Analyzing Techniques for Increasing Power Transfer in the
Electric Grid

by

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ABSTRACT

The worldwide demand for electric energy is slated to increase by 80% between the years 1990 and 2040. In order to satisfy this increase in load, many new generators and transmission lines are planned. Implementations of various plans that can augment existing infrastructure have been hindered due to environmental constraints, public opposition and difficulties in obtaining right-of-way. As a result, stress on the present electrical infrastructure has increased, resulting in congestion within the system. The aim of this research is to analyze three techniques that could improve the power transfer capability of the present electric grid. These include line compaction, use of high temperature low sag conductors and high phase order systems. The above methods were selected as they could be readily employed without the need for additional right-of-way.

Results from the line compaction tests indicate that line compaction up to 30% is possible and this increases the power transfer capability up to 53%. Additional advantages of employing line compaction are the reduction in electric and magnetic fields, increase in system stability and better voltage regulation.

High temperature low sag conductors that were applied on thermally limited lines were seen to increase the power transfer capability. However, a disadvantage of this technique was that the second most congested line, limits the power transfer capability of the system.

High phase (six phase) order system was noted to have several advantages over three phase system such as lower voltage requirement to transfer equal amount of power and lower electric and magnetic field across the right of way.

An IEEE 9 and 118 bus test system were used to evaluate the above mentioned techniques.

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NOMENCLATURE

<i>ACAR</i>	Aluminum Conductor Alloy Reinforced
<i>ACCC</i>	Aluminum Conductor Composite Core
<i>ACCR</i>	Aluminum Conductor Composite Reinforced
<i>ACGIH</i>	American Conference of Governmental Industrial Hygienists
<i>ACSR</i>	Aluminum Conductor Steel Reinforced
<i>ACSS</i>	Aluminum Conductor Steel Supported
<i>B</i>	Magnetic field density
<i>BIL</i>	Basic insulation impulse level
<i>BSL</i>	Basic switching insulation level
<i>C</i>	Capacitance matrix or capacitance
<i>CCT</i>	Critical clearing time
<i>D</i>	Distance of the conductor
<i>E</i>	Electric field vector
<i>ERCOT</i>	Electric Reliability Council of Texas
<i>f</i>	Frequency
<i>GMR</i>	Geometric Mean Radius
<i>h</i>	Depth of conductor
<i>H</i>	Magnetic field intensity
<i>HTLS</i>	High Temperature Low Sag
<i>ICNIRP</i>	International Commission on Non-ionizing Radiation Protection

I_{con}	Current through the conductor
L	Inductance matrix or inductance
$NERC$	North American Electric Reliability Corporation
$NESC$	National Electrical Safety Code
p	Potential coefficient matrix
P_{sil}	Surge impedance loading
Q	Charge on conductor or charge matrix
Q_c	Charge matrix
r	Resistance matrix
RPS	Renewable Portfolio Standards
V_{ll}	Line-to-line voltage
V_{ln}	Voltage matrix
$WECC$	Western Electricity Coordinating Council
X	Reactance matrix
X_m	Mutual reactance
X_s	Self reactance
Z	Impedance matrix
Z_s	Surge impedance
δ	Power angle
μ_o	Permeability of free space
ρ	Soil resistivity
ω	Angular frequency

Φ	Flux linkage
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Chapter 1. Introduction

1.1 Overview of electric power system

The electric power grid is divided into three major sections namely, generation, transmission and distribution as shown in Figure 1.1 [1]. Generating stations generate electric energy using conventional fuels like coal, nuclear, oil and natural gas or non-conventional fuels like wind, solar and biogas. The generated voltage is in the range of 11 kV - 28 kV.

Figure 1.1 Parts of electric power system [1]

Transmission systems transfer electric energy in bulk from generating stations to the load centers. Higher transmission voltage levels enable more power transfer over long distances. Presently, 765 kV is the highest transmission system voltage in the United States, while countries like China and India are using 1000 kV and 1200 kV systems [2][3]. A major portion of transmission system in the United States is operated on alternating current (A.C) while the rest is on direct current (D.C). The distribution systems are the load centers where higher voltages are stepped down to the required lower voltages (480 V, 11 kV, 33 kV and 69 kV) for

utilization. The load centers primarily consist of residential, commercial and industrial customers.

