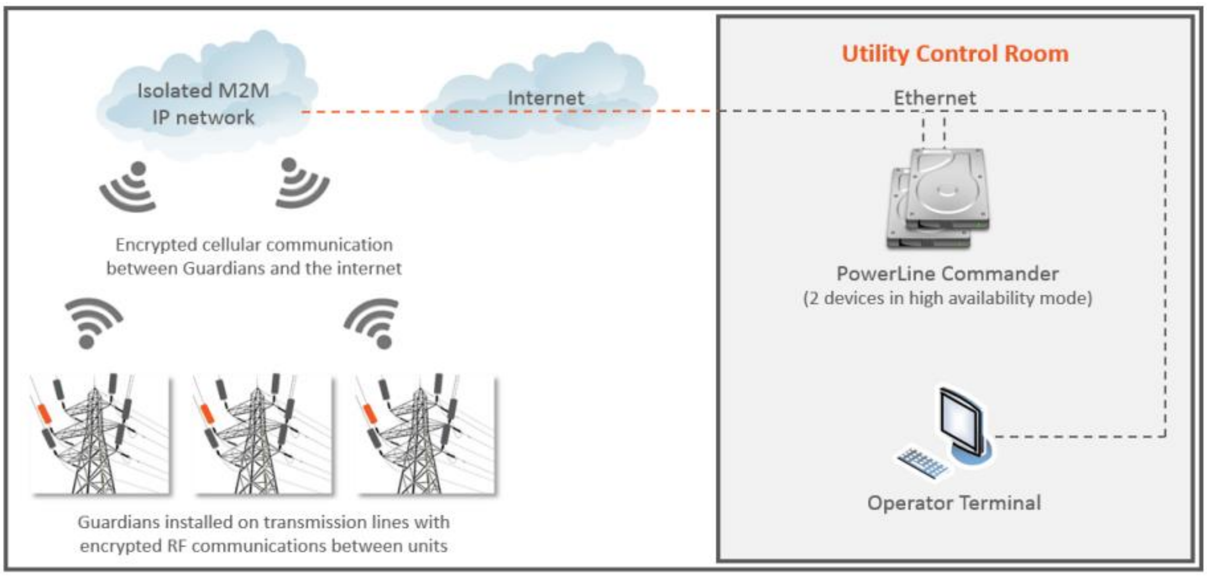


Figure 2.11SmartWires Schematic of Communications [6]

All that information about the status of the line and devices is sent to the control room and displayed on a screen such as the one on Figure 2.12. Through that panel the devices can be monitored and different settings can be selected for the operation of the D-FACTS devices.

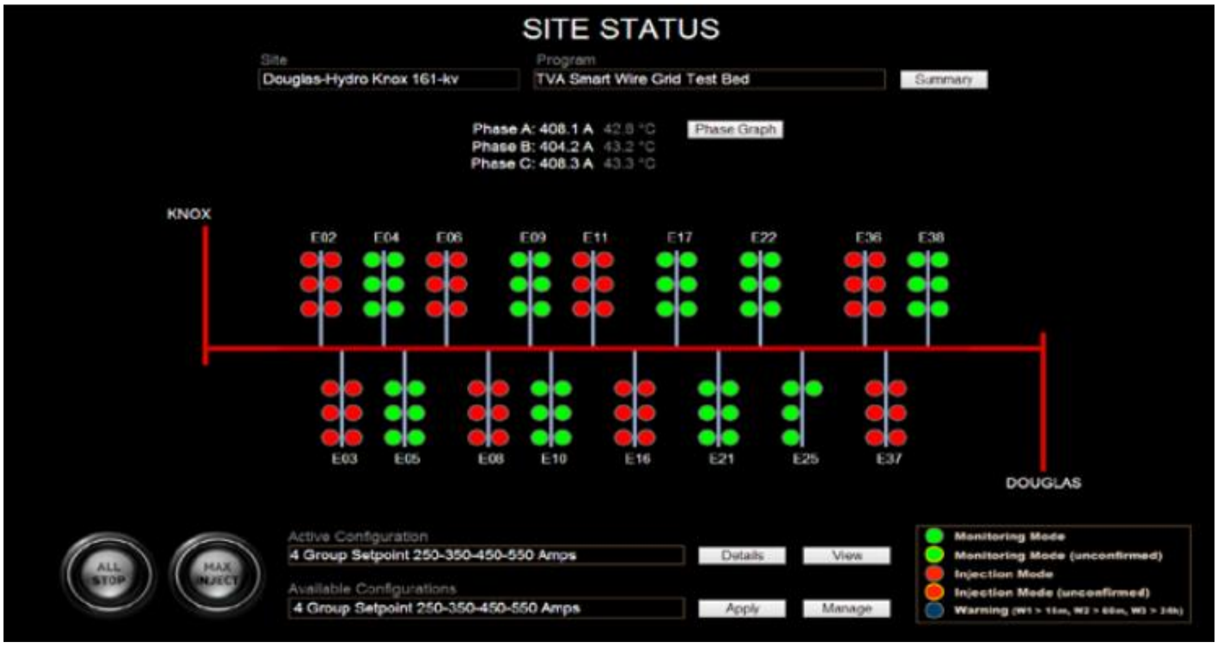


Figure 2.12 SmatWires Control Panel [6]

2.2.6 Limitations

On the other hand there are some limitations for choosing and installing those devices. The cost of each device is estimated to be $10,000 per phase, with installation costs. That means that if a large number of devices is needed on a line in order to improve the system, the initial cost may higher than other solutions such as rewiring the line.

Also if the devices are installed, the line physical and mechanical characteristics need to be considered. The devices weight 120 kilograms each, which generates an increase in tension between towers. Also during summer the extra weight can cause the cable to sag more and increase the risk of faults and reduce the line capacity. That line capacity reduction may counteract the benefits of the D-FACTS devices.

For this thesis the limitations on the number of D-FACTS devices is usually kept under a maximum of 30% of the line impedance or 30 devices per phase whichever is smaller. During each study, those limits may be changed, which will be explained later. Depending on the characteristics of the line the number of devices could be greater, especially in long distance transmission lines.

2.3 Chapter Summary

D-FACTS devices are designed to provide the functionality of FACTS but with a smaller size and at lower cost.

The system capacity can be increased in a decentralized fashion by routing the power the most efficient way using D-FACTS devices. That increase in capacity translates into an increased reliability.

There is only one company that commercializes D-FACTS devices at the time this thesis was written. The selected commercial devices have, 105.7 µh for the D-FACTS device installed in lines with a current up to 500 A and 53.7µH for the D-FACTS device installed in lines with a current up to 1000A.

3 Chapter 3: Test Environment

3.1 PowerWorld®

PowerWorld® Simulator is an interactive power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days. The software contains a highly effective power flow analysis package capable of efficiently solving systems of up to 250,000 buses. [8]

3.2 System studied

This thesis studies the effects of contingencies inside a utility's grid. The studied grid is part of the WECC system shown in Figure 3.1.

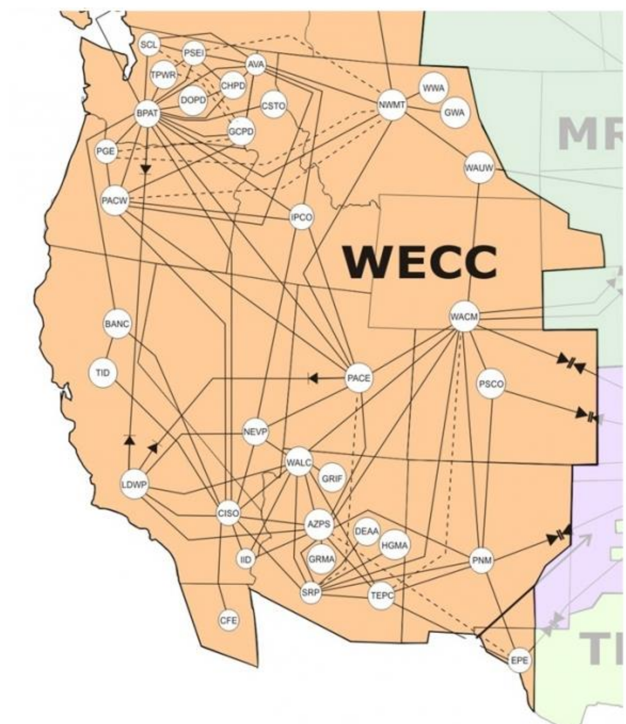


Figure 3.1 WECC System [1]

The specific utility system studied has more than 200 buses. However, the model is part of the WECC system whose PowerWorld® model has more than 20,000 buses. The whole WECC model is used for simulations in order to obtain the most accurate results. Reducing the model with equivalents introduces complexity and errors.

The D-FACTS devices are only placed in lines that can benefit from them and meet the technical requirements such as line current limits. They are only placed in one line at a time and that line is always part of the studied utility's system.

3.3 PowerWorld® settings

3.3.1 Cloud Computing

The studies performed in this thesis research required performing a large number of simulations. In order to increase the computing power at each computer, cloud computing can be set up. This will allow simulations to run in parallel on each core of multicore processors, saving time for a given number of runs. This is because PowerWorld® is a 32bit system and by default only uses one core of each CPU.

3.3.2 Line Characteristics

The top of the dialog window has the basic information about the buses that the line is connected between such as number, name, area, nominal voltage and actual voltage and angle from the previous power flow simulation.

There are five tabs for describing all the different configurations and information specific to the line. The most important ones for the issues at hand are the Status (open, closed), Per Unit Impedance Parameters and MVA Limits. At the second half of the Parameters tab there is line flow information. The important information is the loading of the line and that is expressed in %MVA and %Amps. Those two values tell us the extent to which the line was loaded in the most recent power flow solution.

At the bottom of the Parameters tab there is an option to include D-FACTS devices directly. The "Has D-FACTS" box needs to be checked in order to include the devices. Then upon selecting the "D-FACTS Devices on the Line" button a new window opens and the characteristics of the D-FACTS devices for this line are entered and modified.

