CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

POWER FLOW CONTROL WITH

DISTRIBUTED FLEXIBLE AC TRANSMISSION SYSTEM (D-FACTS)

DEVICES

A graduate project submitted in partial fulfillment of the requirements
For the degree of Master of Science in
Electrical Engineering

By

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ABSTRACT

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Climate change, energy crisis and financial crisis are some of the issues that affect the transformation of power and the power industry. [13] Distributed FACTS or D-FACTS devices are being used today to help correct inefficiencies within the current power grid. These devices can help a utility save money by transferring load off a power line near its thermal limits to one that is lightly loaded. While using D-FACTS devices, each MWh of power that does not have to go into power generation with coal can prevent the introduction of approximately 1 ton of pollution into the atmosphere. The potential of using Distributed FACTS devices in a power network should bring it into more widespread adoption.

Introduction

FACTS devices and the Smart Grid are two tools in dealing with many of the energy problems mankind has now and will have in the future. Climate change, energy crisis and financial crisis are some of the issues that affect the transformation of power and the power industry. [13] The goal of the United States and many other countries are to ultimately get off the oil standard and to go toward more of a low carbon economy, or to put it plainly, just to go away from fossil fuels. The United States, the European Union and China to name a few are seeking to go towards more green energy sources, such as solar and wind generation. Adding newer, local sources of distributed generation will have an impact on power transmission and distribution. Adding a new customer to an existing power line can also have an impact on power transmission and distribution. Whether it is adding new distributed generation or a new customer, the cost involved with installation and commissioning can be very expensive. Even right-a-way issues can even be very complicated or create a big expense when leasing or purchasing the land for new power lines. This might make the building of new power lines less feasible.

The definition of a Smart Grid, by one IEEE paper has it defined as "utilizing advanced monitoring, analysis, control and communications technologies to the electrical power system to maximize the throughput of the systems while reducing the energy consumptions." [13] One could see that the system will utilize or be affected by equipment such as high power electronics, digital protective relays, digital controls, integrated communications and advance control centers. [6]

This paper will demonstrate the justification of using series Distributed FACTS (D-FACTS) devices over series FACTS devices for power flow control. The acronym FACTS stands for Flexible AC Transmission System. FACTS Controllers are devices used to control the various parameters of power systems. It is quite clear that FACTS devices fall under the umbrella of the Smart Grid. They can help control the interrelated parameters that govern the operation of transmission systems some of which include series impedance, shunt impedance, current, voltage and phase angle. [7]

Series FACTS or D-FACTS devices can allow a utility or generator to more effectively utilize power transmission lines closer to their thermal limits for better power flow, therefore making them more efficient. This Smart Grid technology allows utilities to load transmission lines near their true thermal capacity and to keep large power flows in check with more complex power systems and more power being transferred. As mentioned in the first paragraph, it is not always feasible to build new transmission lines due to the shear cost or the ability to get the right-a-way for new installations. Everything comes down to money, and transmission line power flow definitely has to be accounted for.

Background Theory

2.1 System Variables

2.11 Slack Bus

A swing bus (or slack bus) is a generator bus with a generator controlling the terminal voltage, V_t, and angle delta, δ, at the bus. It is also known as a reference bus. The terminal voltage angle would typically be set at 0° with the voltage set at 1 per unit (p.u.) voltage. The terminal voltage is kept constant by adjusting the field current in the generator. With V_t and the angle delta being known parameters for this bus, the two unknown parameters are the real power, P, and the reactive power, Q. The real and reactive power are uncontrolled by the generator, the generator supplies whatever the system demands of it. Other system generators provide a fixed amount of real power, P. This machine swings or takes up the slack; hence it fits its name.

2.12 Generator Bus

A generator bus (or PV) is another generator bus with a synchronous generator controlling the terminal voltage and real power supplied to the bus. The terminal voltage is kept constant by adjusting the field current in the generator. At the same time, this also changes the reactive power supplied by the generator to the system. The prime mover controls the power the generator supplies the system. The generator on this bus has a set amount of real power, P, it provides at or near its capacity. These generators work most efficiently at full capacity. The rest of the real power is picked up by the Swing Bus generator. The P and the V_t are the two known parameters for this bus type. The two unknown parameters for this bus type are the reactive power, Q, and the angle delta, δ.

2.13 Load Bus

A load bus (or PQ bus) is a bus in which the real and reactive power are scheduled or connected. These buses have no generators connected to them. They have known parameters of real power, P, and reactive power, Q. It also has unknown parameters of voltage magnitude, |V|, and angle delta, δ.

2.14 System Branch Parameters

The system branch parameters can be typically found in a table. They are amongst the parameters or data that go into the system model being used. The main reference system used in this paper is the IEEE 14-Bus system. The base case model is a 3-Bus system. The system branch parameters provide the resistive, inductive reactance, and charging values for the network branches in a system. The values for the IEEE 14-Bus System Branch Parameters are found under Table A1.1 in Appendix A.

2.15 System Bus Data

The system bus data can be typically found in a table. They are amongst the parameters or data that go into the system model being used. The main reference system used in this paper is the IEEE 14-Bus system. The base case model is a 3-Bus system. The system bus data tells the user the minimum and maximum real and reactive power generated at the buses. This data tells the user the bus type and the real or reactive loads that may be at the buses. The table also lists the bus numbers. The values for the IEEE 14-Bus Data are found under Table A1.2 in Appendix A.

2.2 Synchronous Generation

Synchronous Generation must be covered before going into Real and Reactive Power Control. Synchronous generators are often used in power networks. A synchronous generator consists of two main parts, a rotor which contains the field windings and the stator (also called the armature) which contains the three phase windings. **Figure 2.1** shows an equivalent armature winding and a field winding for a synchronous machine. By observation the Direct axis is ahead of the Quadrature axis by approximately 90°; the axis for phase 'a' or a-axis is separated from the Direct axis by θ_d. From the following Torque Angle Delta equation (2.1), it can be observed that the θ_d is closest to the a-axis of **Figure 2.1** if time, t, equals 0, therefore θ_d equals θ_{d0}. From this same equation δ lags θ_d by 90° or θ_{d0} if t equals 0. The angle δ or the torque angle plays an important role in the network.

$$\theta_d = (\omega t + \theta_{d0}) = (\omega t + \delta + 90°) \qquad (2.1)$$

Figure 2.2 shows the equivalent phase 'a' circuit of a synchronous machine. The equation for the phase 'a' field or electro-motive force is shown as the following Internal EMF equation **(2.2)**. The Internal EMF is proportional to the field strength as shown in the following RMS Magnitude equation (2.3). Substituting δ + 90° in place of θ_{d0} yields an equation with cosine instead of sine due to a trigonometry identity, shown as the Internal EMF with Delta equation (2.4). The general equation for the circuit in **Figure 2.2** is shown as the equation for Synchronous Internal Voltage (2.5). It must be mentioned that the internal resistance, R, from **Figure 2.2** is typically not considered because of its negligible impact.

$$e_{a'} = \sqrt{2}\,|E_i|\sin(\omega t + \theta_{d0}) \qquad (2.2)$$

$$|E_i| = \frac{\omega M_f I_f}{\sqrt{2}} \tag{2.3}$$

$$e_{a'} = \sqrt{2}\,|E_i| \cos(\omega t + \delta) \tag{2.4}$$

$$E_i = V_a + RI_a + jX_d I_a \tag{2.5}$$

There is quite a bit of theory necessary to describe the relationship between the field windings and the armature windings. It involves mutual inductances, self-inductances, flux-linkages and phase current to describe the relationship. It is not important to go into the details of this, but it is important to show there is a simplified equation to sum up the relationship between the phases of the armature and the field. This is shown by the following DC Field Opposition equation (2.6). In **Figure 2.1** this relationship is shown as an armature equivalent winding rotating with rotor. According to Grainger, "we can, therefore, regard those flux linkages as coming from the steady dc current i_d in a fictitious dc circuit coincident with the d-axis and thus stationary with respect to the field circuit." [5] By inspection, if current is lagging then θ_a of the current is negative for that phase. All three currents in the armature, i_a, i_b, and i_c would have a combined demagnetizing effect. This means i_d in the DC Field Opposition equation (2.6) would have a negative, demagnetizing effect on the current of the field, I_f. The excitation system of the generator would have to increase the field current to counter this. The opposite holds true for leading power factors, the demagnetizing effect on the current of the field would be reduced, thus reducing the amount of field excitation required.

$$i_d = -\sqrt{3}\,|I_a| \sin\theta_a \tag{2.6}$$

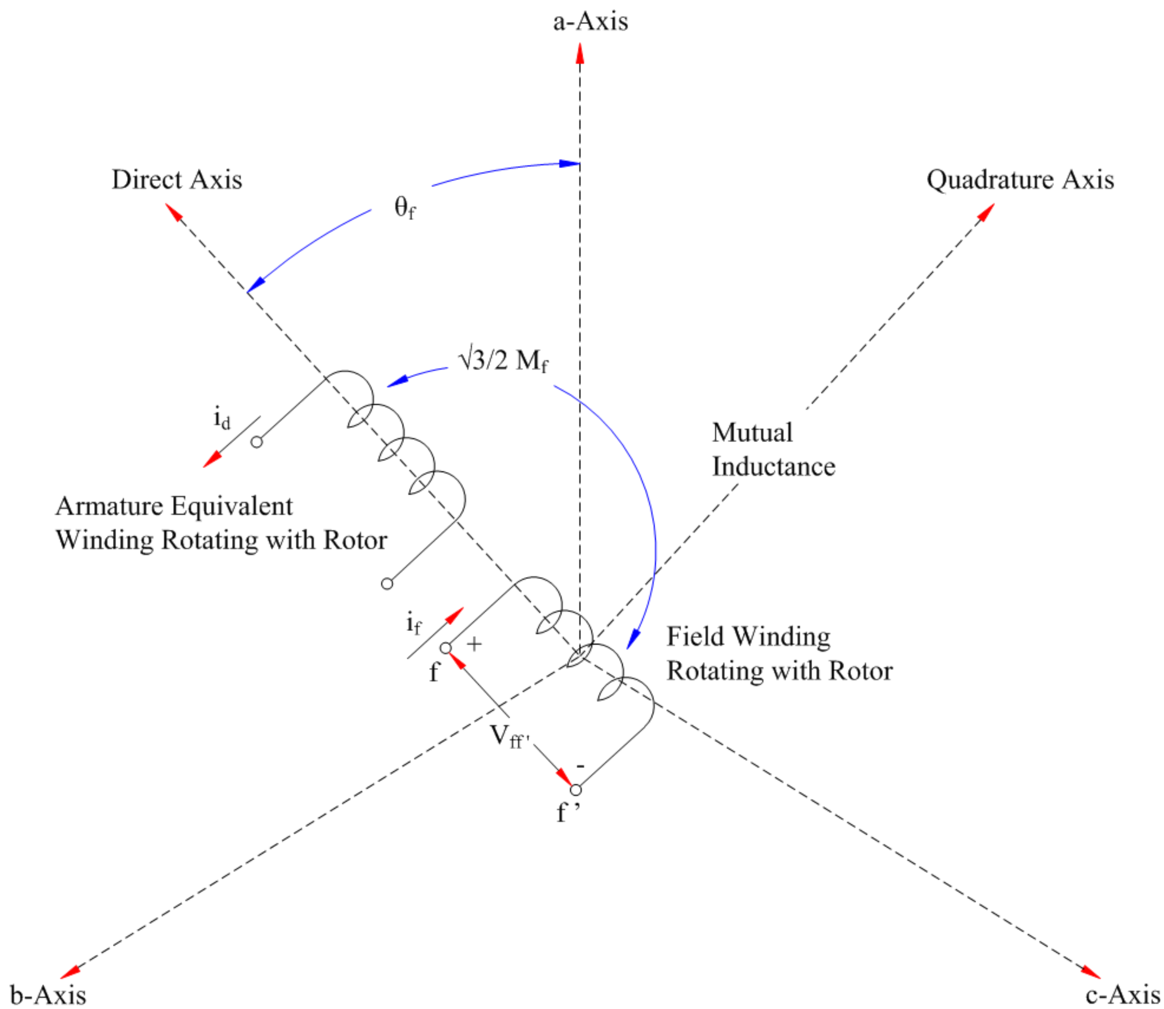

Figure 2.1 - Equivalent Armature Winding and Field Winding [2]

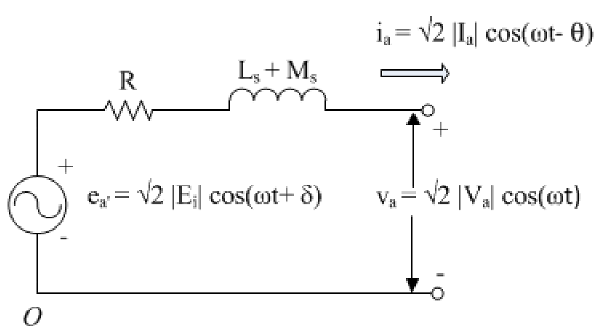

Figure 2.2 - Phase 'a' of Synchronous Machine [2]

2.3 Real and Reactive Power Control Equations and Theory

When the synchronous machine is connected to an infinite bus, its speed and terminal voltage are fixed and unalterable. [5] Two things that are controllable are the torque on the shaft from the prime mover and the current supplied to the generator field. The torque delivered to the shaft by the prime mover is the normal way to vary real power. The torque angle is δ, and it is the angle between E_i and V_t of the generator. The angle can be seen in the top part of **Figure 2.3**.