1.2 Developments in power industry

The electric grid was initially operated as a vertically integrated system, where in generation, transmission and distribution systems were owned by the same utility. Later, the utilities decided to jointly own power plants and interconnect neighboring grids to facilitate the power sales and increase reliability of the system. These developments led to the formation of an electric grid with three major interconnections in the United States [1][4]. The three interconnections are Western, Eastern and Electric Reliability Council of Texas (ERCOT) interconnection as shown in Figure 1.2. Since 1980s, the industry has been going through a process of deregulation and Independent System Operators were established at few regions. In order to maintain safe and reliable operation of the electric grid, the North American Electric Reliability Corporation (NERC) has established eight regions as shown in Figure 1.2 [4]. The Western interconnection region is operated by Western Electricity Coordinating Council (WECC); the Eastern interconnection regions are operated by six regions namely Midwest Reliability Organization (MRO), Northeast Power Coordinating Council (NPCC), Reliability First Corporation (RFC), Southwest Power Pool (SPP), SERC Reliability Corporation (SERC) and Florida Reliability Coordinating Council (FRCC) while the ERCOT interconnection region is operated by Texas Regional Entity [4].

Figure 1.2 NERC reliability regions [4]

In recent years, the industry has faced many problems such as aging infrastructure, lack of investment in maintenance, higher legal and environmental requirements, increased cost of right-of-way and need for better grid security. Moreover, the governmental agencies have established renewable portfolio standards (RPS) under which the utilities are required to generate a fixed portion of electricity using renewable resources [5][6]. It is therefore paramount to have an adequate transmission system. The effects of present trends on each division of power industry are detailed as follows.

Generation

In a vertically integrated system, long term planning was coordinated by a single utility to maintain generation and transmission adequacy with increase in load. Due to deregulation, new generation was permitted to enter the market with free access to transmission system to provide energy at any part of the grid. As a result, new market participants have established generating stations based on load

growth, return on investment and available resources rather than grid requirements and security. Therefore, transmission company planners spend most of their time in altering and accommodating the new generating stations in the electric grid, resulting in lack of coordinated long term planning required to secure future energy requirements [7][8].

Transmission

A transmission system is operated in accordance with the established regulation and maintaining stable network conditions. Since, all generating stations have free access to the transmission grid, maintaining transmission adequacy is one of the many challenges faced by the power industry. With the continuously increasing demand for electric energy, the growth of the transmission system is imperative. Many factors have affected the transmission system growth. All these factors were discussed in detail in Section 1.3.

Distribution

Initially, the distribution system had an effect similar to the transmission system. This trend was alleviated by companies offering quality and reliable energy supply. Other significant changes were the new type of meters for flexible tariff and establishment of distributed generation to satisfy the RPS standards [8].

1.3 Factors affecting transmission growth

Various factors that boost or restrict the transmission growth are listed below:

- *Load growth:* The most important reason for transmission growth is increase in electrical load. The load growth is due to increase in population, urbanization and industrialization. A report by Exxon Mobil has projected the demand for electricity to grow by 80% between the years 1990 – 2040[9]. The demand in the United States has increased by 25% since 1990; and developing countries such as Brazil, China, India and South Africa have increased rapidly in recent years [10]. This increase in demand has been satisfied by increasing the number of generating stations, modifying existing transmission lines and by building new transmission lines [7][9][10].
- *Generator location:* Due to environmental constraints, availability of land, resources and public resistance, generating stations were established at a location distant from the load centers. Moreover, the renewable generation required to satisfy RPS has boosted the requirement for transmission growth.
- *Reliability:* Due to the interconnected nature of power systems, an increase in load is achieved by raising the power flow on inter-tie lines instead of adding local generation and transmission system. This requires higher reliability margin and transmission line capability as the difference between peak load and generating capability decreases. Moreover, the NERC standards require that the electric grid operate reliably despite loss of any one element (i.e. largest generator, transmission line and transformer). This has necessitated additional lines to be connected in the grid.