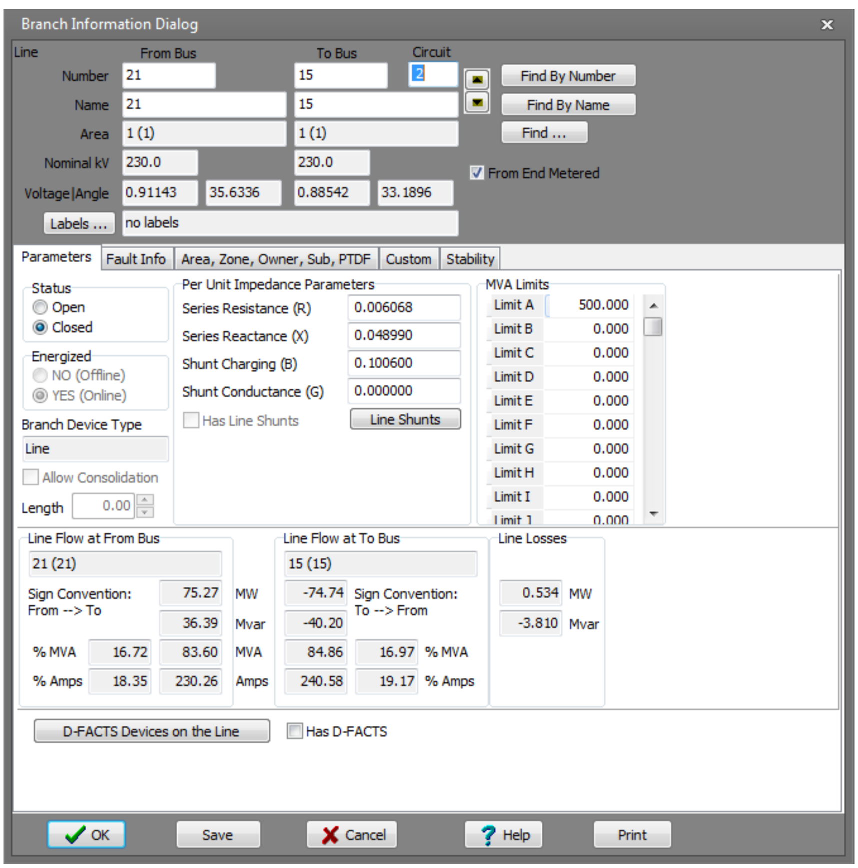


Figure 3.2 PowerWorld® Line Information Dialog

3.3.3 D-FACTS settings

The D-FACTS Devices Window allows full control of the devices. All the settings available are seen in Figure 3.3.

The top part of the window gives the basic information about which line the devices are installed on, and also the "Actual reactance injected" and the "Limits of the Reactance injected per phase."

Under the inputs tab there are the controls for the inductance per module and also the number of modules and set points. The I0 setting is the loading point where the first device will turn on and the Ilim is the loading point where all D-FACTS on the line are on.

There is also the option to select the Mode of Operation for the D-FACTS. For the study only the "Limit based on current" is used. This mode only operates when needed and PowerWorld® chooses the optimal number of devices within the limits during the power flow study.

After a power flow case is solved, the right side of the window shows a plot of the line status. The loading point is marked by a little star as seen in the lower left of the plot in Figure 3.3. The D-FACTS configuration and trigger points are shown on the blue line. The ramp is actually a stair step sequence where each step is the addition of one more D-FACTS device.

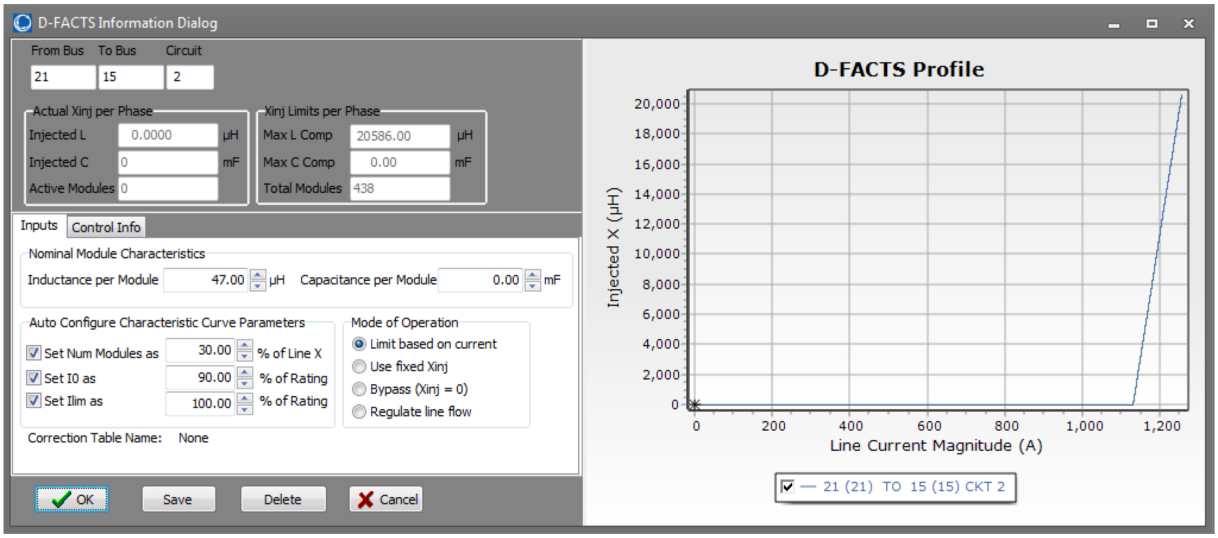


Figure 3.3 D-FACTS Settings Screen

3.3.4 Settings Contingency Analysis

For setting up the contingency analysis cases the simulation must be in Run Mode.

Under the Tools Tab there's an option called Contingency Analysis as shown in Figure 3.4.

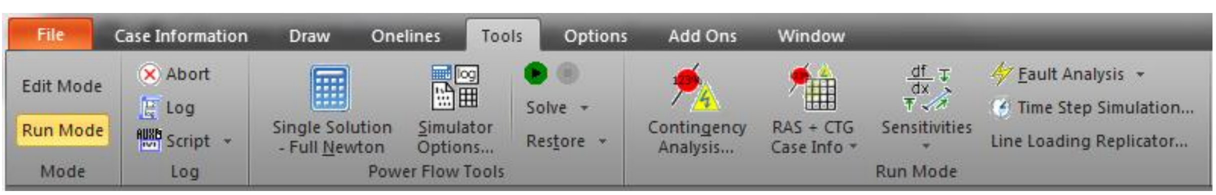


Figure 3.4 PowerWorld® Contingency Tab

Some parameters need to be set in the Contingency Analysis Window Shown in Figure 3.5.

The contingencies can be "Auto Insert" or loaded from an external file. Also Custom Monitors need to be created in order to study the performance of the D-FACTS devices.

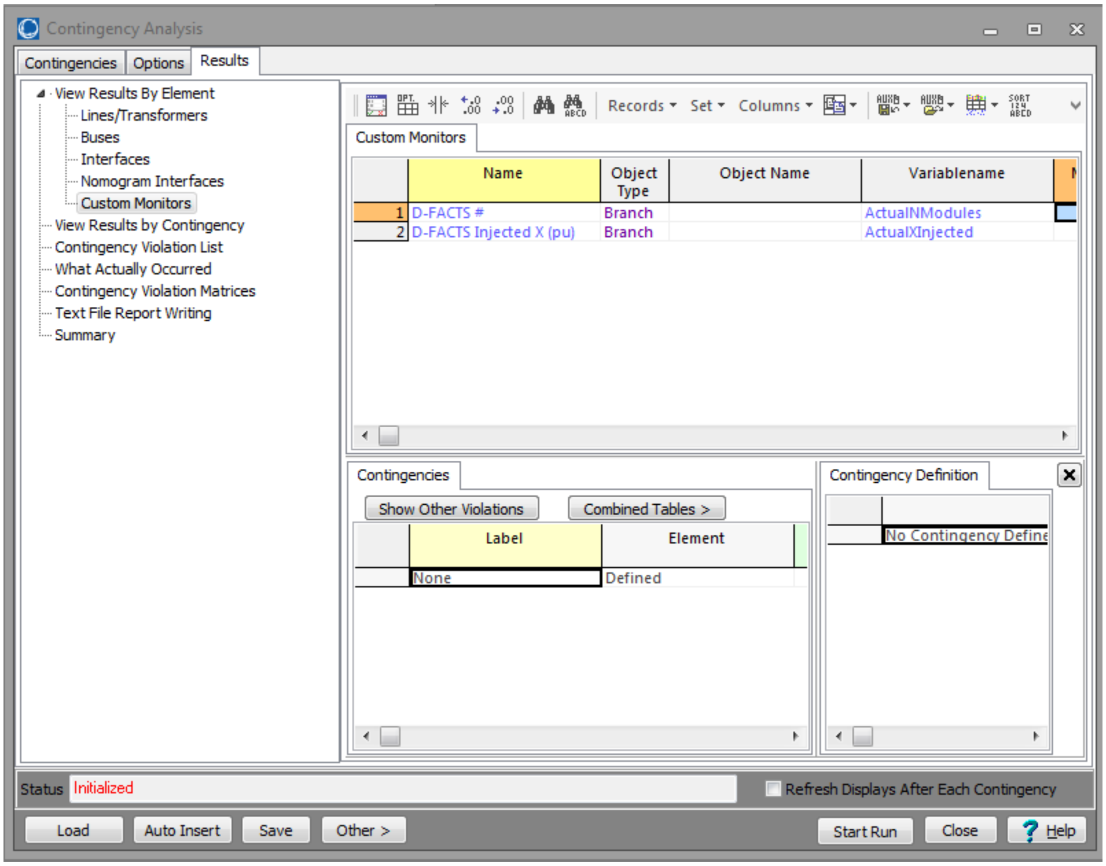


Figure 3.5 PowerWorld® Contingency Window

In the general simulation determining the number of D-FACTS devices inserted in each different line according to each contingency is the objective. Custom monitors need to be introduced on the results tab to monitor the parameters of interest.

On the options tab "Limit Monitoring" and then "Custom Monitors" must be selected from the list on the left. Then make a second click on the table that appears on the right and select "Insert" in Figure 3.6. A new name needs to be used for each custom monitor created.

Next, the authority needs to be set to Branch. That allows to open the right selection of custom monitor options where D-FACTS devices can be found. There is a folder with the name D-FACTS devices and that is the location of the monitors for "Number of Devices"' and "Line Injection in pu".

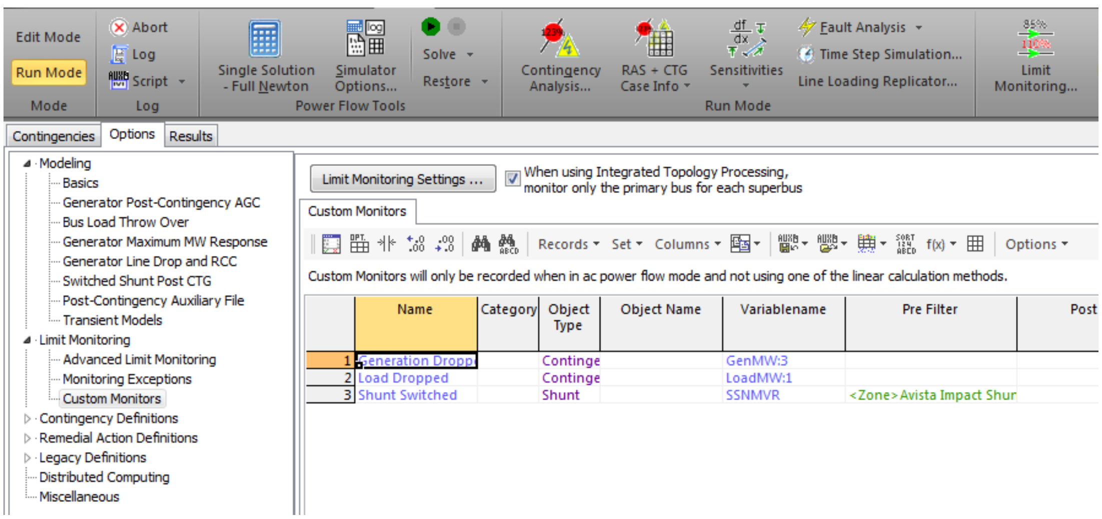


Figure 3.6 PowerWorld® Limit Monitoring

Once the custom monitors are set, the simulation can be run and the studied values will appear on the results tab under custom monitors.