The Complex Power equation (2.7) shows real power and reactive power. The Real Power equation (2.8) and the Reactive Power equation (2.9) are shown following the Complex Power equation (2.7). These two equations make up the real part of reactive power and the imaginary part of complex power. By observation, the Real Power equation (2.8) is dependent on the torque angle. If terminal voltage, V_t, and real power, P, are to remain constant, δ must decrease so E_i can increase. A decrease in δ and an increase in $|E_i|$ would also increase reactive power, Q, if it is already positive. This would be the case when generators are operating at a fixed real power.

Real power of the machine is increased by opening the valve to a turbine. The rotor speed will in turn increase. While holding E_i and V_t constant means δ will increase. This also means that $|I_a|\ X_d \cos\theta$ will increase by observing the top portion of **Figure 2.3**. Since there is more load on the bus from the system, the counter-torque on the prime mover will bring the speed back down to the speed corresponding to the infinite bus. [5] This would be how a generator feeding a swing bus would increase real power load.

$$S = P + jQ = V_t I_a^* = \frac{|V_t||E_i|(\cos\delta - j\sin\delta) - |V_t|^2}{-jX_d} \quad (2.7)$$

$$P = \frac{|V_t||E_i|}{X_d}\sin\delta \quad (2.8)$$

$$Q = \frac{|V_t|}{X_d}(|E_i|\cos\delta - |V_t|) \quad (2.9)$$

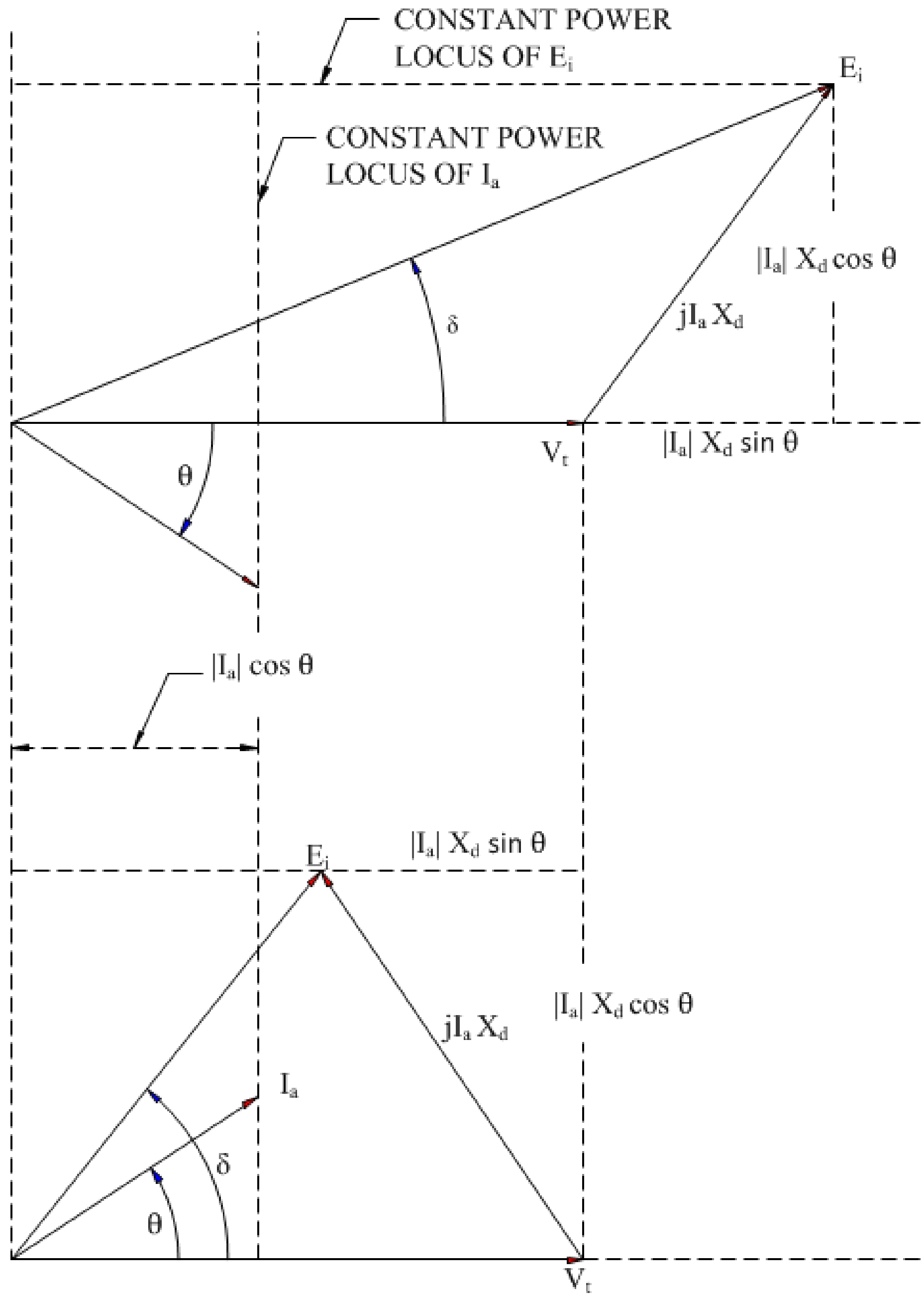

Figure 2.3 - Constant Power Loci [5]

2.4 Power Flow with Static Series Synchronous Compensation

The equations for Real and Reactive Power (2.10 & 2.11), P & Q, are simplified by using the same voltage magnitudes for sending and receiving end, V_s and V_r. The difference between the phase angles is δ. An SSSC, limited by its voltage and current ratings, is capable of emulating a compensating reactance, X_q , (both inductive and capacitive) in series with the transmission line inductive reactance, X_L. [11]

$$P_q = \frac{V_s V_r}{X_L} \sin\delta = \frac{V^2}{X_L} \sin\delta \tag{2.10}$$

$$Q_q = \frac{V_s V_r}{X_L}(1 - \cos\delta) = \frac{V^2}{X_L}(1 - \cos\delta) \tag{2.11}$$

The denominator of the Real and Reactive Power equations (2.13 & 2.14) with Effective Reactance contain the equation for Effective Reactance, X_{eff} (2.12). This reactance is the effective reactance between the two ends of a transmission line. Within the equation for X_{eff} is a ratio of X_q to X_L which is the reactance compensation of the transmission line. The X_q is negative when the SSSC is to be operated in an inductive mode and positive when the SSSC is to be operated in a capacitive mode. [11]

$$X_{eff} = X_L(1 - k) = X_L\left(1 - \frac{X_q}{X_L}\right),\ 0 \le k \le 1 \tag{2.12}$$

$$P_q = \frac{V_s V_r}{X_{eff}} \sin\delta = \frac{V^2}{X_L\,(1 - \frac{X_q}{X_L})} \sin\delta \tag{2.13}$$

$$Q_q = \frac{V_s V_r}{X_{eff}}(1 - \cos\delta) = \frac{V^2}{X_L\,(1 - \frac{X_q}{X_L})}(1 - \cos\delta) \tag{2.14}$$

A SSSC increases the power flow in a transmission line. It has already been stated the SSSC operates by emulating a compensating reactance. When it is capacitive, it can be thought of the same way a TCSC device would be in affecting the system. For the same end voltages the magnitude of the total voltage across the series inductance, V_X, is increased by the magnitude of the opposite voltage, V_C (or V_q), developed across the series capacitor. The voltage added to the series line impedance is in opposite polarity to the line current, as is the impedance of the line itself. Equation 2.15 shows a basic voltage drop equation that emphasizes this. According to Hingorani,

"This results in an increase in the line current. While it may be convenient to consider series capacitive compensation as a means of reducing the line impedance, in reality, as explained previously, it is really a means of increasing the voltage across the given impedance of the physical line." [7]

What Hingorani was referring to was his previous discussion on TCSC devices which insert conventional series compensation in the transmission line. When the SSSC is emulating inductive reactance, it is the opposite case of when the device is emulating capacitive reactance. More on TCSC devices will come later in the paper.

$$V_c = V_q = -jX_cI = -jX_qI \quad (2.15)$$

The phasor diagrams in **Figures 2.4** through **2.6** show the SSSC operated in inductive and capacitive modes. **Figure 2.4** is for the SSSC when operated with approximately 100% inductive reactance compensation. The current decreases from $I_{0\%}$ to $I_{-100\%}$. **Figure 2.5** is for the SSSC when operated with approximately 33% capacitive reactance compensation. The current increases from $I_{0\%}$ to $I_{33\%}$. The third phasor, **Figure 2.6**, represents power transmission with no SSSC compensation.

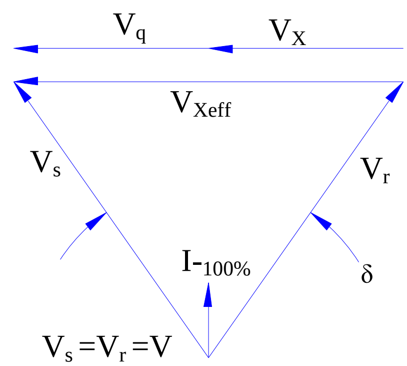

Figure 2.4 - Line with Inductive SSSC Compensation [11]

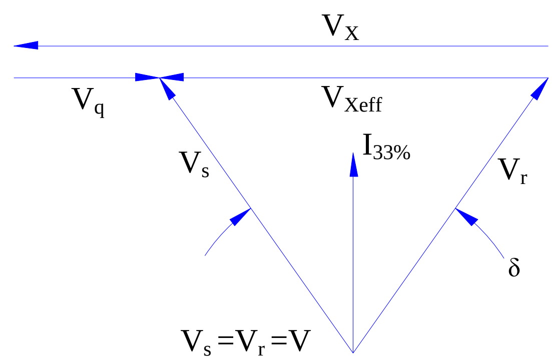

Figure 2.5 - Line with Capacitive SSSC Compensation [11]

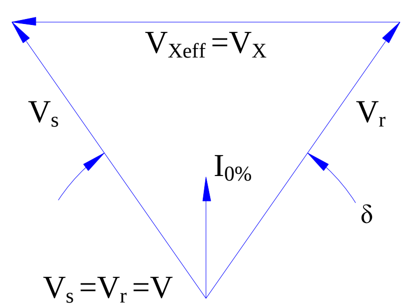

Figure 2.6 - No SSSC Compensation [11]

The Expressions for Normalized Power Flow and the equation for Normalized Effective Reactance of the transmission line are shown in equations (2.16) and (2.17) respectively. **Figure 2.7** shows the effects of the normalized power flow with compensating reactance. When X_q is inductive both P_q and Q_q decrease as X_{eff} increases. When X_q is capacitive both P_q and Q_q increase as X_{eff} decreases.