- **RPS requirement:** Many governmental agencies across the United States and world have established a standard that requires some portion of the electric energy be generated using renewable resources [5][6]. These resources are intermittent in nature and are usually at distant location from the load centers. Hence, in order to incorporate renewable energy and maintain reliable supply, the transmission system needs to be upgraded.
- *Environmental and legal issues:* Environmental effects like land usage, ecological effects, electric and magnetic field effects have to be considered while designing a transmission line. Standards or guidelines were set by various governmental agencies to minimize the effects of electric and magnetic fields arising from transmission lines [11]. Even though all these factors are accounted for during line design and routing, a significant number of planned lines have been delayed, re-routed or cancelled due to legal intervention. These have increased the overall cost of building new lines [4].
- *Investment in infrastructure:* In a vertically integrated system, utilities build the required lines to ensure there is adequate transmission system. After deregulation, many companies jointly own the transmission grid. Since most companies focus mainly on profits and return to shareholders, they prefer an increase in the utilization of current assets rather than investing in newer ones requiring higher investments. Figure 1.3 indicates the capital invested in transmission network as a percentage of the United States electricity revenues [12]. Figure 1.4 indicates that even though the peak demand has increased, the

investment in transmission infrastructure has reduced [12]. This disparity is expected to widen with increase in load.

Figure 1.3 Capital invested as a percentage of electricity revenues [8]

Figure 1.4 United States investment in new electric power transmission [8]

- *Maintenance:* The majority of the expansion of the electric grid occurred between the 1950s and 1970s. With aging infrastructure, the industry was expected to focus on increasing the life span of the grid. However, total trans-

mission maintenance dollars spent in the United States between 1990s and 2002 has reduced by 20% as shown in Figure 1.5 [8].

Figure 1.5 Transmission spending in United States in dollars adjusted to inflation [8]

1.4 Motivation

Low investment in building new transmission lines has gradually congested the existing infrastructure. Studies carried out by WECC, United States - Department of Energy (DOE) and ERCOT indicate various congested lines in the system [13][14]. Congestion limits the power transfer capability of the transmission system and in order to alleviate the congestion and secure the future load demand, several transmission plans have been proposed by various organizations [15][16]. The above fact is supported by a study carried out by the Edison Electric Institute that stated that a high investment is required to mitigate the ongoing problems [17]. Adding new infrastructure is a long-term process with various constraints as discussed in Section 1.3. This research focuses on an alternate

short-term process for improving power transfer capability by analyzing known and recently developed technologies for providing a solution to the problem.

1.5 Techniques studied to increase power transfer

Three techniques were studied that help to increase the power transfer capability of the system. 1) Line compaction 2) High phase (six-phase) order systems and 3) High temperature low sag (HTLS) conductors. These techniques were selected because they use the existing or reduced right of way. A detailed discussion of these techniques is carried out in chapter 4.

1.6 Organization of this thesis

This work is organized into six chapters. Chapters 2 and 3 present basic concepts of line parameters, electric and magnetic field calculation, power transfer capability and limitations of the line.

Chapter 4 describes in detail, the three techniques discussed for increasing power transfer capability of the system. Chapters 5 show the application of various techniques in the IEEE 9 and 118 bus test case systems and benefits achieved.

Chapter 6 presents contributions, conclusions drawn from the test systems and future studies required for the implementation of these techniques.

There are three appendix sections at the end of this thesis. Appendix – A provides different electric and magnetic field standard established by various organizations. Appendix – B provides the dynamic parameters for the generators in

IEEE 9-bus test system. Appendix – C provides the system parameters for IEEE 118 bus test system.

Chapter 2. Line parameters and power transfer limitations

2.1. Introduction

Power transfer capability of a high voltage transmission line depends on various factors like surge impedance loading, thermal and sag limits, stability limits and voltage stability [7]. Surge impedance loading depends on the transmission line parameters i.e. inductance and capacitance. While thermal and sag limits determine the maximum current rating of the conductor and the minimum clearances required from conductor to ground. The rotor angle stability is the ability of an interconnected system to remain in synchronism when subjected to a disturbance. Voltage stability indicates voltage variations at the buses across the system in case of any event. This chapter explains in detail the limitations on the power transfer capability of a transmission lines.