3.4 Power flow analysis

In power engineering, the power-flow study, or load-flow study, is a numerical analysis of the flow of electric power in an interconnected system. A power-flow study usually starts from a system map which can use simplified notation such as a one-line diagram and per-unit system. The study focuses on various aspects of AC power parameters, such as voltage magnitudes, voltage angles, real power and reactive power. It analyzes the power systems in normal steady-state operation and compares the calculated operating point with constraints or limits.

Power-flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best or most secure operation of existing systems. The principal information obtained from the power-flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line. [9]

3.5 Contingency analysis

Contingency analysis (CA) is used as a study tool for the off-line analysis of contingency events, and as an on-line tool to show operators the effects of potential future outages starting from the present system operating state. This allows operators to be better prepared to react to outages by using pre-planned recovery scenarios.

The purpose of contingency analysis is to analyze the power system in order to identify the overloads and problems that can occur due to a "contingency." A contingency is the failure or loss of an element (e.g. generator, transformer, transmission line, etc.), or a change of state of a device (e.g. the unplanned opening of a circuit breaker in a transformer substation) in the power system.

CA is one of the "security analysis" applications in a power utility control center that differentiates an Energy Management System (EMS) from a less complex SCADA system.

Therefore contingency analysis is an application that uses a computer simulation to evaluate the effects of removing individual elements from a power system.

After a contingency event, power system problems can range from:

- none - when the power system can be re-balanced after a contingency, without overloads to any element, to
- severe - when several elements such as lines and transformers become overloaded and risk damage, to
- critical - when the power system becomes unstable and will quickly collapse.

Current electric utility operating policies (such as NERC's) require that each utility's power system must be able to withstand and recover from any "first contingency" or any single failure. Which translates into no, power system problems but a reduced system capacity.

By analyzing the effects of contingency events in advance, problems and unstable situations can be identified, critical configurations can be recognized, operating constraints and limits can be applied, and corrective actions can be planned. In the planning mode, apart from analysis of the complete power system for overall security, CA is also used for scheduling the withdrawal of power system equipment for periodic or restorative maintenance. The schedule for planned outages is arranged for minimal risk of problems by using these CA studies, to avoid scheduling concurrent outages of critical system elements. [10]

3.5.1 N-1 Contingency Analysis

An N-1 contingency analysis studies the loss or failure of a small part of the power system (e.g. a transmission line), or the loss/failure of individual equipment such as a generator or transformer. Repeated power flow solutions are performed with one device at a time out of service starting from a common base case.

3.5.2 N-2 Contingency Analysis

An N-2 contingency analysis study is a CA performed to analyze system performance in the event of the loss or failure of two lines or pieces of equipment at the exact or almost exact same time. Repeated power flow solutions are performed with two devices at a time out of service starting from a common base case.

N-2 contingencies can be separated in 2 groups:

- N-2: This means that two independent parts of the system fail at the same time due to unrelated contingencies.
- N-1-1: This means that right after one part of the system fails a second one follows immediately due to the first contingency.

3.6 System Losses

Evaluation of the change in system losses helps understand how the system changes when the D-FACTS devices are installed. It also helps understand the changes in power flow.

The total system losses are a quick indicator of the status of a system. The issue with System Losses Analysis is that many studies have shown that direct relationships between the effects created by line outages on the system and transmission losses in the power network cannot be established. The losses in the transmission system are a function of the generation and load pattern of the system. The impact of each contingency on the system performance and network losses in an electric power system are related to the network topology and the relevant parameters at all system buses.

The system losses studied in this thesis showed little to no change other than the extra impedance of the D-FACTS devices. This behavior is shown in Figure3.7.

System one in Figure 3.7 has a total system losses of 4075.7MW and -25629.9Mvar, before installing any D-FACTS device. With the device installed the losses change to 4075.7 and -25628.6. Notice that the real part of the losses (MW) hasn't change. But the reactive has been reduced by 1.3Mvar. This is the exact value introduced by the 29 D-FACTS devices, which means that there are no major changes in the total system losses.

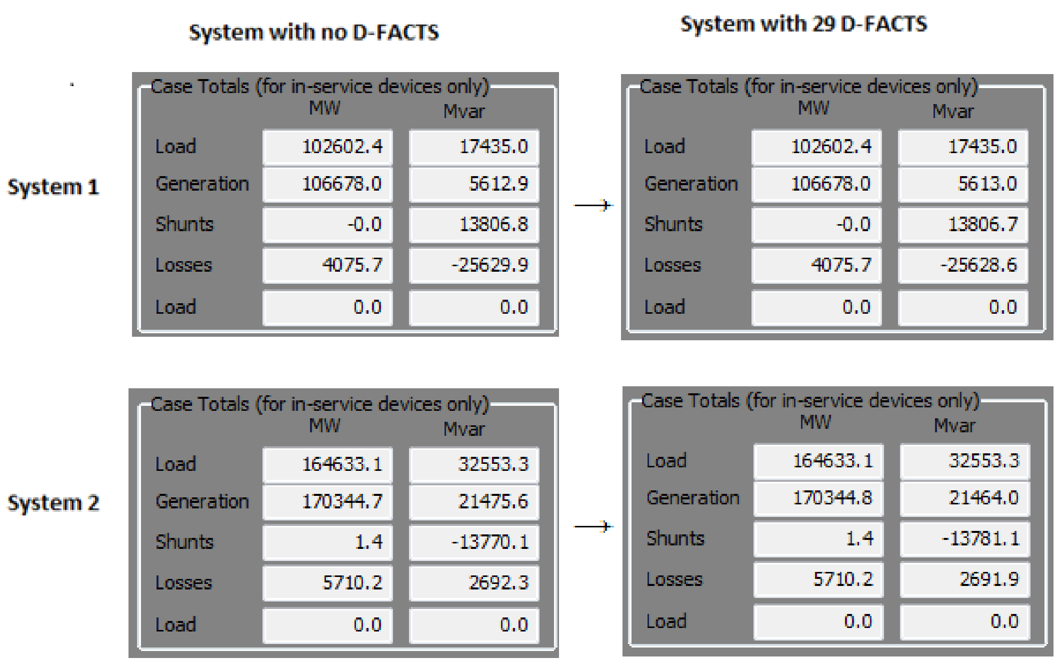


Figure 3.7 System Losses Study

3.7 Chapter Summary

PowerWorld® Simulator is the software tool used in this study of D-FACTS on large systems. And how to set up the models, contingencies and D-FACTS is explained.

The specific utility system studied has more than 200 buses. However, the model is part of the WECC system whose PowerWorld® model has more than 20,000 buses. The whole WECC model is used for simulations in order to obtain the most accurate results.

Power flow studies analyze the power systems in normal steady-state operation and compare the calculated operating points with constraints or limits.

Contingency analysis is used to analyze the power system in order to identify the overloads and problems that can occur due to a "contingency."

The thesis covers two main types of contingency analysis, N-1 and N-2, plus the base case and the system losses.

4 Chapter 4: Analysis and Results

The study is separated in two different sections, Steady State Base Case and Contingencies.

To recreate the most critical conditions, high loaded WECC base cases are used in this thesis. Those cases are summer periods where there is the highest demand. The model uses the whole WECC system in order to avoid loss of information and obtain more accurate results as explained in Chapter 3.2.

4.1 Steady State Base Case

The base case scenario was selected using heavy loading conditions during summer. This is due to the high demand of electricity during those periods due to air conditioner loadings and the constraints in some types of generation such as hydro due to reduced seasonal flow. Variable renewable energy generators such as solar have a high output during the summer time.

The base case was studied to identify lines that may have a high loading condition during normal operation of the system.

4.2 Contingencies N-1

N-1 contingency analysis studied here focuses on identifying critical lines. It also tries to maintain system capacity by incrementally turning on D-FACTS devices on every single line of the studied system. This was done to identify candidate sites for installation. Those selected lines are the ones that help with overloading on a specific line during contingencies. The more contingencies a line with D-FACTS devices can help mitigate the better candidate the line is.

After performing the N-1 contingency analysis, some lines are found to be good candidates for installing the D-FACTS in order to improve the system reliability and capacity.

For the N-1 study the following conditions were applied for controlling the D-FACTS devices:

- Performed using 5 different loading trigger levels to turn on the D-FACTS (75%, 80%, 90%, 95%, and 100% of line capacity).
- D-FACTS having a line inductance of 47µH.
- The maximum number of D-FACTS devices per phase is 30% of the line impedance.

The results of the general N-1 studies are shown in Table 4.1. The system studied has a lot of extra capacity, which means that lines don't get overloaded even during N-1 contingencies. Also there are some lines that are open during the contingency because they are part of a longer line where the fault happened.

For the 85% line loading capacity trigger point, there are seven different contingencies that require other lines to turn on D-FACTS in order to keep the system loading capacity. This 85% loading level was chosen to provide a good safety margin for times when external conditions may limit the line current.

Table 4.1 shows that the same line was the most critical for all loading levels and that the line requires the full 54 D-FACTS devices to increase the system capacity.

Table 4.1 N-1 Contingencies

	Contingencies with D-FACTS turned on	Number of Lines affected	Highest Number of devices in a line
75 %	26	17	54
85 %	7	7	54
90 %	1	1	54
95 %	1	1	54
100 %	1	1	54

4.3 Contingencies N-2

The N-2 analysis was performed only cases with the failure of two major transmission lines. Transformer and generator failures were not included. Those major transmission lines are all 230kV lines and are each key to the function of the system. This was due a limited access to CPUs to run the large amount of possible combinations of contingencies, which totaled more than 30,000 cases.

The N-2 studies are focused on keeping the maximum number of loads supplied during the contingencies. The idea is to reroute power and keep the maximum amount of customers online during rare events.

In most cases the contingencies result in loss of parts of the system due to overloads but in some other D-FACTS devices are able to save some critical lines.

For the N-2 study the following conditions were applied:

- Performed using only 1 trigger level for the D-FACTS: 90% line loading.
- D-FACTS having a line impedance of 47µH at first study.
- D-FACTS having a line impedance of 53.7µH or 105.7µH, with device selection according to line characteristics, during second study.
- The maximum number of D-FACTS devices per phase is 30% of the line impedance.

Table 4.2 N-2 Contingencies

	Contingencies with D-FACTS turned on	Number of Lines affected	Highest Number of devices in a line
47μH	28	15	77
53.7μH or 105.7 μH	80	12	57

Table 4.2 shows the difference between using the standard D-FACTS model in PowerWorld® versus the commercially available D-FACTS devices. The number of lines that would benefit from using D-FACTS is lower when the commercial device is installed. But the number of contingencies that benefit from having D-FACTS is larger. This is due to the larger inductance of the commercial devices compared to the standard model in PowerWorld®. The amount of devices needed in the worst case is lowered by 20 devices which reduces the costs.

4.4 Neighboring N-1 Contingency

Neighboring N-1 contingencies are cases where outages happen in lines belonging to a neighboring utility near the studied system. Those contingencies are critical failures in lines, buses or transformer limiting or close to the studied system. This may be an indication of the reliability of the studied system and the response it has to external issues.