$$\frac{P_q}{P} = \frac{Q_q}{Q} = \frac{1}{(1-\frac{X_q}{X_L})} \tag{2.16}$$

$$(1-\frac{X_q}{X_L}) \tag{2.17}$$

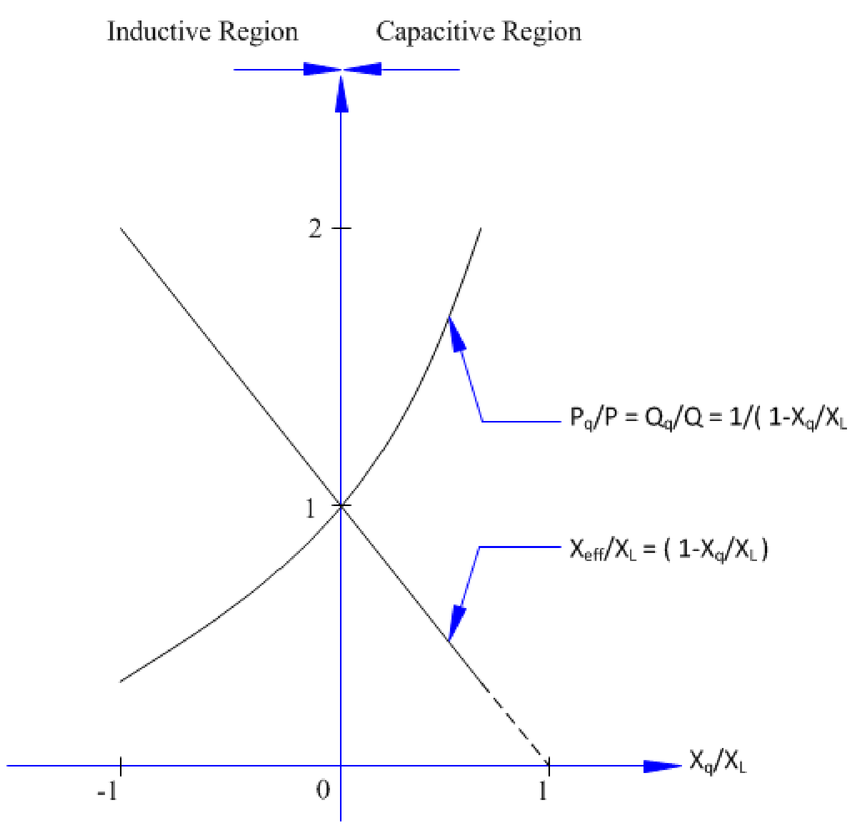

Figure 2.7 - Effect of Compensating Reactance on Power Flow and X_{eff} [11]

2.41 Basic Static Series Synchronous Compensation Circuit

A DSSC module is essentially a small, self-contained package system. According to Divan, "DSSC modules consist of a small rated (~10 KVA) single phase inverter and a single turn transformer (STT), along with associated controls, power supply circuits and built-in communications capability." [1] The module is broken down into two parts than can be clamped around the power line conductors. The magnetic circuit is formed after the module and the mechanical parts are clamped around the conductor or cable. **Figure 2.8** shows a basic schematic of a DSSC module. Since the DSSC module weight and size are small, they can be suspended along power lines. The device floats at the potential of the power line; it does not need the insulation of a device that would see phase-to-phase voltage which helps with the weight of the device.

The STT current provides excitation for the dc control power supply transformer. The normally closed switch S_m consists of a mechanical switch and a thyristor pair that both keep the unit in bypass mode until the inverter is powered up. When the line current reaches 100A the module can be turned on by the dc power supply. Divan also mentions, "A simple single-switch pre-regulator is used to control the dc voltage of the control power supply. As the switch S_M is turned off, the inverter dc bus is charged up and inverter operation is initiated." [1] The inverter would be now ready to inject a quadrature voltage into the power line.

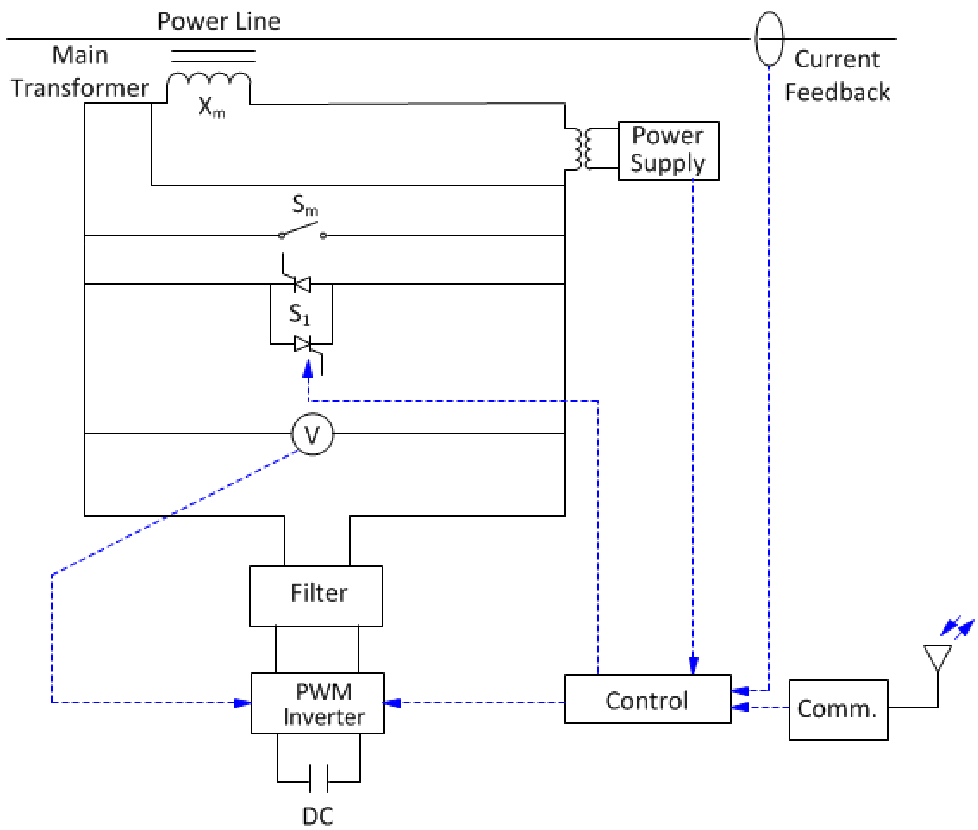

Figure 2.8 - SSSC Circuit [1]

2.5 Power Flow with Thyristor-Controlled Series Capacitor

Most of the information about power flow and the SSSC applies to the TCSC device. The power equations apply as well as the normalized expressions. The Impedance of TCSC equation is shown in equation (2.18). It is the steady-state impedance of a parallel LC circuit. By inspection, it is a parallel circuit with a capacitive reactance in parallel with a variable inductive reactance adjusted by α. The symbol α is the firing angle and will be adjusted through power electronics. The inductive reactance, X_L (α), of the TCSC circuit equation (2.19) is affected by the four modes of basic circuit operation. **Figure 2.10** will help the reader in understanding the modes. To further explain this, Glanzmann interpreted operation of the TCSC from Song's book as, "

- Bypass mode (α = 0°): Thyristor valve is triggered continuously. The basic circuit behaves like a parallel connection of the series capacitor and the inductor.
- Inductive boost mode ($0° < \alpha < \alpha_{res}$): For α below the resonance angle the equivalent reactance, X_{eq}, is positive corresponding to an inductance.
- Capacitive boost mode ($\alpha_{res} < \alpha < 90°$): If the firing angle is larger than the resonance angle, the equivalent reactance is negative resulting in capacitive behavior.
- Blocking mode (α = 90°): Thyristor is not triggered and therefore kept in non-conducting state. Simply the fixed capacitor contributes to the reactance. " [3] [12]

$$X_{TCSC}(\alpha) = \frac{X_C(\alpha)X_L}{X_L(\alpha) + X_C} \quad (2.18)$$

$$X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha - \sin\alpha},\ X_L \leq X_L(\alpha) \leq \infty \quad (2.19)$$

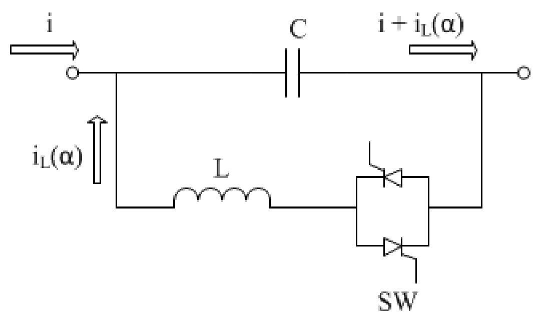

Figure 2.9 - Thyristor-Controlled Series Capacitor [7]

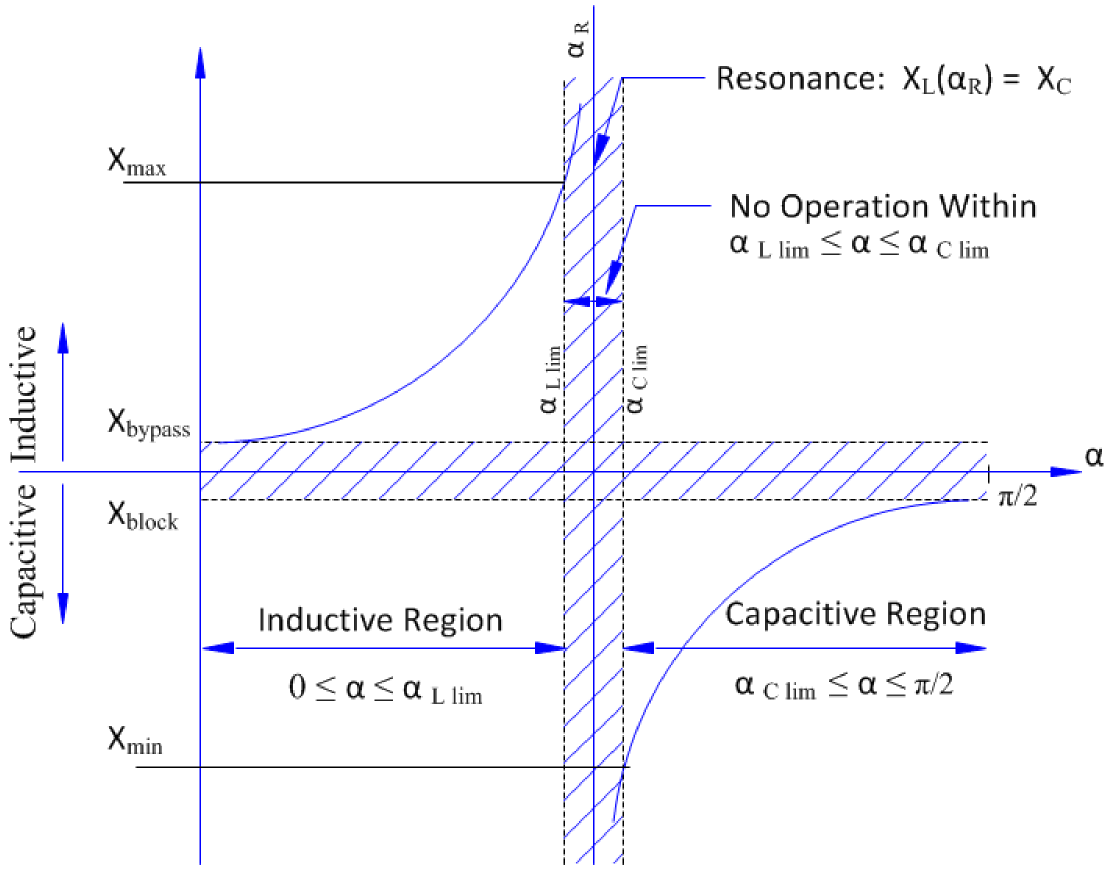

Figure 2.10 - Impedance versus Delay Angle Characteristic of TCSC [7]

2.6 Modeling the Series Devices

To simulate an actual SSSC in a power network, the network would have to be modeled differently. A SSSC device cannot be modeled as simple impedance in series with the transmission line with the utility power programs used in this paper. The branch or line will be separated from one of the buses and attached to a new, separate bus to model SSSC compensation. The branch impedance would not be modified for the system being compensated. Voltages would have to be modified to simulate a SSSC in the system. **Figure 2.11** shows what SSSC compensation would look like in a 3-Bus network. The 3-Bus network with this compensation looks a lot different than the 3-Bus, Base Case networks of **Figure 3.10** or **Figure 3.11** which will be explained later.