2.2. Surge impedance loading

The power transfer capability of a transmission line could be approximated by knowing the surge impedance. This characteristic of the line is called surge impedance loading (P_{sil}). Equation 2.1 shows the power transfer capability of a three-phase transmission line with a surge impedance of (Z_s) and rated line-to-line voltage (V_{ll}). The surge impedance of a line depends on the inductance and capacitance of the line as shown in Equation 2.2,

$$P_{sil} = \frac{|V_{ll}|^2}{Z_s} \quad (2.1)$$

$$Z_s = \sqrt{\frac{L}{C}} \quad (2.2)$$

This shows that the line parameters are important factor in determining the power transfer capability of a transmission line.

2.2.1 Line parameters calculation

Transmission line parameters depend on various factors such as, conductor selection, soil resistivity, temperature and frequency. The factors like soil resistivity, temperature and frequency could be considered as constant. A program developed in MATLAB using the equations given in this section to obtain the line parameters for three phase single circuit, three phase double circuit and six phase single circuit lines.

Impedance calculation: The impedance calculation for the circuit depends on the conductor location and selection. Figure 2.1 indicates the schematic three phase horizontal configuration with shield wire. In order to replicate the effect of return current caused by earth, the earth return effects are replaced by placing imaginary return conductors below ground level as shown in Figure 2.1.

Figure 2.1 Schematic of three phase horizontal configuration with earth return
The depth of the return conductor is a function of soil resistivity and system frequency is,

$$h = 658.5 \sqrt{\rho/f} \quad (2.3)$$

where,

ρ = soil resistivity (Ω/m)

f = frequency (Hz)

h = depth of conductor (m)

Hence, the flux linkage (ϕ) of conductors could be represented by,

$$\phi_{(x,y)} = I_{con(x)} \frac{\mu_0}{2\pi} \ln \left(\frac{h}{GMR} \right) + I_{con(y)} \frac{\mu_0}{2\pi} \ln \left(\frac{h}{D_{(x,y)}} \right) \quad (2.4)$$

where,

Φ = a matrix of flux linkage between conductors. (Wb)

I_{con} = current through conductor (A)

GMR = Geometrical Mean Radius of conductor in meters.

D = distance of conductors in meters if $x \neq y$; GMR of conductor if

$x = y$

The reactance of a three-phase single circuit line is calculated using

$$X_{(x,y)} = \omega \frac{\phi_{(x,y)}}{I_{con}} \quad (2.5)$$

Where,

X = reactance matrix in (Ω /mile)

ω = angular frequency (rad/sec)

Equation 2.6 and 2.7 give the resistance matrix for the line

$$r_{(x,y)} = r_{ground} ; \text{where } x \neq y \quad (2.6)$$

$$r_{(x,y)} = r_{ground} + r_{cond} ; \text{where } x = y \quad (2.7)$$

r = resistance matrix (Ω /mile)

Combining the Equation 2.5, 2.6 and 2.7 gives the impedance matrix as shown by,

$$Z_{(x,y)} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & \cdots & Z_{1(3+n)} \\ Z_{21} & Z_{22} & Z_{23} & \cdots & Z_{2(3+n)} \\ Z_{31} & Z_{32} & Z_{33} & \cdots & Z_{3(3+n)} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ Z_{(3+n)1} & Z_{(3+n)2} & Z_{(3+n)3} & \cdots & Z_{(3+n)n} \end{bmatrix} \quad (2.8)$$

A Gauss elimination technique was applied to Equation 2.8 to obtain the reactance matrix,

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \Omega/\text{mile}. \quad (2.9)$$

As the transmission line was considered completely transposed, from Equation 2.9

$$Z_{11} = Z_{22} = Z_{33} = Z_s \text{ (Self impedance)}$$

$$Z_{12} = Z_{13} = Z_{21} = Z_{23} = Z_{31} = Z_{32} = Z_m \text{ (Mutual impedance).}$$

A simplistic formula for the positive sequence reactance is given as shown in Equation 2.10.

$$X_1 = X_s - X_m \quad (2.10)$$

Similarly, an impedance calculation could also be repeated for a three phase double circuit as well as six-phase single circuit.