This study was performed focusing on some critical regions inside the system where the neighbors' infrastructure is a major concern. The studies showed that contingencies involving loss of some buses and transformers can critically influence their regions. Areas were both utilities serve joint buses and loads are more prone to have lines were D-FACTS devices can help reroute power flow.

The other concerns are the interconnection have higher current ratings than the ones that the D-FACTS can withstand. Another constraint with high voltage transmission lines is the design. Some of them have bundled conductors, that two or more conductors per phase are used to transfer power. Those cables are 45 centimeters apart from each other which limits the installation of D-FACTS. Due to the necessity of both D-FACTS functioning with the exact same characteristics at all times it is a better idea to use other commercial products such as the Tower Router instead of the Power Line Guardian.

4.5 Lines Selected

After analyzing the previous studies some lines were selected for further in depth study and possible implementation of the D-FACTS.

The conditions that a line must meet are:

- At least one contingency where D-FACTS can be effective in reducing overloads. More contingencies preferable.
- Be highly loaded during contingency.
- Being critical for the normal operation of the system.
- No known limitations for installing D-FACTS.

Based on the above criteria, several lines where selected in order to study the system performance and level of possible improvement.

4.6 Line Study Example Cases

Three examples are presented out of the set of cases evaluated in the study:

1. Line from Bus A to Bus B for an N-1 contingency occurring inside the studied utility's system.
2. Line from Bus K to Bus L for an N-2 contingency occurring inside the utility's system.
3. Line from Bus 1 to Bus 2 for an N-1 contingency occurring on a neighbor's system.

These examples are used to show the process of analysis and evaluation of the optimal placement and number of devices to improve post contingency performance. All the candidate lines are evaluated following the same process and changing the amount of devices required depending on the characteristics of each line such as line impedance or maximum current.

4.6.1 N-1 Contingency Example

In this example a double connection between buses forming a loop through the system is used to illustrate the effects of a contingency in one of the lines.

There is a direct line between Bus A and Bus B, shown in Figure 4.1, which needs to support extra current when a contingency happens on either line from Bus A to Bus C, Bus C to Bus D or Bus D to Bus B. At a normal condition the loading on the line is around 25.8MVA, which is 45% of the line's capacity.

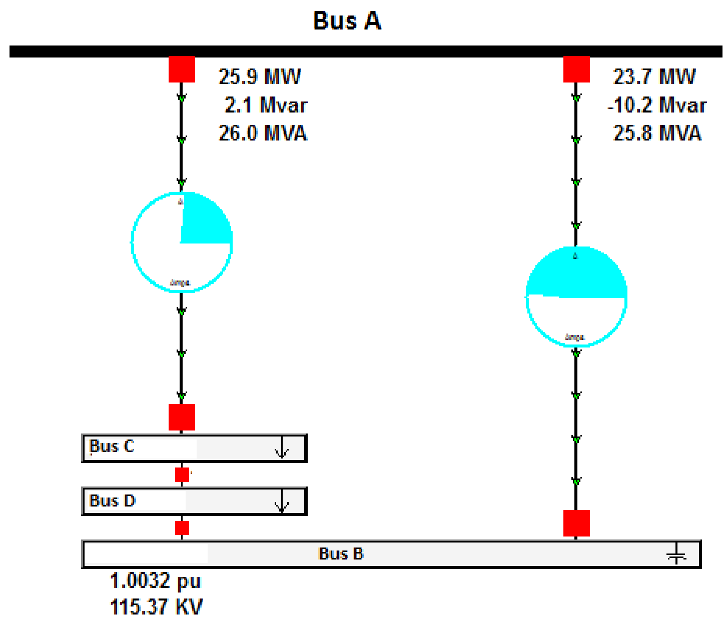


Figure 4.1 N-1 PowerWorld® Bus view illustrated pre-contingency conditions for Example 1

4.6.1.1 Base case

Using a high loaded summer peak scenario the base case power flow is calculated and shown in Figures 4.2 and 4.3. Those figures show Buses A and B before the contingencies.

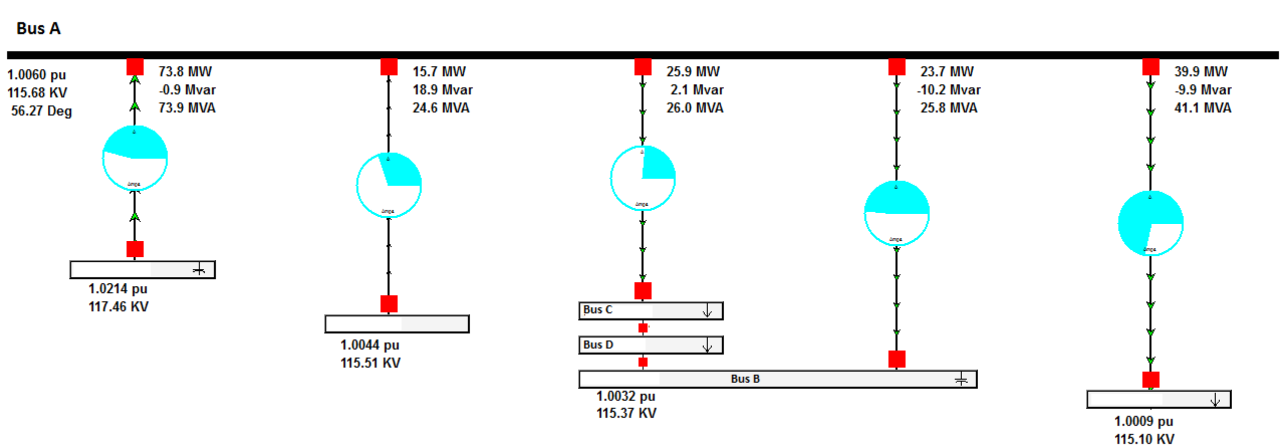


Figure 4.2 N-1 Base Case Bus A

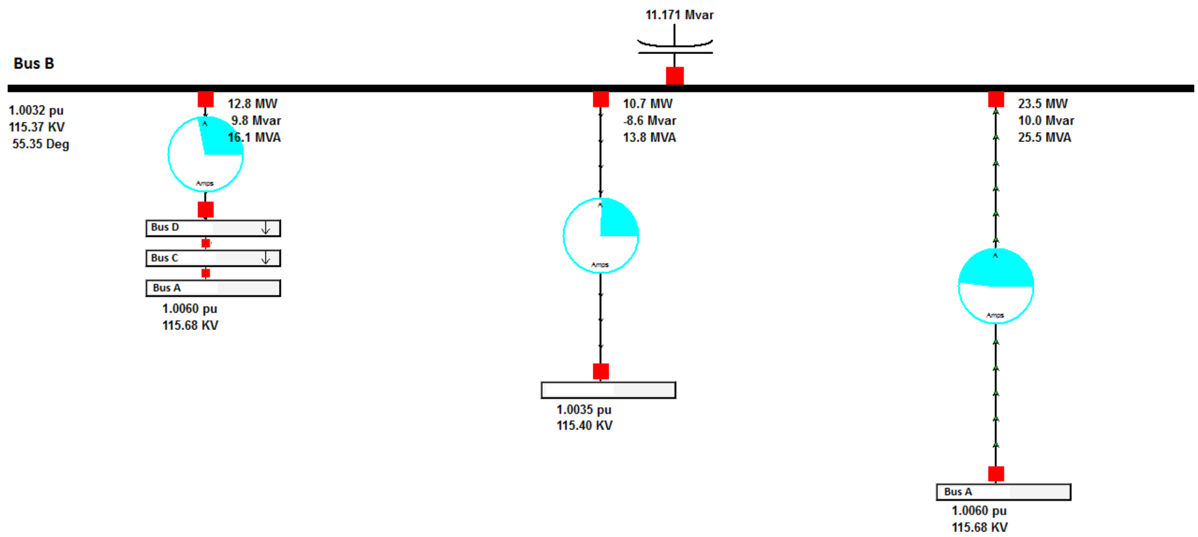


Figure 4.3 N-1 Base Case Bus B

4.6.1.2 Critical Contingency

The critical contingency in this scenario occurs when the line from Bus A to Bus C, shown in Figure 4.1 is opened.

Opening the line from Bus A to Bus C causes the overloading of the line from Bus A to Bus B. The line loading increases to 88% as seen in Figure 4.4. Figure 4.4 also depicts the open line from Bus A to Bus C in green and the line from Bus A to Bus B in orange, which means overloading.

The contingencies generated by the loss of lines connecting C to D, or D to B are not as critical due to power flowing through other connecting lines and loads shown in the figures 4.2 and 4.3.

4.6.1.3 Fault condition

The line between Bus A and Bus C is offline. Overloading of the line from Bus A to Bus B occurs. The affected line gets loaded at 88% which is more than the set cut off of 85%. This is due to the topology of the system and the loop connection between those two buses. If any of the lines between the buses A, C, D or B fails the other side of the loop gets overloaded.

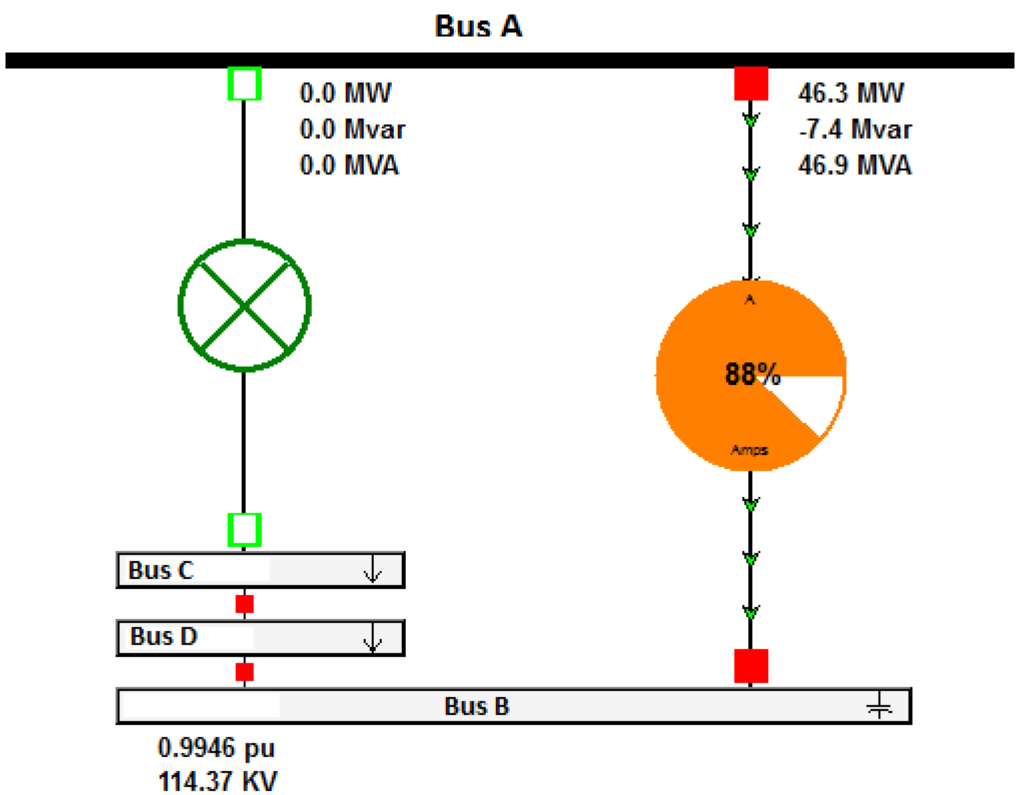


Figure 4.4 N-1 Contingency. Line between Bus A and Bus C Open

4.6.1.4 D-FACTS to Improve Fault Condition

Figure 4.5 shows that in order to reduce the loading on the line from A to B to the desired 85%, D-FACTS devices are inserted on the line to increase series inductance. The number of devices added is equivalent to adding 30% of the line reactance, on X devices.