Modifying the network this way creates issues. Looking at **Figure 3.10**, the reader can see only a small difference at Bus 3 in this figure compared to the δ at Bus 3 of the SSSC compensated network. If many SSSC units are added to the transmission line, this opens up the issue of how would the variables at the new inserted buses be handled? There would be discontinuities in power flow to model the SSSC devices. This is especially the case since many would be used in series for Distributed FACTS. Power flow in the transmission line comes down to effective impedance and the SSSC mimics inserting a reactance in the transmission line. The SSSC impact will be handled by simply modifying the transmission line impedance for X_{eff}.

TCSC compensation does not need to be modeled with special symbols in the network. Only the branch impedance has to be modified to show the impact of the TCSC compensation on that branch. If TCSC compensation was being used in the 3-Bus networks of **Figure 3.10** or **Figure 3.11** the network models would look the way they are now. A series capacitive reactance could possibly be shown, but it is not necessary. Additional calculations have to be performed to give the true impact of any series impedance. They are the calculations to solve for the transmission line ABCD parameters.

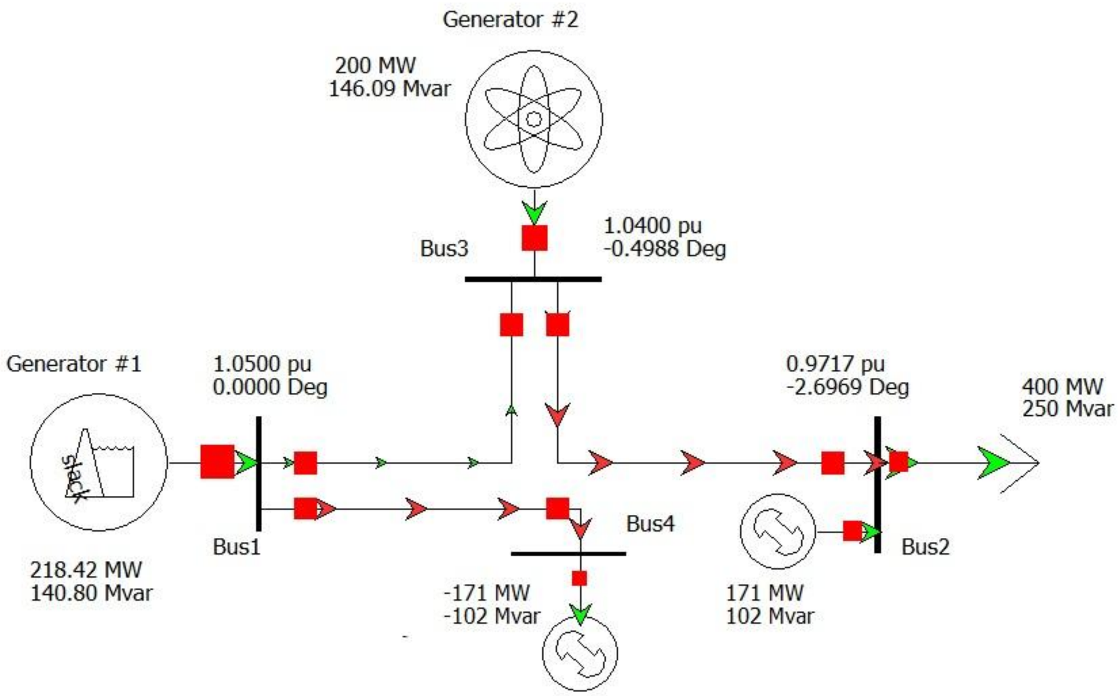

Figure 2.11 - SSSC Compensated 3-Bus Network with PowerWorld Simulator

2.7 Transmission Line Impedance Calculations

Transmission line parameters are needed to help calculate the effective impedance, X_{eff}, of the transmission lines. The parameters are referred to as the ABCD parameters (also known as the generalized constants). The parameters will be used in conjunction with the compensation to calculate the X_{eff} of the transmission lines. There are three general classifications of transmission line lengths:

- Short-length transmission lines that are less than 50 miles long
- Medium–length transmission lines that are between 50 and 150 miles long
- Long-length transmission lines that are greater than 150 miles long

Different calculations follow the different transmission line lengths with long-length calculations being the most accurate. Short-length transmission lines are modeled as simple series AC circuits with series line impedance. Medium-length transmission lines introduce the shunt admittance of the line. Medium-lengths transmission lines are modeled as a nominal π. The total shunt admittance of the line is divided into two equal parts and placed at the sending and receiving ends of the line. [5] The long-length transmission line calculations take into consideration the uniform nature of the impedance and admittance along the transmission line. They are modeled without bulk values as in the previous models. The long-length calculation can be used for any length of transmission line, but they are mainly used for the long-length calculations.

For purpose of this paper, the calculations for medium-length lines will be used. The medium-length transmission line calculations are acceptable for this paper, the transmission line lengths are assumed to be medium- length lines.

2.71 Medium Length Transmission Line Equations

Equations (2.20) through (2.22) are the core equations for the parameters of medium-length lines known as the ABCD parameters. The parameters A and D are dimensionless and will be equal will be equal to each other if the line is the same when viewed from both directions. [5] The units for the parameter B is ohms and the units for parameter C is siemens or mhos. When ABCD parameters are solved, they form a 2x2 matrix that is instrumental in solving for the effective line impedance. The matrix they form is similar to the first one found in equation (2.36).

$$\mathrm{A} = \mathrm{D} = \frac{\mathrm{ZY}}{2} + 1 \quad (2.20)$$

$$\mathrm{B} = \mathrm{Z} \quad (2.21)$$

$$\mathrm{C} = \mathrm{Y} * \left(1 + \frac{\mathrm{ZY}}{4}\right) \quad (2.22)$$

To solve for the impedance, Z, and susceptance, Y, of these parameters, two groups of calculations have to take place first. One group is used in solving the inductance of a transmission line and the second group is used in solving the capacitance of a transmission line. These two groups of calculations follow this paragraph.

2.72 Inductance Calculations

Equations (2.23) through (2.25) cover several conductor bundle types of the Equivalent Geometric Mean Radius, GMR_{eq}, of a transmission line. They are three standard bundle types of two, three and four conductor bundles in that order. The equation GMR_{eq} contains D_s being the conductor's self GMR which can be found listed under the parameters of the transmission cable in Table B1.1 of Appendix B. The GMR_{eq} equation contains d which is the distance between conductors in the bundle. **Figure 2.12** shows examples of standard power cable bundle arrangments. They are two, three and four conductor arrangements from left to right.

Equation (2.26) is the Geometric Mean Distance between transmission conductor bundles. The GMD equation contains d_{ph} which is the distance between phases of a transmission line. Equation (2.27) or L is simply the inductance of the transmission line. One must ensure the units of GMReq and GMD are the same before solving for L. One must take note that N for GMReq and GMD is simply the number of conductors in the bundle for a transmission line phase. The equation (2.28) provides the inductive reactance of the transmission line with f or frequency being 60 Hz here in the United States.

$$\mathrm{GMR}_{eq}^{2b} = \sqrt[N^2]{(D_s * d)^2} = \sqrt[2]{D_s * d} \tag{2.23}$$

$$\mathrm{GMR}_{eq}^{3b} = \sqrt[N^3]{(D_s * d * d)^3} = \sqrt[3]{D_s * d^2} \tag{2.24}$$

$$\mathrm{GMR}_{eq}^{4b} = \sqrt[N^4]{(D_s * d * d * \sqrt{2} * d)^4} = 1.09\sqrt[4]{D_s * d^3} \tag{2.25}$$

$$\mathrm{GMD} = \sqrt[N]{d_{ph} * d_{ph} * 2 * d_{ph}} \tag{2.26}$$

$$L = 2 * 10^{-7} * \log\left(\frac{\mathrm{GMD}}{\mathrm{GMR}_{eq}}\right) \tag{2.27}$$

$$X_L = 2\pi * f * L * 1000 \tag{2.28}$$

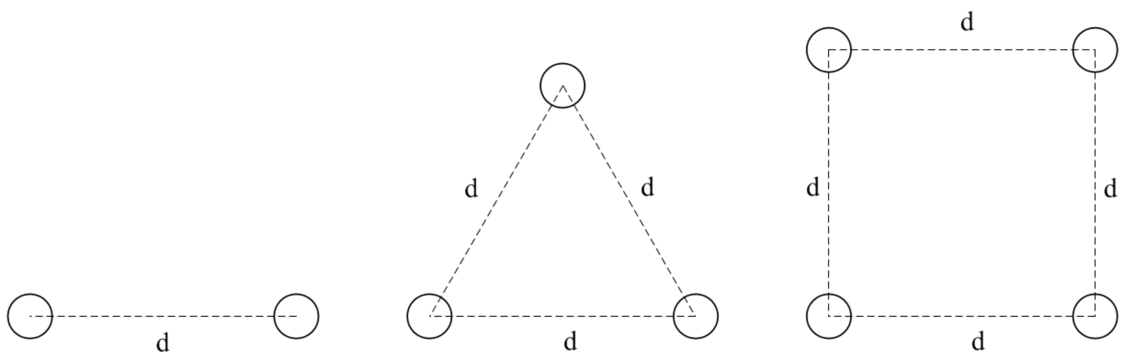

Figure 2.12: Standard Power Cable Bundle Arrangements

2.73 Capacitance Calculations

Equations (2.29) through (2.31) cover several conductor bundle types of the Equivalent Geometric Mean Radius for capacitance, GMRc_{eq}, of a transmission line. They are three standard bundle types of two, three and four conductor bundles in that order. The equation GMRc_{eq} contains r being the conductor's radius found listed under the parameters of the transmission cable in Table B1.1 of Appendix B. The GMRc_{eq} equation also contains d which is the distance between conductors in the bundle. **Figure 2.12** shows the examples of the standard bundle types.

The GMD from the previous section is used when calculating the Capacitance to neutral in F/m for C_n in Equation (2.32). The capacitance of the transmission line is product of length of transmission line, l_{run}, and of result of Equation (2.33). Equation (2.34) would provide the susceptance of the line in siemens, S. It is the variable Y to be used in the ABCD parameters. Equation (2.35) provides S/mile for the transmission line. Equation (2.36) is the capacitive reactance of the line and it is simply the reciprocal of the line susceptance.

$$GMRc_{eq}^{2b} = \sqrt[N^2]{(r * d)^2} = \sqrt[N]{r * d} \quad (2.29)$$

$$GMR_{eq}^{3b} = \sqrt[N^3]{(r * d * d)^3} = \sqrt[N]{r * d^2} \quad (2.30)$$

$$GMR_{eq}^{4b} = \sqrt[N^4]{(r * d * d * \sqrt{2} * d)^4} = 1.09\sqrt[N]{r * d^3} \quad ` \quad (2.31)$$

$$C_n = \frac{2\pi*(8.854*10^{-12})}{\log\left(\frac{GMD}{GMRc_{eq}}\right)} \quad (2.32)$$

$$C_{line} = C_n * l_{run} \quad (2.33)$$

$$Y = 2\pi * f * C_{line} \quad (2.34)$$

$$Y_{mi} = \frac{Y}{l_{run}} \quad (2.35)$$

$$X_c = \left(\frac{1}{Y}\right) \quad (2.36)$$

2.8 Effective Line Reactance

Figure 2.13 shows a simple transmission line with a single FACTS device. Inserting a series device on the line changes the ABCD parameters. Equation (2.37) is for Matrix Multiplication with Single FACTS Device. The matrix output contains the transmission line X_{eff} in the B value of the output matrix.