Capacitance calculation: The capacitance of the line depends on the height and distance between the conductors. Capacitance effect is observed between conductors as well as between the conductor and ground. Energization of the line causes charges on the conductor and ground. The effect of ground charges was simulated by placing imaginary conductors as shown in Figure 2.1. This image conductor carries negative charge. The voltage difference generated by the charges between any two conductors is given by,

$$[V_{ln}] = [p] \times [Q_c] \quad (2.11)$$

$$[p_{(x,y)}] = \frac{1}{2\pi\epsilon_0} \times \ln\left(\frac{D_{(x,y)}}{d_{(x,y)}}\right) \quad (2.12)$$

where,

V_{ln} = Voltage vector of size $n \times 1$, where n is the number of conductors.

p = Potential coefficient matrix of size $n \times n$.

d = Distance matrix of charge conductors ($n \times n$)

D = Distance matrix of charge conductors and return conductors ($n \times n$)

Q_c = Charge matrix on conductors of size $n \times 1$

In Equation 2.11 voltages on the conductors and the potential coefficient matrix are known and hence charges on conductor are obtained as

$$[Q_c] = [C] \times [V] \quad (2.13)$$

$$[C] = [p]^{-1} \quad (2.14)$$

Where,

C = Capacitance matrix of size $n \times n$.

A Gauss elimination method was applied to the capacitance matrix to obtain the capacitance for a three-phase single circuit line resulting in a 3×3 matrix,

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \text{ nF/mile} \quad (2.15)$$

Similarly, the capacitance for a three phase double circuit and six-phase single circuit line could be calculated.

Consider an example of a 230 kV horizontal configuration having a phase-to-phase distance of 4.8 m, phase to tower distance of 2.4 m and height of the conductor being 10 m using a Bluebird conductor. The impedance, capacitance and the surge impedance loading for that line were obtained using Equations 2.9, 2.15 and 2.2 respectively is shown in Table 2-1

Table 2-1 Line parameters for the 230 kV example

Resistance	0.0505 (Ω /mile)
Reactance	0.7064 (Ω /mile)
Capacitance	16.23 (nF/mile)
Surge impedance	339.73 Ω
Surge impedance loading	269.7 MW

2.3. Thermal and sag limits

The bare self-supporting overhead conductors of a high voltage transmission line carry high current. As the current carried by the conductor increases, the temperature of the conductor increases resulting in its elongation. This elongation reduces the conductor height from the ground level. A minimum distance between conductor height and ground has to be maintained. National Electrical Safety Code (NESC) standardizes the minimum clearance for safe live line operation and maintenance [18]. The other limitations are the temperature and current carrying capacity of the conductors. The maximum allowable temperature for an ACSR conductor is 75°C (167°F). However, due to thermal heating the actual temperature might go higher than that desired due to extreme weather conditions limiting the current carrying capacity on the line. For example, the current carrying capacity of drake conductor is 900 A at 75°C [19].

2.4. Stability limits

The rotor angle stability is ability of an interconnected power system to get back in synchronism after occurrence of an event. Transmission system is de-

signed such that all generators operate in synchronism in steady as well as in transient state condition. Hence, it is important to consider the stability criteria for obtaining the maximum power transfer capability of a transmission line. It is known that power transfer over a transmission line, connected to a larger system on both ends, is inversely proportional to the reactance and directly proportional to the power angle δ as given by Equation 2.16. Thus, reactance sets a limit on the maximum power transmitted over a high voltage transmission line [7][20],

$$P = \frac{V_1 V_2}{X} \sin \delta \quad (2.16)$$

Under steady state condition, the maximum power transfer occurs with $\delta = 90^\circ$. However, a transmission system operating with many synchronous machines must withstand abrupt changes in generation or load, faults on the system resulting in loss of generation, transmission line or load. These variations cause transient effect on system voltages and angles. Therefore, the observed power angle is much lesser than 90° . Equal area criteria determines the maximum operating condition which reduces the power angle operating in the range of 30° to 45° [7][8][20][21].