With all those devices on the line goes back to an acceptable 85% loading. This means that only 45.3 MVA is flowing through that line.

The other 1.3 MVA is being rerouted through other lines in the system, but none are overloaded. The change due to the usage of D-FACTS devices is more noticeable if we look at the other values. There's a difference of 1.5MW and 1.1Mvar. This is because the D-FACTS devices are just inductors attached to the line and that only change the line reactance.

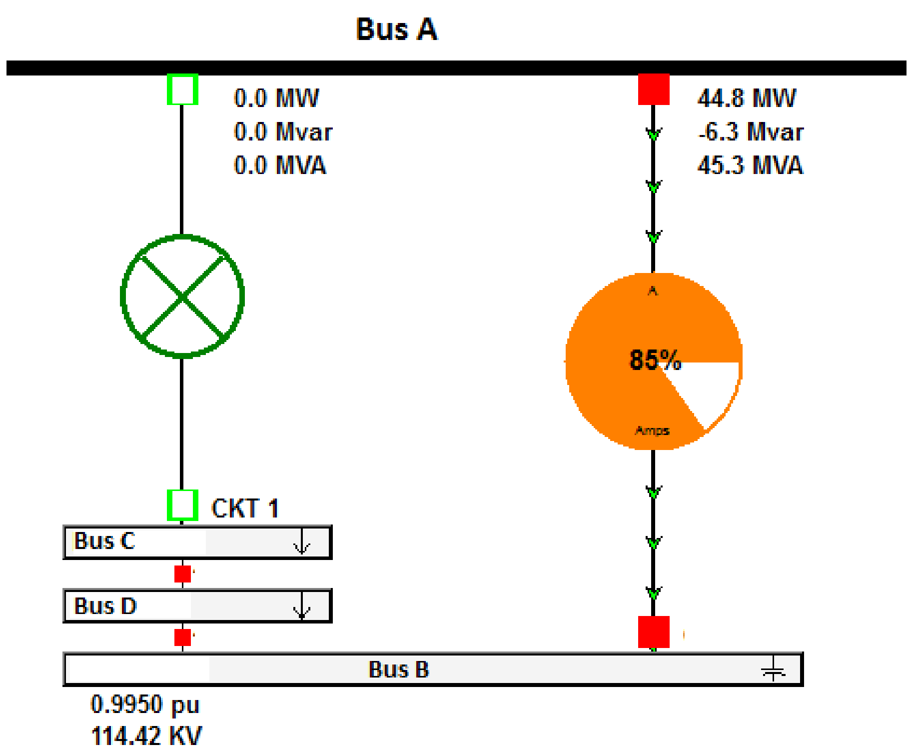


Figure 4.5 N-1 Contingency with D-FACTS

4.6.1.5 Evaluation

Figure 4.6 shows the evolution of the line studied and how it went from 45% loading to an 88% loading when the contingency happens. Then after introducing the D-FACTS devices the line goes back to the desired 85% loading. No other line gets overloaded at more than the critical levels.

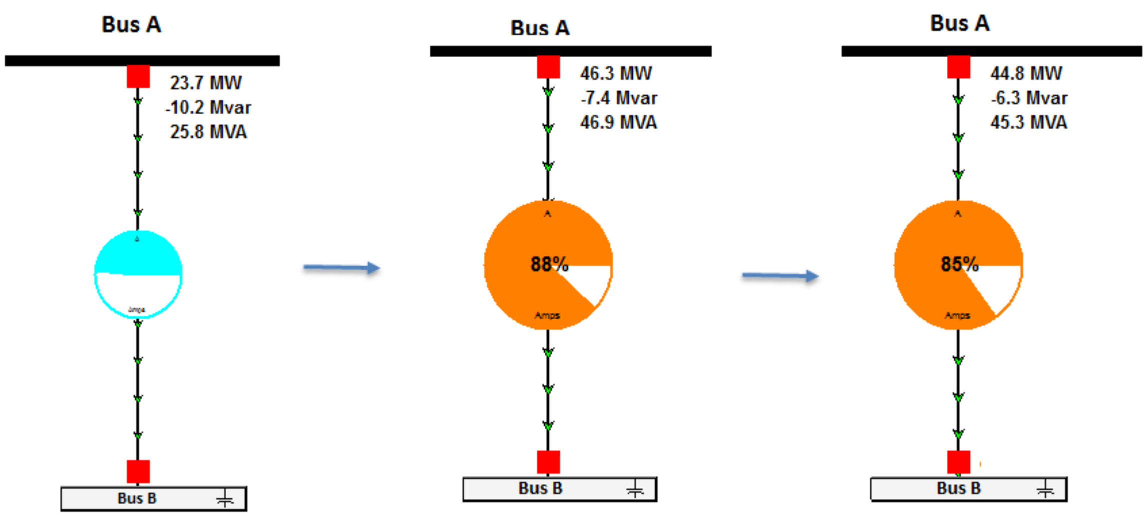


Figure 4.6 N-1 Line loading evolution with D-FACTS added

4.6.2 N-2 Contingency Example

The 115kV line from Bus K to Bus L becomes overloaded when two 230kV lines elsewhere in the system are offline. Those 230 kV lines are not directly tied to either Bus K or Bus L. The line from K to L is a bottleneck in the system that potentially benefits from the inclusion of D-FACTS.

For this case the set cut offs for the D-FACTS are 90% and 95%. The 90% is the desired line loading and so is the point when D-FACTS devices start to turn on. The 95% is the critical line loading. Passing that limit is dangerous and to avoid it all D-FACTS devices are turned on at 95% line loading and more.

4.6.2.1 Base case

First we need to study the line at a no fault condition to know how heavily loaded it is and the capacity, maximum current, and reactance.

As seen on Figure 4.7 the line is loaded at 40% during normal operation.

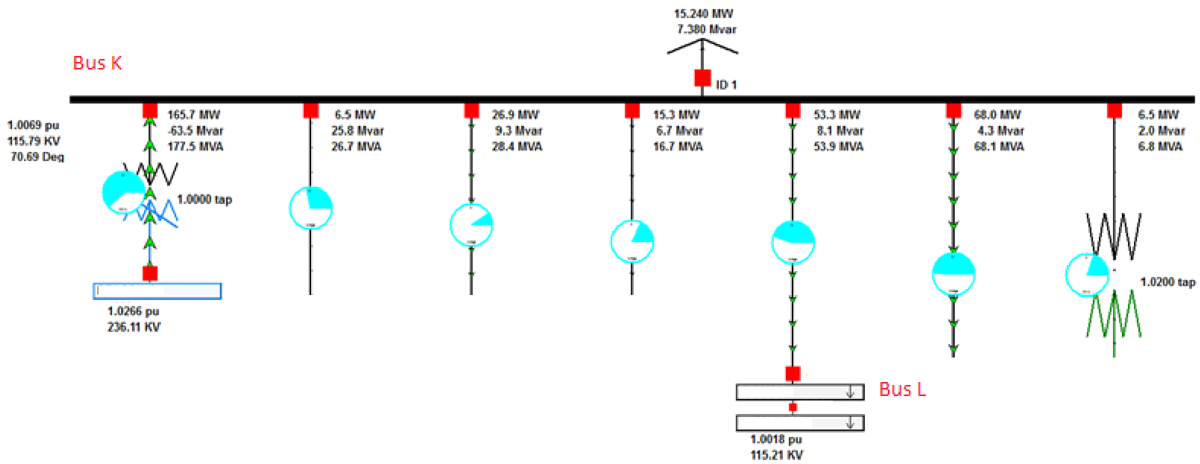


Figure 4.7 N-1 Example. Base Case

4.6.2.2 Critical Contingency

In order to replicate a critical contingency, within the computational limitations, the two 230kV lines are switched off to create the overloading on the line studied. These two lines are main transmission lines on the studied system and losing both lines will probably be part of a more widespread outage.

The two lines are connected to the same transmission bus, and come from different places as seen on Figure 4.8

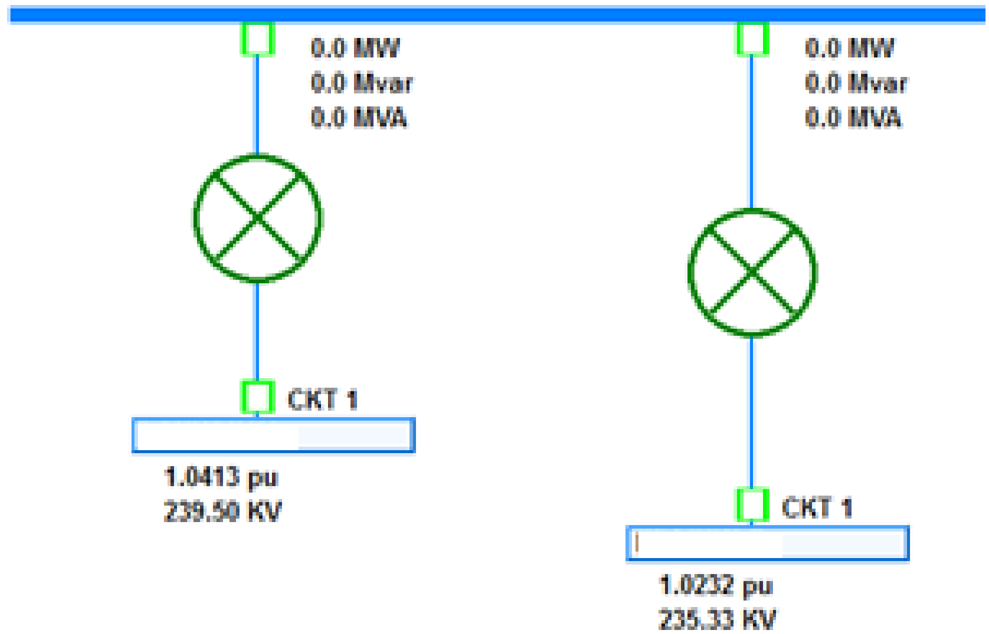


Figure 4.8 Double outage of two 230 kV transmission lines

4.6.2.3 Fault condition

When the double contingency happens and both 230kV transmission lines are opened, our line of study gets overloaded. The loading level goes to a dangerous 96%. That is more than the desired 90% and the critical 95%.

Figure 4.9 shows how the power flow is rerouted through the system. All the lines in Bus K have a different loading level than previously. The line studied shows the loading circle in orange and almost full to show the almost maximum loading. If the loading was 100% or more, the circle will be red.