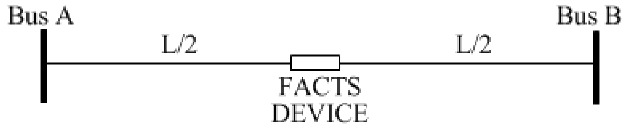

Figure 2.13 -Transmission Line with Single FACTS Device

$$X_{eff} = \begin{bmatrix} A_{1/2} & B_{1/2} \\ C_{1/2} & D_{1/2} \end{bmatrix} * \begin{bmatrix} 1 & X_q \\ 0 & 1 \end{bmatrix} * \begin{bmatrix} A_{1/2} & B_{1/2} \\ C_{1/2} & D_{1/2} \end{bmatrix} \quad (2.37)$$

Figure 2.14 shows a simple transmission line with multiple D-FACTS devices. Inserting several series devices on the line will change the ABCD parameters. Equation (2.38) is for Matrix Multiplication with Multiple D-FACTS Device. The matrix output contains the transmission line X_{eff} in the B value of the output matrix.

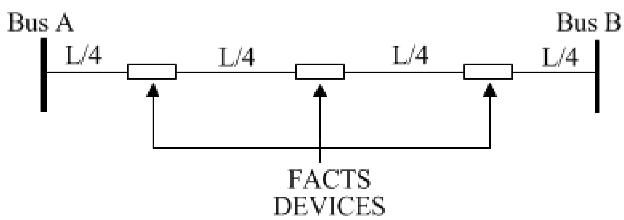

Figure 2.14 - Transmission Line with Multiple D-FACTS Devices

$$X_{eff} = \begin{bmatrix} A_{1/4} & B_{1/4} \\ C_{1/4} & D_{1/4} \end{bmatrix} * \begin{bmatrix} 1 & X_q \\ 0 & 1 \end{bmatrix} * \begin{bmatrix} A_{1/4} & B_{1/4} \\ C_{1/4} & D_{1/4} \end{bmatrix} * \begin{bmatrix} 1 & X_q \\ 0 & 1 \end{bmatrix} * \begin{bmatrix} A_{1/4} & B_{1/4} \\ C_{1/4} & D_{1/4} \end{bmatrix} * \begin{bmatrix} 1 & X_q \\ 0 & 1 \end{bmatrix} * \begin{bmatrix} A_{1/4} & B_{1/4} \\ C_{1/4} & D_{1/4} \end{bmatrix} \quad (2.38)$$

System Application

3.1 Justification of Using D-FACTS over FACTS Devices

Figure 3.1 is a series TCSC FACTS device platform located in Imperatriz, Brazil. It is part of the North-South Interconnection of the 500kV network in Imperatriz. The TCSC is rated at 550kV, 1500A, 107 nominal MVAR with a 5% nominal degree of compensation. This would be expensive anywhere for installation and commissioning.

Figure 3.1 -Transmission Line Series ABB TCSC on Platform [16]

As of 2009, the cost is around Rs. 12000/KVA or $234.78 in India for a FACTS installation and commissioning. It would be Rs. 4000/KVA or $78.26 in India for a D-FACTS installation and commissioning. The D-FACTS installation is only a third of the cost. The 107 MVAR, TCSC installation would then cost around $25.12 million dollars in India. If that same TCSC were to be constructed in the United States it most likely would cost more with right-a-way issues or the labor rates in the U.S.

Both FACTS devices and D-FACTS devices can be placed almost anywhere. With FACTS devices such as a TCSC device, once they are installed they will most likely remain. The FACTS devices have a bulk, single point of effect in the system. If there are unforeseen system changes the lone FACTS device might be limited in what it can do in the system. For instance, if there is a parallel pair of unbalanced power lines, the FACTS device will only be able impact one of the lines. Without a big FACTS installation in the other power line, the problem might remain. If one of the lines is at its thermal limit, the more lightly loaded line could be limited.

Distributed FACTS devices can be placed anywhere, anytime. The previous paragraph talks about a parallel pair of power lines with a FACTS device on one of them. D-FACTS devices could be moved onto the other line without the need for breaking the line or the need for a platform. An SSSC module is broken down into two parts that can be clamped around the power line conductors. The magnetic circuit is formed after the module and the mechanical parts are clamped around the cable as shown in **Figure 3.3**. **Figure 2.8** shows a basic schematic of a DSSC module. Since the DSSC module weight and size are small, they can be suspended along power lines as shown **Figure 3.2**.

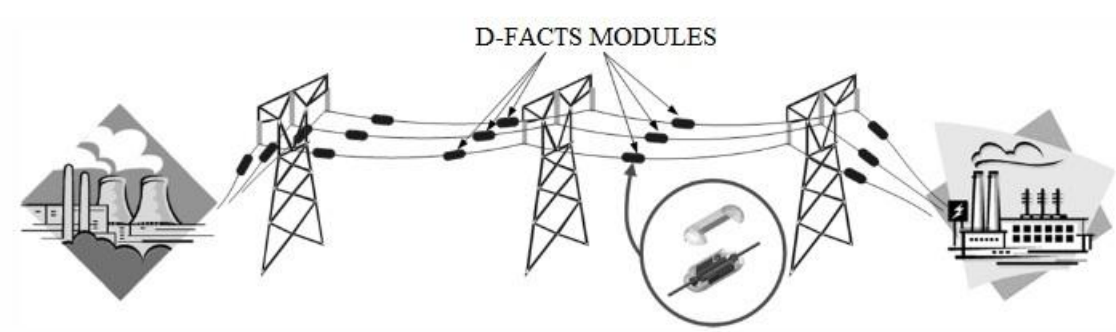

Figure 3.2 – Distributed FACTS on Power Lines [1]

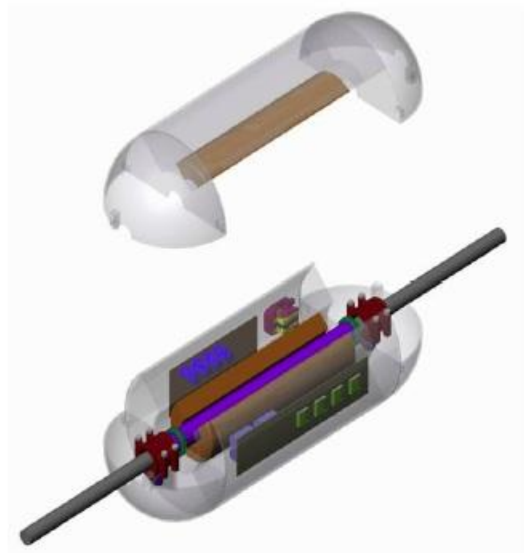

Figure 3.3 – Distributed FACTS Module [1]

Both D-FACTS devices and FACTS devices can provide savings in not having to install new local distributed generation which prevents new pollution sources. A lot of power generation pollutes the atmosphere. The following table illustrates this based on coal pollution in generation. By observation, it is easy to see why new ways to reduce pollution have to be found. If 50 MW were to be saved with D-FACTS, it could possibly prevent approximately 50.3 tons of pollution per hour from entering the atmosphere if the country does not have environmental protection requirements such as air scrubbers.

Table 3.1 – Coal Pollution [9]

Major Pollutants	Emission g/KWh
Carbone dioxide (CO_2)	991.0
Sulphur dioxide (SO_2)	7.6
Nitrogen oxide (NO)	4.8
Suspended Particulate Matter (SPM)	2.3
Total Emission g/KWh	1005.7

Having multiple D-FACTS devices can ensure compensation is still available if one or more devices fail. If a FACTS device fails the system would lose its bulk compensation. D-FACTS devices are superior in this regard. The introduction of D-FACTS is huge in making a transmission network more efficient. They can be placed all over a network for power flow control. A FACTS device has mainly a single point of effect on a transmission line such as with the TCSC Platform shown in **Figure 3.1**. Putting them all over a network would be far more costly making D-FACTS the better choice in this regard. D-FACTS devices such as the one shown in **Figure 3.3** do not need to have a break in the transmission line when it is being installed. A FACTS device will and that make D-FACTS the better choice again. This paragraph sums up the main justification of using D-FACTS over FACTS devices.

3.2 D-FACTS Device Size Consideration Example

A given 138kV transmission line with has an impedance, X_L, of 0.79 Ω/mile with a thermal capacity of 770A at 184MVA. [1] If 2% reduction of line impedance is required for a desired power flow, appropriately sized D-FACTS module would need to be installed. A simple calculation of 2% of 0.79 Ω/mile results in 0.0158 Ω/mile. The result of 0.0158 Ω/mile is inserted into Equation (2-28) and the equation is re-arranged to show inductance is 41.9 μH. This results in a reactive load of 9.367 KVAR and dividing by 770A yields in approximately 12.16V of injected voltage. The unit size falls below the typical 10kVA rating mentioned earlier. The engineer or designer must always keep target size in mind when calculating the desired power change. The utility can then install the units per length as required.

3.3 Example 2-Bus Applications

3.31 First 2-Bus Application Example

Figure 3.4 shows two parallel transmission lines with one line already its 770A thermal limit. In **Table 3.2** Divan illustrates the usage of D-FACTS modules to increase power flow through a pair of transmission lines as in **Figure 3.4**. By inspection, it is easy to see the Transferred Power increased by as much as 70.2 MW. The X_{eff} were matched which provided a greater throughput of power. This could have prevented the need in building new, local distributed generation near a customer or community. This could also prevent the need to add new transmission lines. Both of these options would be very costly.

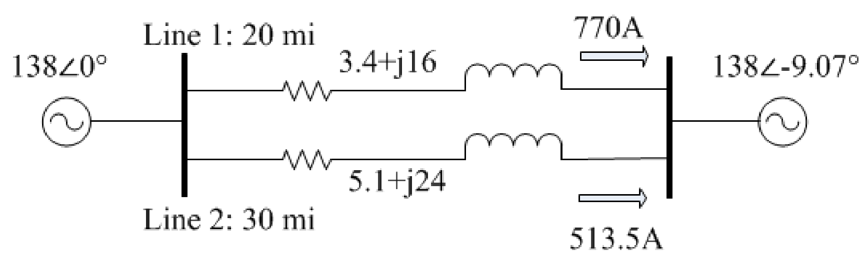

Figure 3.4 – Basic Example with 2-Bus System [1]

Table 3.2 – Increase in Power Transfer [1]

Line Reactance (Ω)	Line Currents (A)	Load Angle (Deg.)	Line Power (MW)	Transferred Power (MW)
X_1=16 X_2=24	I_1=770 I_2=513.5	δ = -9.07°	P_1=176.5 P_2=117.7	294.2
X_1=19.2 X_2=19.2	I_1=770 I_2=756	δ = -10.81°	P_1=171 P_2=169.4	364.4

3.32 Second 2-Bus Application Example

Figure 3.5 is the reference two-bus network in this example. This example is a discussion of simulations performed by Porate. [9] The power available to be transmitted between the buses was 1200 MW. There was 1089.4 MW received from the reference bus to the other with a loss of 110.6 MW, 9.22%, in the system. The lines currents are shown as 1064A and 798A in the system schematic with a power angle of δ = -54.04°.

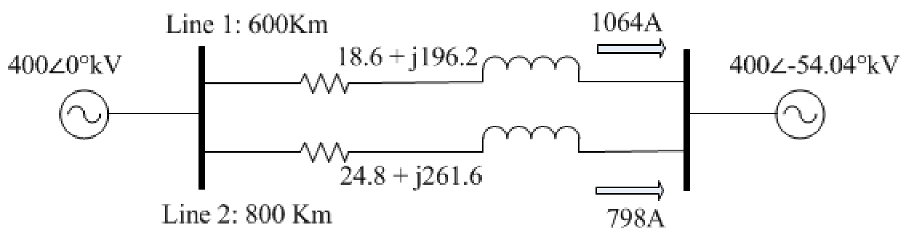

Figure 3.5 – 1200 MW 2-Bus System [9]

Table 3.3 – Line Parameters [9]

Parameters	**Rating**
Length, Line 1	600 km
Length, Line 2	800 km
Sending & Receiving End Voltages V_1=V_2=V	400kV
Line Impedance	0.31+j0.327 Ω /Km
Line Thermal Rating I Maximum	1064A

If the network of **Figure 3.5** had 1275 MW of power available to be transmitted, the top branch would be past its thermal limit of 1064A. The power losses would be 156.44 MW (12.27%). Using simulation software the author diverted approximately 75 MW from the overloaded line to the other using 9% compensation on each line. Taking 9% of 0.327

Ω/Km results in 0.0294 Ω/Km. The top branch at 600 km would be an require an insertion of 17.64 Ω and the bottom branch would require an insertion of 23.52 Ω. By inspection this results in 33.28 KVAR/km and 31.32 V/km for the top branch. For the bottom branch this results in 26.8 KVAR/km and 23.48 V/km for the bottom branch. Both branches would require approximately 3-10KVA compensation units per phase per km if the series SSSC units are available. The two following figures show the system with the two types of effective compensation, passive and active compensation. The system sends over 1144 MW of power with a loss of 131 MW, 10.27%. The new line currents are shown as 1064A and 954.4A in the system schematic with a power angle of δ = -59.28°. The losses went down to 10.27% from 12.27%. **Table 3.4** shows the Compensation Data for this example in a separate table for reader reference.