2.5. Voltage stability

Voltage stability indicates the ability of power system to attain a stable voltage level after any change in load or loss of an element in the system [22]. The accepted voltage variation at the bus level is $\pm 5\%$ of the rated voltage [7][8]. A transmission line carrying current has a voltage drop due to resistance and reactance of the line. This results in a lower receiving end voltage (V_2) as compared to

sending end voltage (V_I). The percentage difference between the sending end voltage and receiving end voltage is called voltage regulation. This difference is kept low, as power transfer is directly proportional to the product of sending and receiving end voltages as shown in Equation 2.16

2.6. Limits on power transfer capability on line length

Various power transfer capability limitations were discussed in the previous sections. The role of each factor on the power transfer capability is a function of line length. As shown in Figure 2.2 the primary limiting factor for power transfer on a short transmission line is thermal and sag limits while for medium and long transmission lines voltage regulation and stability limit are considered respectively [21].

Figure 2.2 Line loadability as a function of line length [21]

Chapter 3. Electric and magnetic fields

3.1 Introduction

Electric and magnetic field are the factors considered while designing transmission lines. The electric and magnetic field strength determines the corona, radio and audible noise interferences [7][8]. In recent years, a lot of research has been conducted on electric and magnetic field effects on human body [23][24]. As a result many states across the United States and countries across the globe have imposed limitations on electric and magnetic strength at the edge of the right of way [25][26]. For example, the State of New York has a standard established for electric and magnetic field strength of 1.6 kV/m and 200 mG/m respectively at the edge of the right of way [8]. Two organizations (International Commission on Non-Ionizing Radiation Protection (ICNIRP) 1998 and the American Conference of Governmental Industrial Hygienists (ACGIH)) were established to standardize operational and public exposure of electric and magnetic field. The standards for maximum public and occupational exposure to electric and magnetic field are shown in Appendix A. Therefore, there is a need to study the effect of electric and magnetic field in the present scenario. A MATLAB program is developed using the equations given in this chapter to calculate electric and magnetic field at any point in space [7][8].

3.2 Electric field calculation

Electric fields in nearby area of AC transmission line are calculated assuming no free charge in space. The charges on the conductors (Q) are determined through the voltage (V) matrix and Maxwell potential coefficient (P) matrix as shown in Equation 3.1

$$[Q] = [P]^{-1} [V] . \quad (3.1)$$

The charge matrix can be written in terms of its real and imaginary components as shown in equation 3.2.

$$[Q] = [Q_r] + j [Q_i] . \quad (3.2)$$

Once the charges on the conductors are known, for any point $P(x, y)$ in space, the electric field can be calculated. The electric field due to conductor A and its image conductor as shown in Figure 3.1 is given by,

Figure 3.1 Electric field vectors due to phase A at any point in the space

$$\vec{E}_A = E_{x,A}\vec{u}_x + E_{y,A}\vec{u}_y \quad (3.3)$$

Where,

$E_{x,A}$ and $E_{y,A}$ are the electric field magnitudes given by Equation 3.4 and 3.5 respectively, while $\vec{u}_x$ and $\vec{u}_y$ are the unit vectors along the horizontal and vertical axis respectively.

$$E_{x,A} = \frac{(q_{ra} + j q_{ia})(x - x_a)}{2\pi\epsilon[(x - x_a)^2 + (y - y_a)^2]} - \frac{(q_{ra} + j q_{ia})(x - x_a)}{2\pi\epsilon[(x - x_a)^2 + (y + y_a)^2]} \quad (3.4)$$

$$E_{y,A} = \frac{(q_{ra} + j q_{ia})(y - y_a)}{2\pi\epsilon[(x - x_a)^2 + (y - y_a)^2]} - \frac{(q_{ra} + j q_{ia})(y + y_a)}{2\pi\epsilon[(x - x_a)^2 + (y + y_a)^2]} \quad (3.5)$$