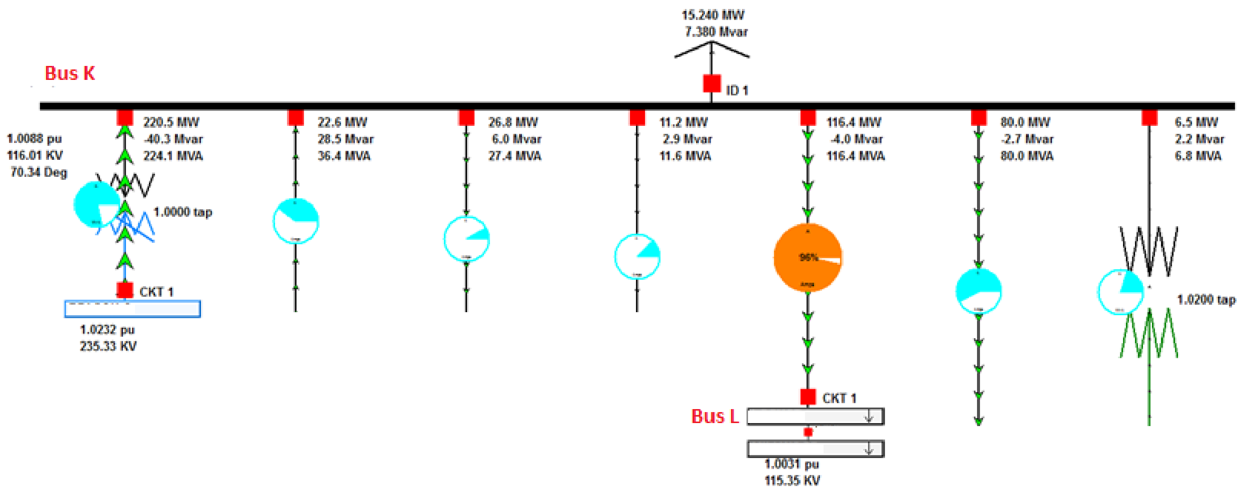


Figure 4.9 Bus K Fault Condition

4.6.2.4 D-FACTS to Improve Fault Condition

Figure 4.10 shows Bus K with the D-FACTS devices installed and the power flow analysis recalculated. The image shows that with 29 D-FACTS devices the line goes to 94% loading which is below the critical 95% but still not enough to reach the 90%. The addition of 29 D-FACTS adds 3065.3 µH.

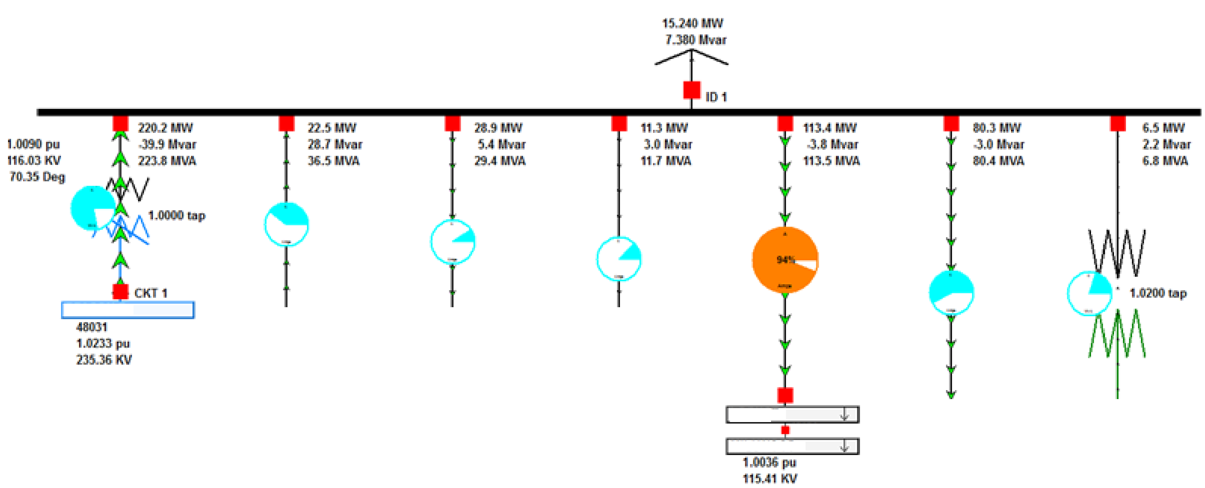


Figure 4.10 Bus K Fault with D-FACTS

4.6.2.5 Evaluation

Figure 4.11 shows the evolution of Line K to L when:

- there is no contingency
- fault happens
- D-FACTS are applied
- Maximum number of D-FACTS applied

The fourth part of the image shows that even with the maximum amount of D-FACTS devices that the line can withstand based on the line impedance. The 48 devices lower the line loading to 91%. The 91% is still above the desired 90% but it is close and the amount of devices is still reasonable, no more than 50 per phase. This maximum amount of devices is established through repeated simulations.

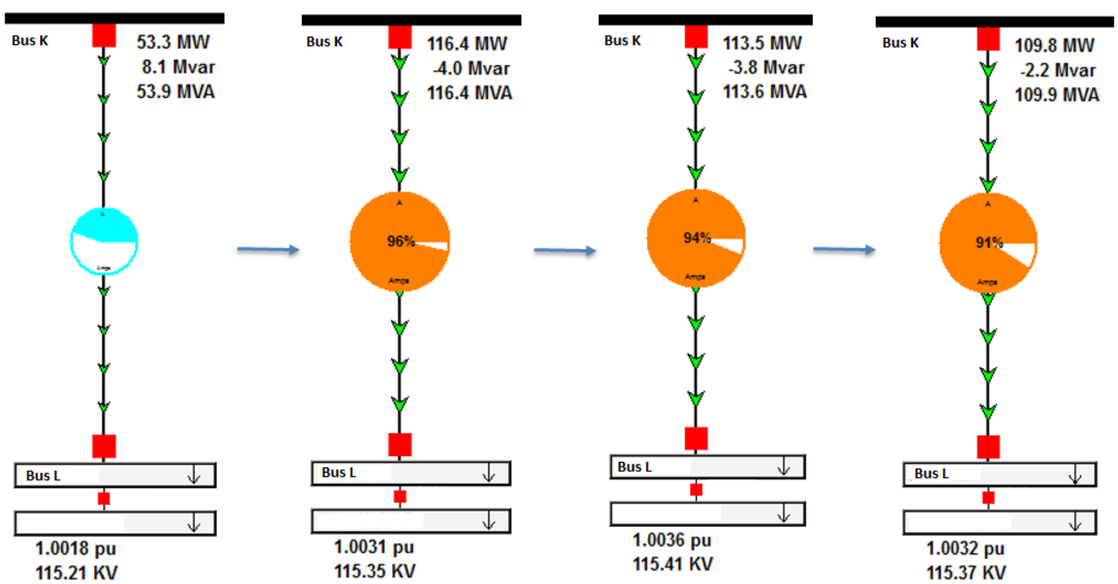


Figure 4.11 N-2 Line Loading Evolution

4.6.3 N-1 Neighbor's System Contingency Example

The 115kV line from Bus 1 to Bus 2 is affected by contingencies occurring on a neighboring system. Those contingencies are critical for understanding and operating the interconnected grid.

4.6.3.1 Base case

First, we need to study the line at a base condition to know how heavily loaded it is, and the line capacity, maximum current and reactance. The line characteristics are shown in Figure 4.12. The line is loaded at 28% capacity and there's no fault on the system.

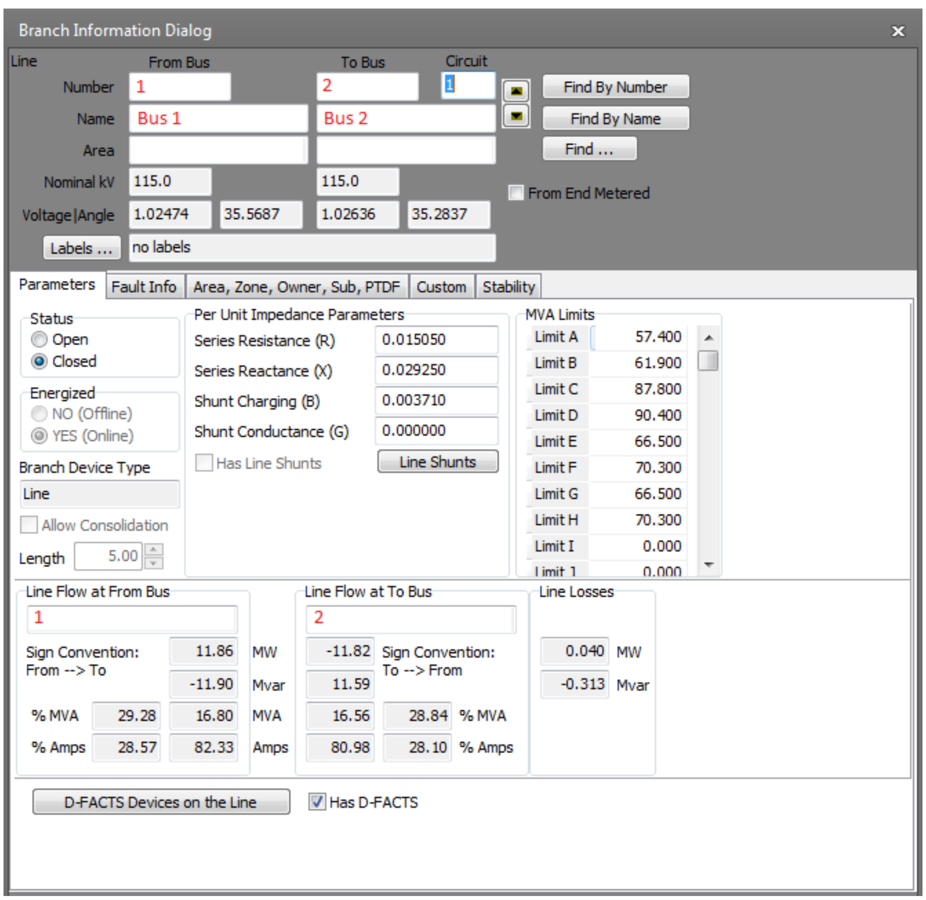


Figure 4.12 Line Settings for line from Bus 1 to Bus 2

Figures 4.13 and 4.14 show the condition on Buses 1 and 2 before any contingency happens. That gives a good perspective of the line studied as well as loading of the near by lines.