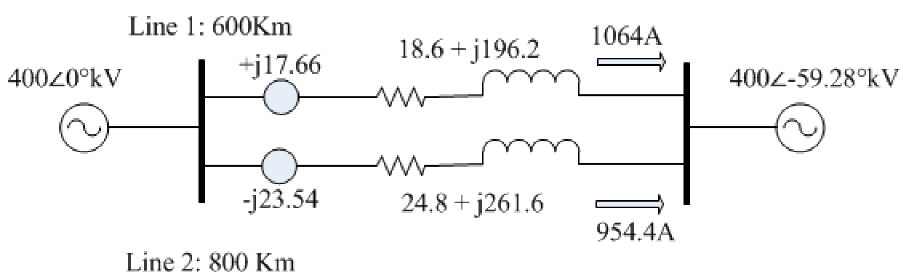

Figure 3.6 – 1275 MW 2-Bus System with Passive Compensation [9]

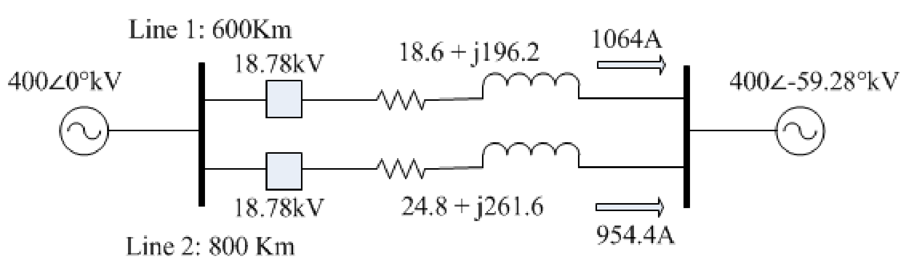

Figure 3.7 – 1275 MW 2-Bus System with Active Compensation [9]

Table 3.4 – Compensation Data 1275 MW 2-Bus System

Parameters	Top Line	Bottom Line
Injected Active / km	0.0313 kV / km	0.0235 kV / km
Injected Passive / km	j0.0294 Ω / km	-j0.0294 Ω / km
Injected Active Bulk	18.78 kV	18.78 kV
Injected Passive Bulk	j17.66 Ω	-j23.54 Ω

Porate saw δ change from -54.04° to -59.28°. According to Porate this was system unstable. The fix was to add 20% compensation in the bottom feeder but not touch the top. A small calculation of 20% of 0.327Ω/Km results in 0.0654Ω/Km. A total compensation of 52.32Ω is required for passive compensation and a total compensation of 41.75kV is required active compensation. Only the bottom branch was affected. This requires 41.8 KVAR per phase per km. This is approximately 4-10KVA units per phase per km. When calculating the new compensation, the engineer or designer must not forget not to use the original current value from the base case of an uncompensated system. **Table 3.5** shows the Compensation Data for this example in a separate table for reader reference.

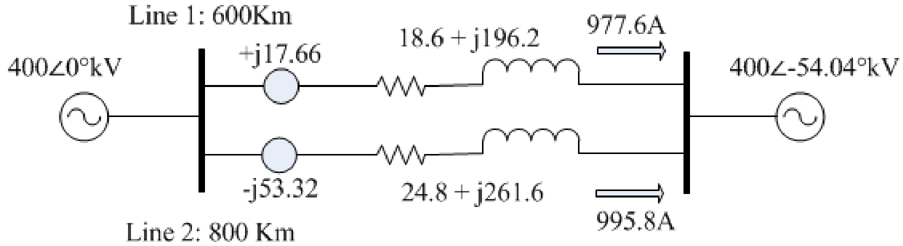

Figure 3.8 – 1275 MW 2-Bus System with Passive Compensation for Instability [9]

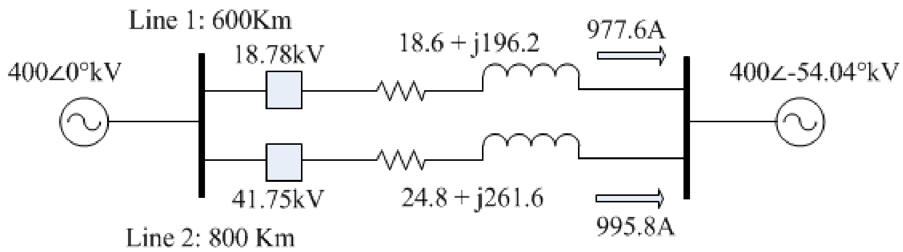

Figure 3.9 - 1275 MW 2-Bus System with Active Compensation for Instability [9]

Table 3.5 – Compensation Data 1275 MW 2-Bus System for Instability

Parameters	Top Line	Bottom Line
Injected Active / km	0.0313 kV / km	0.0522 kV / km
Injected Passive / km	j0.0294 Ω / km	-j0.0294 Ω / km
Injected Active Bulk	18.78 kV	41.75 kV
Injected Passive Bulk	j17.66 Ω	-j52.32 Ω

3.4 Software Base Cases

Two different utility power programs are being used to model the same 3-bus networks. This was performed to demonstrate that the programs operate nearly identically and that the programs are being used correctly. The following two figures both show the same 3-Bus base cases: PowerWorld Simulator and PSS/E. Each of these 3-bus networks is modeled with a swing bus, a voltage-controlled bus and a load bus. **Figures 3.10** and **3.11** show the base cases.

Each network had to maintain a 1.05 p.u. voltage and a delta, δ, angle of 0° on each of their Swing Buses, Bus 1 for each. Each 3-bus network had 400 MW and 250 MVAR of connected load on their Load Buses, Bus 2 for each. Each network had to maintain a fixed 200 MW by Generator #1 and a 1.04 p.u. voltage each on each of their voltage-controlled buses, Bus 3 for each. By inspection one can see the final values were nearly exact. The values were taken out to several significant digits to show the programs operated nearly identically.

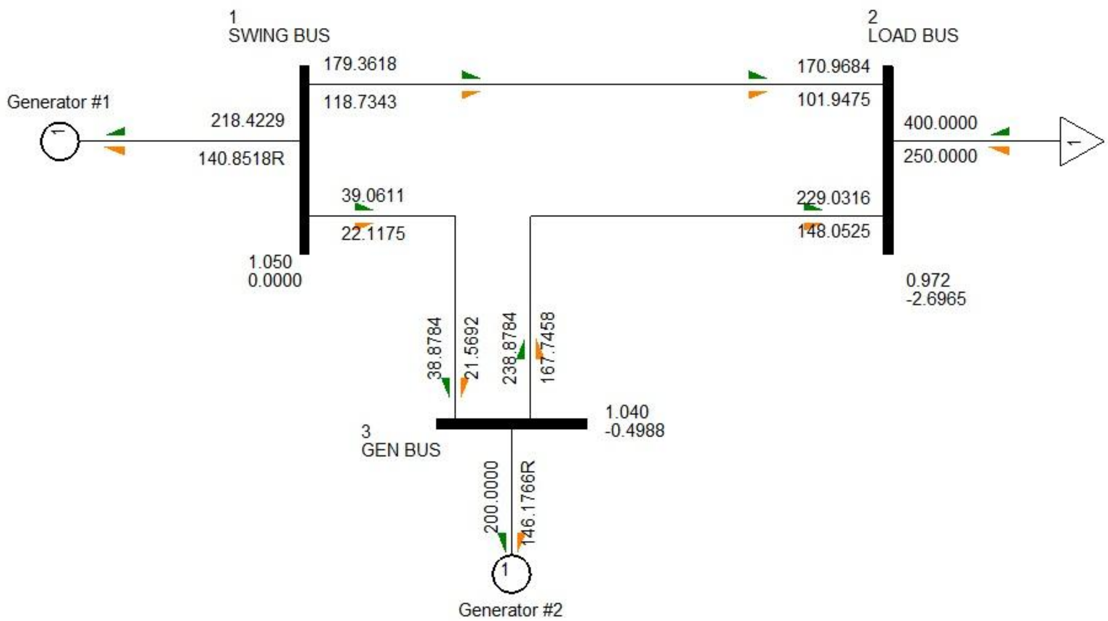

Figure 3.10 - PSS/E 3-Bus Network

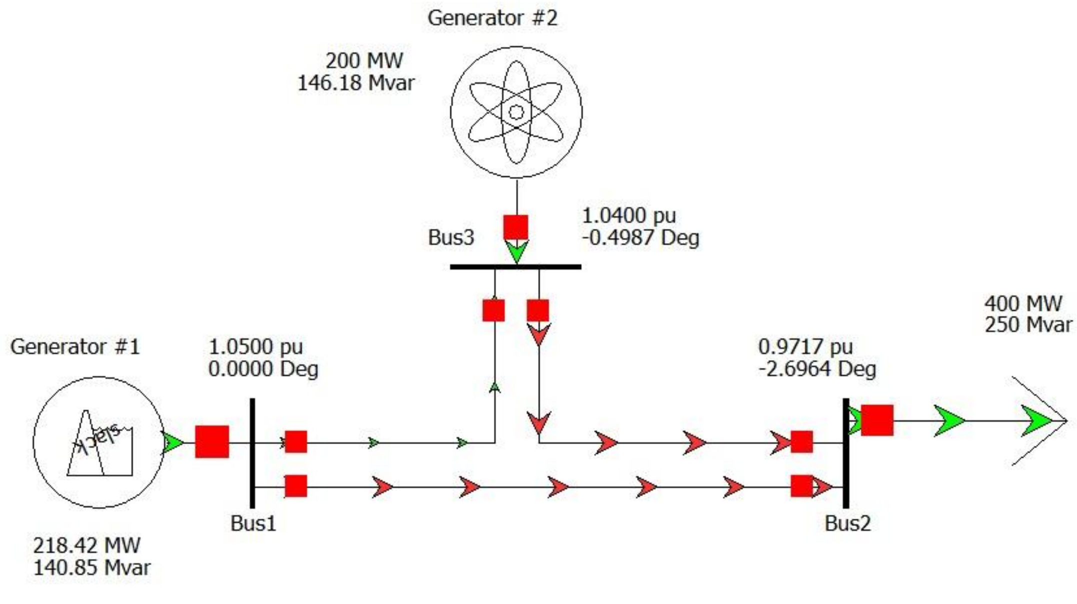

Figure 3.11 - PowerWorld Simulator 3-Bus Network

3.5 IEEE 14-Bus Network Test Systems

The following Figures, **Figure 3.12** and **Figure 3.13**, are based on the IEEE 14-Bus Network. It is use as a reference model for PowerWorld Simulator and Siemens PSS/E. The values for the IEEE 14-Bus System Branch Parameters are found under **Table A1.1** in Appendix A. The values for the IEEE 14-Bus Data are found under **Table A1.2** in Appendix A. The network contains such items as generators, buses, synchronous condensers, bulk loads and transmission line impedances. The IEEE 14-Bus Networks were built with each software program.

The IEEE 14-Bus network will be used to demonstrate a simple application of Distributed Facts in a transmission system. The dashed box on **Figure 3.12** indicates where the focus will be for the PowerWorld Simulation. The simulation will only be run on the PowerWorld Simulation Software.