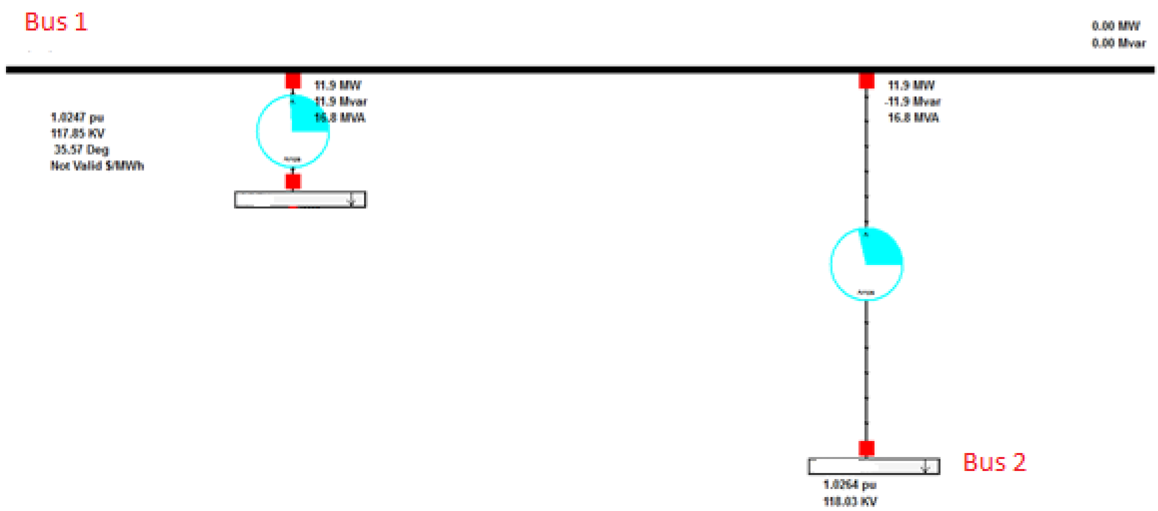


Figure 4.13 PowerWorld®. N-1 Neighbor's contingency. Bus 1 loading during base case

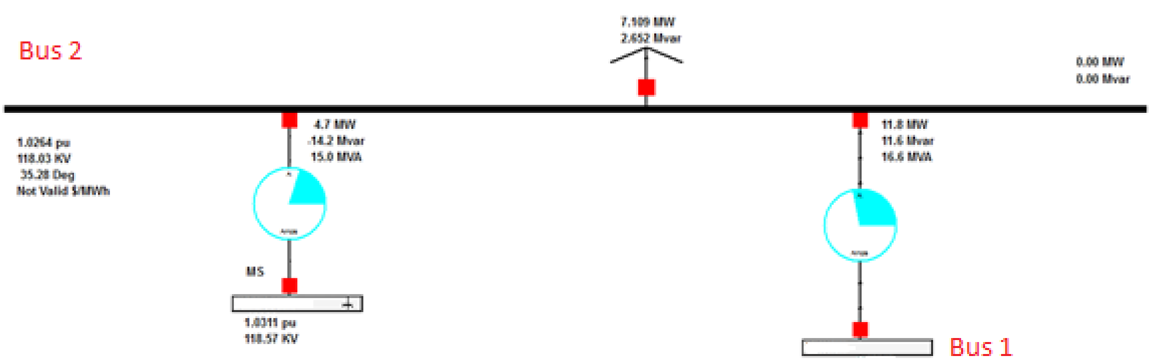


Figure 4.14 PowerWorld®. N-1 Neighbor's contingency. Bus 2 loading during base case

4.6.3.2 Critical Contingency

For illustration purposes in this example, an external contingency is selected as the most critical contingency to be considered. This helps protect the studied utilities system from outages started in other parts of the system not under their control. Connections between utilities and nearby systems have a strong influence in other areas of the grid. The main concern for the studied system is to stay in normal operation when external failures happen.

Three classes of contingency analysis are performed (N-1, N-2 and Neighboring N-1) in order to find the most critical contingencies where D-FACTS devices can be helpful.

Table 4.3 N-1 Neighbor's contingency. Worst case contingencies.

Contingency	**Element**	**Value**	**Reference Value**	**Change Value**
[Neighbor] TXF Bus EXT 230/115 (Neighbor)	Line from Bus 1 to Bus 2	29	0	29
[Neighbor] Bus EXT 115 (Neighbor)	Line from Bus 1 to Bus 2	29	0	29

Table 4.3 shows the most critical contingencies and how they affect the studied line. The three columns on the right show from left to right, the number of devices needed to help during the contingency, the number of D-FACTS devices injecting inductance before the contingency and the difference between those two values.

Both contingencies are located at external Bus EXT own by a different utility. One is the failure of the bus itself and the second one is the failure of the 230/115 kV transformer that supplies that bus.

The most critical contingency in the studied case is the one created by the failure of a bus or transformer owned by a neighboring utility.

For the N-1 Neighbor's Contingency Study the following conditions were applied:

- Performed using only one trigger level for turning on the first D-FACTS: 90%.
- D-FACTS are all on when line reaches 95% of loading capacity.
- Apply D-FACTS having a line impedance of 105.7μH based on commercial options and the maximum line current.
- The maximum number of D-FACTS devices per phase is 30% of the line impedance or no more than 30 devices.
- Application is considered successful if the line stays under 95% of current loading capacity with D-FACTS added.

4.6.3.3 Contingency condition

As soon as the fault happens on the neighbor's system the loading level of the line from Bus 1 to Bus 2 goes to a critical 97% as seen in Figure 4.15.

Figure 4.16 shows the characteristics of the line and how the loading has changed. The current has increased to 280 Amps which is more than triple the prefault loading.

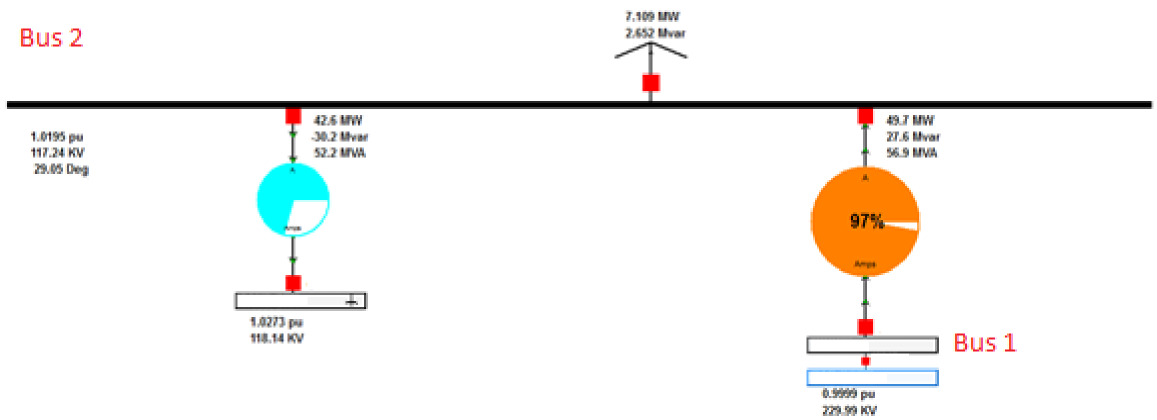


Figure 4.15 Bus 2 during Contingency with no D-FACTS

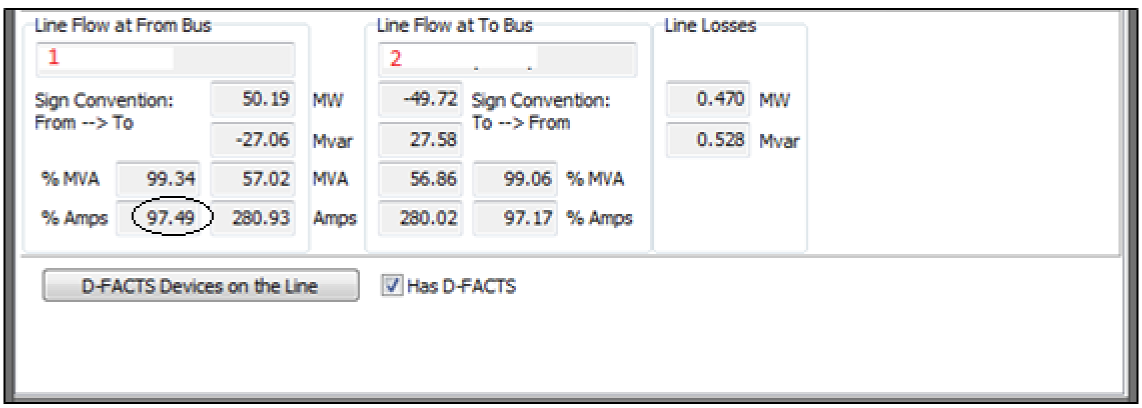


Figure 4.16 Line Conditions during Contingency

After the contingency happens the line goes from a 28.5% loading to a 97.5%. That means that the threshold of 90% is crossed.

4.6.3.4 D-FACTS to Improve Fault Condition

If the D-FACTS devices are applied following the conditions stated in point 4.6.3.2, the line loading changes and gets reduced to 96%

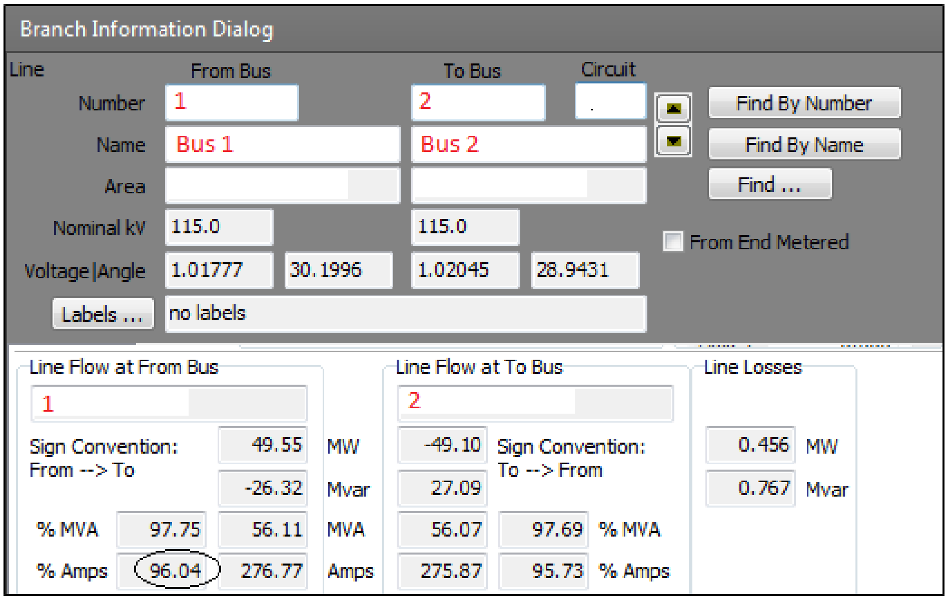


Figure 4.17 Line Conditions during Contingency with D-FACTS

This 96% current loading doesn't meet the requirement of staying under 95% loading capacity.

If more D-FACTS devices are installed on the line the 95% loading capacity is achieved. For that to happen the line needs more D-FACTS devices as shown in Figure 4.19.