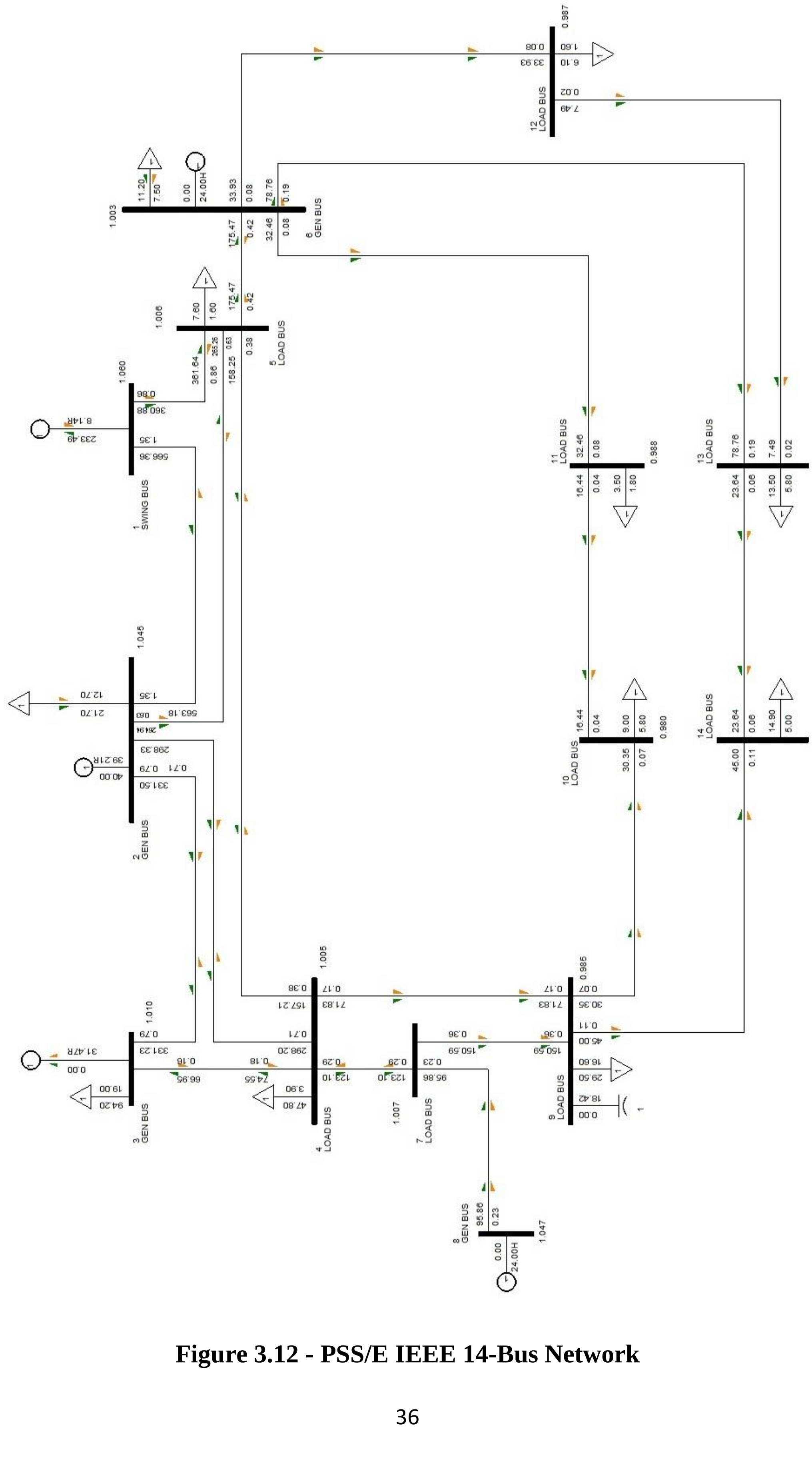

Figure 3.12 - PSS/E IEEE 14-Bus Network

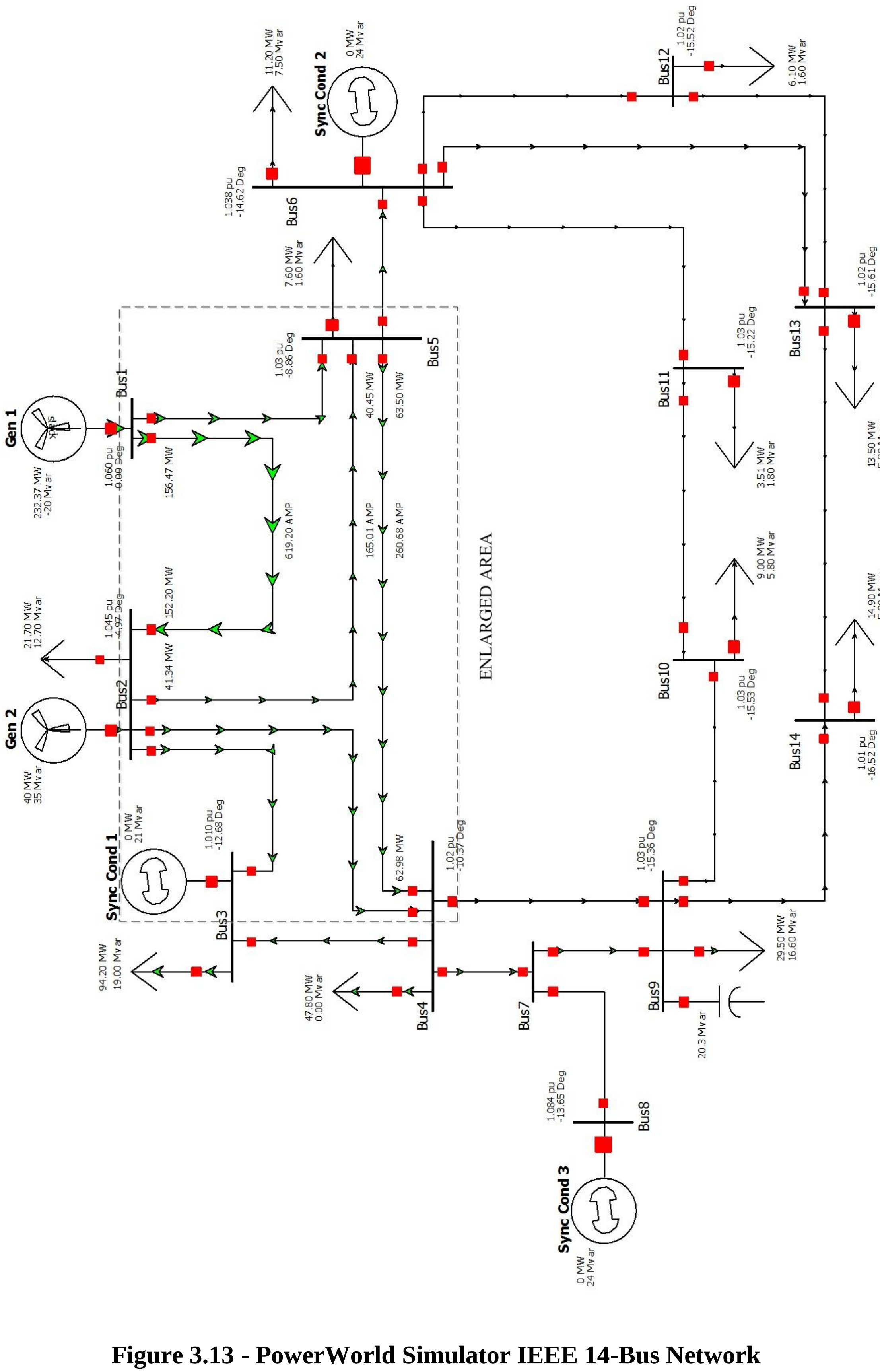

Figure 3.13 - PowerWorld Simulator IEEE 14-Bus Network

3.51 IEEE 14-Bus Network Test System Example

Power flow in a network like this is far from linear. Some iteration or trial and error has to take place to get a desired outcome. **Figure 3.14** will be used for this example. The branches of interest are the three horizontal lines with current in amperes showing. The top transmission line is shown as 619.20A with the bottom line shown as 260.68A. This is from a hypothetical network in Fresno, CA. A system operator looking at his panel noticed that the top branch is close to its thermal limits at 625A. The bottom line is far from hitting its thermal limits since it is of the same material as the top line and it is shorter in length. The operator wants to transfer roughly 10A or more off the top line and add approximately that same amount on the bottom. The operator remotely operates the compensation devices to change power flow in the transmission lines. The operator does not bother with the middle transmission line because it can handle a lot lower ampacity than the other two.

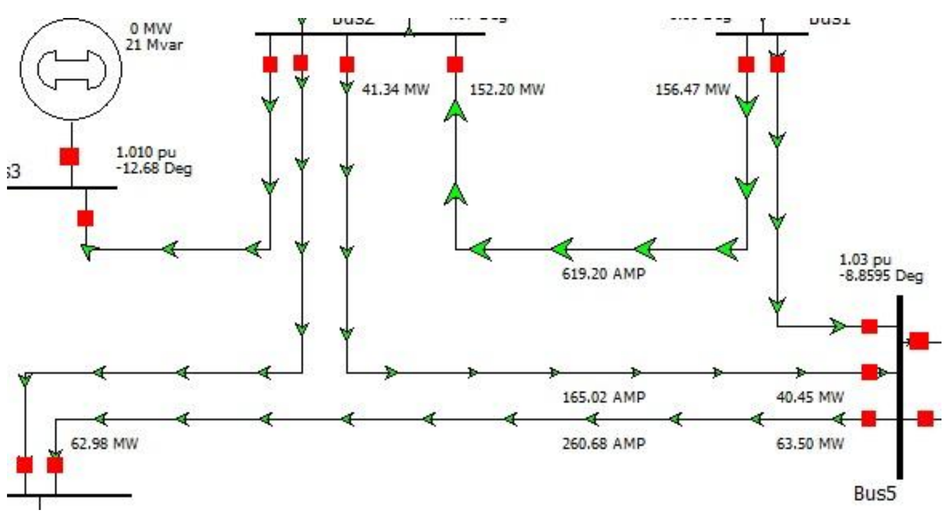

Figure 3.14 - Partial IEEE 14-Bus Network without Compensation

Using equation (2-13) the per-unit, p.u., power flow for the top transmission line results in 1.6219 p.u. Taking 10% off the top line reduces the value by 0.1622 p.u. to 1.4596 p.u. Solving the new X_{eff} p.u. for the top transmission line results in a final value of 0.06575 **Ω** p.u. This would require an injection of 0.006576 **Ω** p.u. given the original X_{eff} for that line was 0.05917 **Ω** p.u. The PowerWorld Simulator has a voltage base value of 138kV and an MVA base value of 100MVA. Multiplying the 0.006576 **Ω** p.u impedance by the base impedance calculated by equation (3-1) would make this a 1.2523 **Ω** change. This would be inductive 480.142 KVAR bulk injection. This would be a 775.4242V active injection or 1.2523 **Ω** inductive, passive injection. This would be distributed over the length of line. **Table 3.6** shows the Compensation Data for this example in a separate table for reader reference.

$$Z_b = \frac{(\mathrm{kV}_{LL})^2}{\mathrm{MVA}_{3\emptyset}} \tag{3.1}$$

Using equation (2-13) the per-unit (p.u.) power flow for the bottom transmission line results in 0.6574 p.u. Adding the p.u. value from the top transmission line and adding it to the bottom increases the bottom p.u. value to 0.8196 p.u. p.u. Solving for the new X_{eff} for the bottom line results in a final value of 0.03384 **Ω** p.u. This would require a negative injection of 0.0082712 **Ω** p.u. Multiplying by the base impedance calculated by equation (3-1) this would be a 1.57517 **Ω** change. This would be a capacitive 107.039 KVAR injection. This would be a 410.4256V active injection or 1.57517 **Ω** capacitive, passive injection. This would be distributed over the length of line. **Table 3.6** shows the Compensation Data for this example in a separate table for reader reference. The values of Injected Active and Passive values per km are shown as not applicable, N/A. This is due to the fact that impedance and other values in PowerWorld are per-unit.

Table 3.6 – Compensation Data PowerWorld Example

Parameters	Top Line	Bottom Line
Injected Active / km	N/A	N/A
Injected Passive / km	N/A	N/A
Injected Active Bulk	775.424 V	410.426 V
Injected Passive Bulk	j1.2523 Ω	-j1.5752 Ω
Reactive Power	480.142 KVAR	107.039 KVAR

Figure 3.15 shows a reduction in the top transmission line of 14.25A and the bottom line increased by 14.63A. The middle line increased by small amount of 0.28A. The top branch is further away from its thermal limits which was the desired outcome.

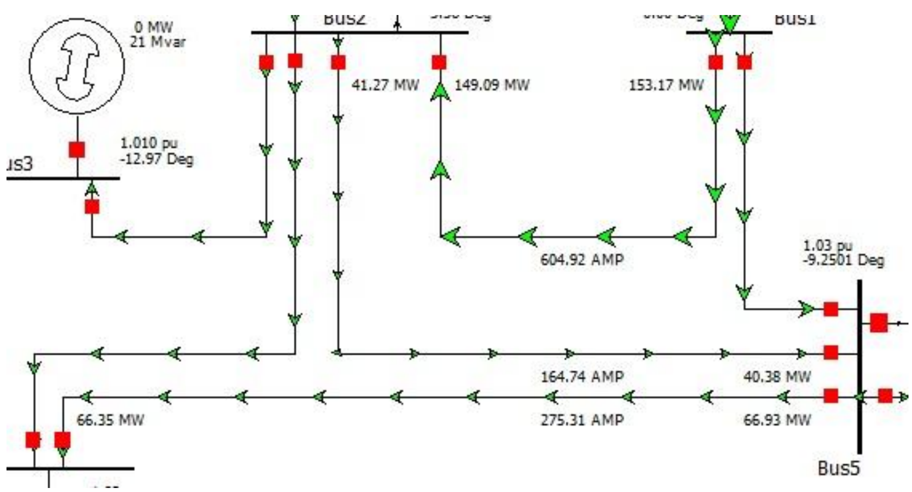

Figure 3.15 Partial IEEE 14-Bus Network with Compensation

Conclusion

The justification of Distributed FACTS devices was explained. These devices have the ability to transfer load from one line to another. This can provide a lot of cost savings in not having to build new distributed generation, new transmission lines or dealing with right-a-way issues. The introduction of new generation will bring pollution unless it is from a renewable source such as solar or wind.

With D-FACTS bring dynamic control of a transmission network. If one transmission line is nearing its thermal limits a system operator can lower load on one line and allow the other lines to absorb the difference in the network.

It was mentioned in the paper that adjusting impedance on a transmission line first requires the transmission line to be evaluated for the ABCD parameters. Once the parameters are known then the insertion of the Distributed FACTS devices can be made. The examples in this paper along with the PowerWorld Simulator example were done to get the effective impedance, X_{eff}, of the transmission line. The engineer or designer still has to solve for the system parameters and utilize them in conjunction with the desired compensation. All this would be performed during the iteration or trial and error it takes to get the desired outcome within the network.

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Appendix A. IEEE 14-Bus System Information

Table A1.1 - IEEE 14-Bus System Branch Parameters

From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Line Charging (p.u.)	Tap Ratio
1	2	0.01938	0.05917	0.05280	1.0
1	5	0.05403	0.22304	0.04920	1.0
2	3	0.04699	0.19797	0.04380	1.0
2	4	0.05811	0.17632	0.03740	1.0
2	5	0.05695	0.17388	0.03400	1.0
3	4	0.06710	0.17103	0.03460	1.0
4	5	0.01335	0.04211	0.01280	1.0
4	7	0.00	0.20912	0.00	0.978
4	9	0.00	0.55618	0.00	0.969
5	6	0.00	0.25202	0.00	0.932
6	11	0.09498	0.19890	0.00	1.0
6	12	0.12291	0.25581	0.00	1.0
6	13	0.06615	0.13027	0.00	1.0
7	8	0.00	0.17615	0.00	1.0
7	9	0.00	0.11001	0.00	1.0
9	10	0.03181	0.08450	0.00	1.0
9	14	0.12711	0.27038	0.00	1.0
10	11	0.08205	0.19207	0.00	1.0
12	13	0.22092	0.19988	0.00	1.0
13	14	0.17093	0.34802	0.00	1.0

Table A1.2 - IEEE 14-Bus Data

Bus No.	P Generated (p.u.)	Q Generated (p.u.)	P Load (p.u.)	Q Load (p.u.)	Bus Type*	Q Generated Max. (p.u.)	Q Generated Min. (p.u.)
1	2.32	0.00	0.00	0.00	2	10.0	-10.0
2	0.4	-0.424	0.2170	0.1270	1	0.5	-0.4
3	0.00	0.00	0.9420	0.1900	2	0.4	0.00
4	0.00	0.00	0.4780	0.00	3	0.00	0.00
5	0.00	0.00	0.0760	0.0160	3	0.00	0.00
6	0.00	0.00	0.1120	0.0750	2	0.24	-0.06
7	0.00	0.00	0.00	0.00	3	0.00	0.00
8	0.00	0.00	0.00	0.00	2	0.24	-0.06
9	0.00	0.00	0.2950	0.1660	3	0.00	0.00
10	0.00	0.00	0.0900	0.0580	3	0.00	0.00
11	0.00	0.00	0.0350	0.0180	3	0.00	0.00
12	0.00	0.00	0.0610	0.0160	3	0.00	0.00
13	0.00	0.00	0.1350	0.0580	3	0.00	0.00
14	0.00	0.00	0.1490	0.0500	3	0.00	0.00

* Bus Type: (1) Swing Bus, (2) Generator Bus (PV Bus) and (3) Load Bus (PQ Bus)

Appendix B. Conductor Table

Table B1.1 – Electrical Characters of Bare Aluminum Conductors Steel-Reinforced (ACSR) Conductors [5]

TABLE A.3

Electrical characteristics of bare aluminum conductors steel-reinforced (ACSR)* Resistance Ac, 60 Hz spacing, 60 Hz

Code word	Aluminum area, cmil	Stranding Al/St	Layers of aluminum	Outside diameter, in	Resistance: Dc, 20°C, Ω/1,000ft	Resistance: AC, 60 Hz 20°C, Ω/mi	Resistance: AC, 60 Hz 50°C, Ω/mi	GMR Ds ft	Reactance per conductor 1-ft spacing, 60 Hz: Inductive Xa, Ω/mi	Reactance per conductor 1-ft spacing, 60 Hz: Capacitive X'a, MΩ.mi,
Waxwing	266,800	18/1	2	0.609	0.0646	0.3488	0.3831	0.0198	0.476	0.1090
Partridge	266,800	26/7	2	0.642	0.0640	0.3452	0.3792	0.0217	0.465	0.1074
Ostrich	300,000	26/7	2	0.680	0.0569	0.3070	0.3372	0.0229	0.458	0.1057
Merlin	336,400	18/1	2	0.684	0.0512	0.2767	0.3037	0.0222	0.462	0.1055
Linnet	336,400	26/7	2	0.721	0.0507	0.2737	0.3006	0.0243	0.451	0.1040
Oriole	336,400	30/7	2	0.741	0.0504	0.2719	0.2987	0.0255	0.445	0.1032
Chickadee	397,500	18/1	2	0.743	0.0433	0.2342	0.2572	0.0241	0.452	0.1031
Ibis	397,500	26/7	2	0.783	0.0430	0.2323	0.2551	0.0264	0.441	0.1015
Pelican	477,000	18/1	2	0.814	0.0361	0.1957	0.2148	0.0264	0.441	0.1004
Flicker	477,000	24/7	2	0.846	0.0359	0.1943	0.2134	0.0284	0.432	0.0992
Hawk	477,000	26/7	2	0.858	0.0357	0.1931	0.2120	0.0289	0.430	0.0988
Hen	477,000	30/7	2	0.883	0.0355	0.1919	0.2107	0.0304	0.424	0.0980
Osprey	556,500	18/1	2	0.879	0.0309	0.1679	0.1843	0.0284	0.432	0.0981
Parakeet	556,500	24/7	2	0.914	0.0308	0.1669	0.1832	0.0306	0.423	0.0969
Dove	556,500	26/7	2	0.927	0.0307	0.1663	0.1826	0.0314	0.420	0.0965
Rook	636,000	24/7	2	0.977	0.0269	0.1461	0.1603	0.0327	0.415	0.0950
Grosbeak	636,000	26/7	2	0.990	0.0268	0.1454	0.1596	0.0335	0.412	0.0946
Drake	795,000	26/7	2	1.108	0.0215	0.1172	0.1284	0.0373	0.399	0.0912
Tern	795,000	45/7	3	1.063	0.0217	0.1188	0.1302	0.0352	0.406	0.0925
Rail	954,000	45/7	3	1.165	0.0181	0.0997	0.1092	0.0386	0.395	0.0897
Cardinal	954,000	54/7	3	1.196	0.0180	0.0988	0.1082	0.0402	0.390	0.0800
Ortolan	1,033,500	45/7	3	1.213	0.0167	0.0924	0.1011	0.0402	0.390	0.0885
Bluejay	1,113,000	45/7	3	1.259	0.0155	0.0861	0.0941	0.0415	0.386	0.0874
Finch	1,113,000	54/19	3	1.293	0.0155	0.0856	0.0937	0.0436	0.380	0.0866
Bittern	1,272,000	45/7	3	1.345	0.0136	0.0762	0.0832	0.0444	0.378	0.0855
Pheasant	1,272,000	54/19	3	1.382	0.0135	0.0751	0.0821	0.0466	0.372	0.0847
Bobolink	1,431,000	45/7	3	1.427	0.0121	0.0684	0.0746	0.0470	0.371	0.0837
Plover	1,431,000	54/19	3	1.465	0.0120	0.0673	0.0735	0.0494	0.365	0.0829
Lapwing	1,590,000	45/7	3	1.502	0.0109	0.0623	0.0678	0.0498	0.364	0.0822
Falcon	1,590,000	54/19	3	1.545	0.0108	0.0612	0.0667	0.0523	0.358	0.0814
Bluebird	2,156,000	84/19	4	1.762	0.0080	0.0476	0.0515	0.0586	0.344	0.0776

* Most used multilayer sizes.

** Data, by permission, from Aluminum Association, Aluminum Electrical Conductor Handbook, 2nd ed., Washington, D.C., 1982.

Appendix C. Software Primers

PowerWorld Simulator Primer

The PowerWorld Demo Software can be downloaded at the following link: http://www.powerworld.com/downloads/demosoftware.asp. There is a pop-up window which asks the user to input some information such as a First Name, Last Name, Email Address and Company Name. Once this information is submitted, the student will get an Email with the path to download the program. This version of the software is limited to 12 buses.

The following link is from the 5th Edition Power System Analysis and Design Textbook by J. Duncan Glover, Mulukutla S. Sarma and Thomas J. Overbye: http://www.powerworld.com/gloversarma.asp. This textbook is used in the ECE610 course taught at California State University, Northridge. There is a pop-up window which asks the user to input some information such as a First Name, Last Name, Email Address and Company Name. Once this information is submitted, the student will get an Email with a link to download the program. This link leads to the simulator and files that would be needed for the student to do the homework in the course when those problems require PowerWorld Simulator. This simulator is also capable of running up to 40 buses.

Several User Guides are also found on the PowerWorld Website. They are for current and older student demo versions of the software. The PowerWorld User Guides can be found at the following link: http://www.powerworld.com/downloads/general.asp. The User Guides will help the student construct power networks. The student can also use the internet to find other sources of information such as walkthroughs and examples by other universities and students.

Siemens Power System Simulator for Engineering (PSS/E) Primer

The PSS/E University Demo Software can be downloaded at the following link: https://www.pti-us.com/pti/software/psse/psse_university_request.cfm. There is a form that is required to be filled out which asks the user to input some information such as a First Name, Last Name, Email Address and Company Name. It requires more information than that is required for a PowerWorld Simulator download. Once this information is submitted, the student will get an Email with the path to download the program. This version of the software is limited to 50 buses.

The Siemens PSS/E software has a very powerful built-in Help feature. Under the link for Help, there is a link for Help Topics. The student simply has to simply navigate for what he/she wants within Help Topics. It will provide the student with many documents that will be useful in constructing power networks.