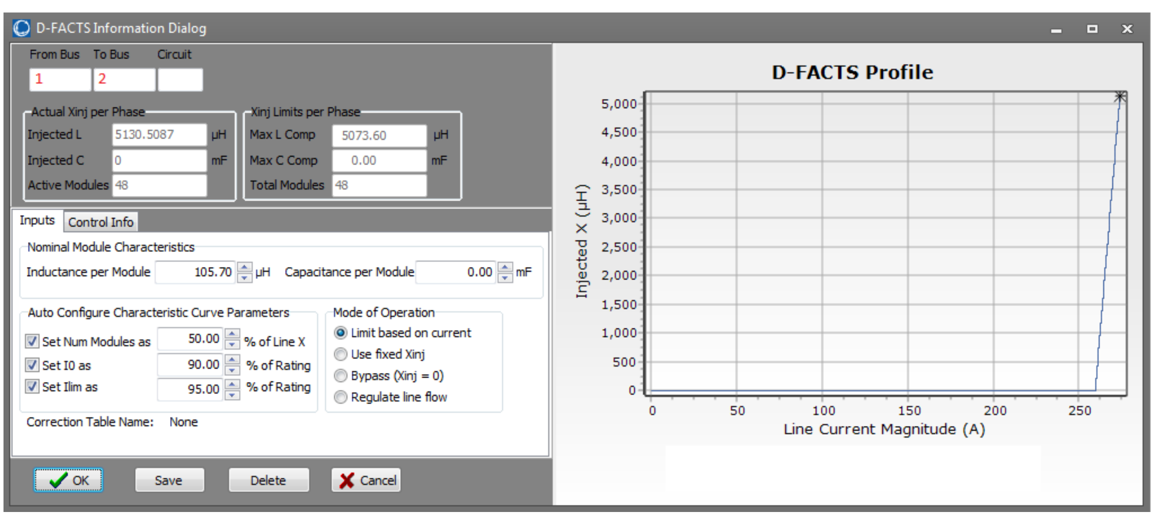


Figure 4.18 D-FACTS Setting at 50% of Line Reactance

Figure 4.18 shows the option of "Set Number of Modules" set as 50% of the line reactance. That introduces 48 D-FACTS devices on and the line current loading reduces to 95% as seen on Figure 4.19.

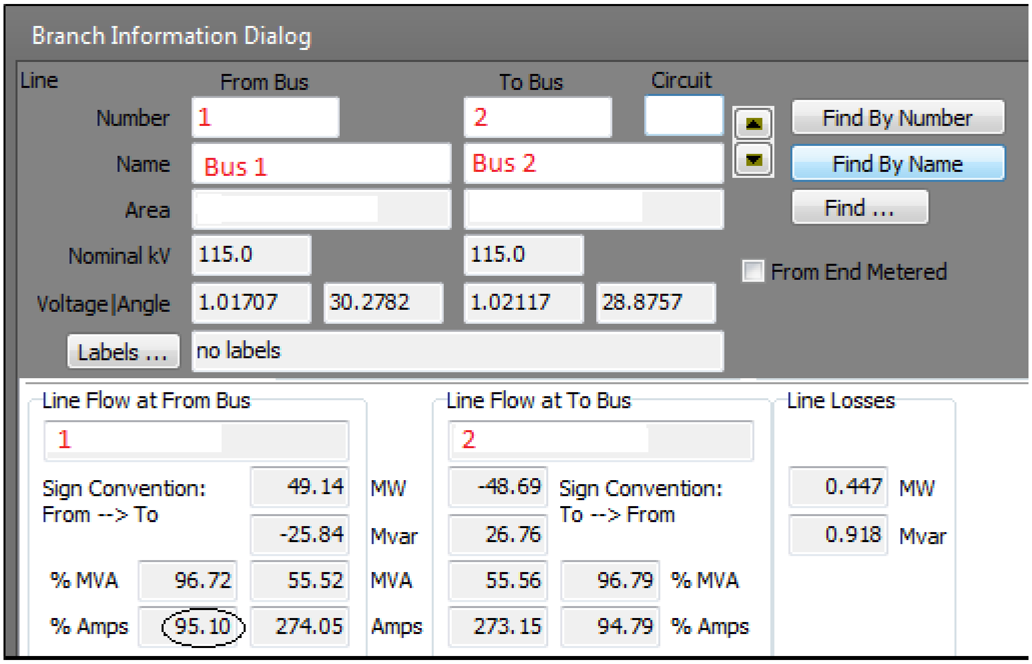


Figure 4.19 Line from Bus 1 to Bus 2 with 50 D-FACTS

4.6.3.5 Evaluation

Figure 4.20 shows the evolution of the studied line. The main concern on this line is the large amount of devices required to reduce the loading to 95%.

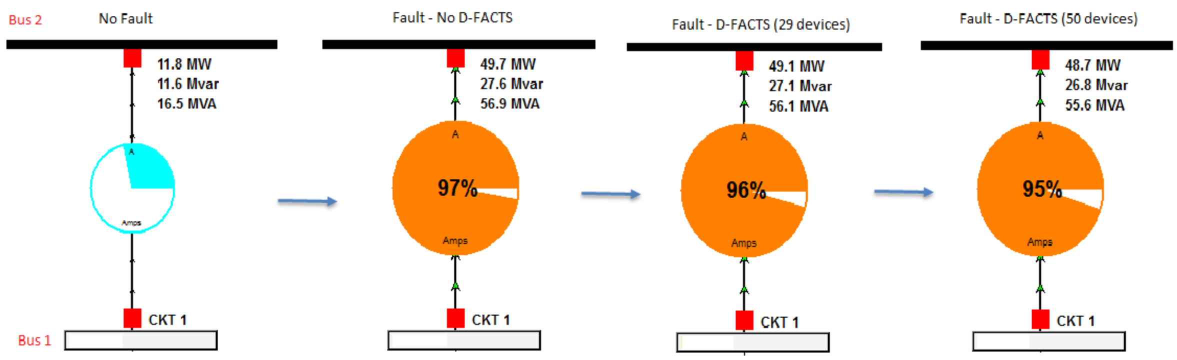


Figure 4.20 Line Fault Evolution

4.7 Line Recommendations for D-FACTS Installation

After all the testing done some recommendations on the line characteristics can be given in order to select a line that is a good candidate for installing D-FACTS devices.

Some of the physical requirements a line must meet are:

D-FACTS devices need to be installed on overhead lines with single conductor due to their size and clamping characteristics precluding lines with bundled conductors. As they go directly attached to the line an underground cable is not an option due to the insulation around the cable and the presence of sheath. Bundled conductors are not suitable due to the space limitations and distance between conductors. The restrictions on the cable size are less critical but need to be taken into account, such as not being bigger than a 1272 kcmil according to the manufacturer as shown in Chapter 2.

Other considerations are the line electrical characteristics, such as the line capacity. The first one being the line maximum current rating. If that value is over a 1,000 Amps, then there are no commercially available D-FACTS options for that line at the time this thesis was written.

If the line capacity is lower than 50 MVA then the installation of D-FACTS devices may not be economically beneficial.

The lines selected for the D-FACTS preferably needs to be a critical path or an existing line that needs an increase in capacity due to overloading. This is in order to maximize the benefits and reduce the repay time. D-FACTS are a more economical option than reconductoring a line or adding new lines, but there is still an investment that needs to be repaid over a reasonable period of time based on a utility’s payback criteria. This period is stablished in order to accommodate future changes in D-FACTS technology and in the grid.

4.8 Chapter Summary

Three different contingency scenarios are analyzed, and in all of them the D-FACTS devices proved to be beneficial during the contingency.

The N-1 contingency analysis studied here focuses on identifying critical lines. An objective of the study is to maintain system capacity by incrementally turning on D-FACTS devices on every single line of the studied system. There were up to 26 lines identified on the N-1 general study for the more in depth one line study. The example N-1 contingency showed that D-FACTS can reduce the line loading from 88% to the desired 85%.

As N-2 contingencies are more complex the studies were focused on keeping the maximum number of loads supplied during the contingencies. The idea is to reroute power and keep the maximum amount of customers online during rare events. There were 15 lines identified on the N-1 general study for the more in depth study. And on the N-2 study example the D-FACTS proved to be able to reduce current line loading on the critical line from 96% to 91%.

A study was performed focusing on some critical regions inside the system where outages on neighbors' infrastructure is a major concern. The example shows that faults in external systems can generate overloading in the studied utility's system. The line loading on the studied line goes from 30% to 97% when the studied contingency occurs. With 50 D-FACTS devices per phase the line loading was reduced to 95% which is the highest acceptable operating point.

5 Chapter 5: Conclusions and Future Work

5.1 Conclusions

Increasing demand for electricity is putting increasing pressure on the existing transmission and distribution infrastructure, creating bottlenecks and congestion. The conventional solution of increasing system capacity by building additional lines is expensive and is subject to regulatory delays. Under such conditions, it becomes imperative to utilize the existing asset base more effectively, improving line capacity and system reliability.

D-FACTS devices are a simpler solution. The main advantage is their modularity. Being small and easy to install makes their deployment attractive. Their portability is also an obvious advantage.

This thesis studied the application of D-FACTS devices on the transmission system of a utility in the western part of the U.S. In the studied cases the D-FACTS proved to be effective in order to keep the lines operating within limits. As seen in the three examples discussed in detail, D-FACTS devices can reroute power through other less loaded lines in order to keep the transmission bottlenecks loaded under the set limits. For each of the examples D-FACTS have proven to have an impact on the system with a reasonable amount of devices and cost.

With D-FACTS, power can be rerouted through other lines during normal operation to help balance loading between different areas. The devices can also serve to reroute power through other utilities' paths and to control power exchange between utilities.

Performing the N-1 contingency analysis showed that the utility's system is well designed, but there were cases where the D-FACTS devices proved to be advantageous. The N-1 study helps understand the critical contingencies and bottlenecks. Being able to reroute power during contingencies makes the system more reliable and reduces the cost and risk of outages.

The N-2 contingency study focused on keeping the system within limits when two simultaneous outages occur. The idea is to be able to reroute the extra loading that some lines will see in response to the N-2 contingency. In the example shown in this thesis 29 D-FACTS devices are installed in order to keep the line in question under its critical loading of 95%.

The N-1 contingency analysis pertaining to a fault on neighboring interconnected systems shows that D-FACTS can mitigate the effect of such an external fault. Appropriately placing and controlled D-FACTS devices can maintain system integrity.

5.2 Future Work

For a more detailed study of the installation of D-FACTS devices on power transmission lines, we require more information about the mechanical and physical design characteristics of the line at hand. Results will help determine the most optimal places to locate the D-FACTS devices. Lines with wood poles may not be an option for D-FACTS installation due to their weight limitations but a study determining a minimal redesign, e.g., replacing only a few poles, may be insightful. Also there may be other situations, e.g., locations prone to icing, which may influence D-FACTS placement.

Future studies should include better integration of the D-FACTS to impact power flow under daily operation. Perform studies to optimize the entire system based on minimizing losses, improvement stability margins or by other measures through the use of D-FACTS devices. Including more than one line with installed D-FACTS can improve system capacity, rerouting options to increase efficiency, stability and reliability.

The impact of D-FACTS devices on protection schemes needs to be studied in depth. The change in line impedance and the quick disconnect when the D-FACTS sees a fault will affect the relays. Relays need to know how many devices are on and where are they located in order to operate correctly and avoid false tripping. For example, D-FACTS devices are known to distort a distance relay's estimate of distance to a fault. Research into the advantages of having D-FACTS devices communicate directly to relays is worth pursuing.

Study the security and reliability of the communications system in order to retrieve real time data and avoid undesired access and control. As mentioned in Chapters one and two, communications and their security are critical. Hacking into the devices or the utilities system can generate major contingencies and security concerns.

Another interesting study would be developing a small scale model of a D-FACTS device to test it on a power model. This would give additional understanding of how D-FACTS devices work and help develop more accurate models. In the power lab located at the University of Idaho, a scale model of D-FACTS could be used to test the response of commercial relays when D-FACTS are installed on a known system.

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