Similarly, horizontal and vertical components of electric field are calculated for conductors B and C respectively. The total horizontal and vertical components $\vec{E}_x$ and $\vec{E}_y$ due to three conductors are calculated as per Equations 3.6 and 3.7 respectively. Equation 3.8 gives the magnitude of the total electric field caused due to three conductors at a point P in space,

$$\vec{E}_x = \vec{E}_{x,A} + \vec{E}_{x,B} + \dots \quad (3.6)$$

$$\vec{E}_y = \vec{E}_{y,A} + \vec{E}_{y,B} + \dots \quad (3.7)$$

$$|E| = \sqrt{(E_x)^2 + (E_y)^2} \quad (3.8)$$

Using the above equations the electric field was calculated for the example configuration discussed in Chapter 2. The electric field was calculated at 1 m above the ground level at mid - span with maximum sag of 1.1 m. Figure 3.2 indicates the electric field plot across the right of way for the example configuration.

Figure 3.2 Electric field measured at 1 m above the ground level

3.3 Magnetic field calculation

The magnetic field of a transmission line was calculated using a two dimensional analysis of parallel lines over a flat earth. Figure 3.3 shows a conductor $A (x_A, y_A)$ carrying a current I_A . Equation 3.9 gives the magnetic field strength at any arbitrary point $P (x, y)$ in the plane due to the current carrying conductor.

Figure 3.3 Magnetic field lines due to conductor A at any point in space

$$\vec{H}_A = H_{x,A} \vec{u}_x + H_{y,A} \vec{u}_y \quad (3.9)$$

Where,

$\vec{H}_A$ is the magnetic field intensity caused due to conductor A at point P.

$H_{x,A}$ and $H_{y,A}$ are the magnitudes of the magnetic field given by equation 3.10 and 3.11.

$\vec{u}_x$ and $\vec{u}_y$ are the unit vectors along the horizontal and vertical axis.

$$H_{x,A} = \frac{I_A(y - y_A)}{2\pi[(x - x_A)^2 + (y - y_A)^2]} \quad (3.10)$$

$$H_{y,A} = \frac{I_A(x - x_A)}{2\pi[(x - x_A)^2 + (y - y_A)^2]} \quad (3.11)$$

Similarly, horizontal and vertical components of magnetic field intensity for conductors B and C could be calculated. Hence, the total horizontal and vertical components $\vec{H}_x$ and $\vec{H}_y$ due to three conductors are calculated using Equation 3.12 and 3.13. The total magnitude of magnetic field intensity is given by Equation 3.14.

$$\vec{H}_x = \vec{H}_{x,A} + \vec{H}_{x,B} + \dots \quad (3.12)$$

$$\vec{H}_y = \vec{H}_{y,A} + \vec{H}_{y,B} + \dots \quad (3.13)$$

$$|H| = \sqrt{(H_x)^2 + (H_y)^2} \quad (3.14)$$

Magnetic field density across the span is given by equation 3.15

$$\vec{B} = \mu_0 \vec{H} \quad (3.13)$$

Where, μ_0 = permeability of free space.

Using the above equations, the magnetic field was computed for the horizontal example configuration discussed in chapter 2. The magnetic fields for a

point 1 m above the ground level with conductor sag of 1.1 m at mid-span for the example configuration shown in Figure 3.4.

Figure 3.4 Magnetic field measured at 1 m above the ground level

Chapter 4. Techniques for increasing power transfer

4.1 Introduction

Transmission line design is governed by various factors such as conductor voltage gradient, switching and lightning over voltages, corona and reduced electrical strength due to contamination [7][8]. Transmission structures must be designed such that the phase-to-phase and phase-to-tower clearances are able to withstand the switching and lightning surges, swinging and galloping of the conductors under abnormal weather conditions [7][8]. The National Electrical Safety Code (NESC) standardized the minimum phase-to-phase and phase-to-tower clearances required for safe operations and maintenance [18]. While designing the transmission lines, these clearances are generally higher than the minimum requirement for protection against lightning and switching surges, swinging and galloping of conductors[7][8]. Hence, line compaction could be achieved by using techniques like inter-phase spacers, which controls conductor motion, and line arresters for protection against lightning and switching surges [27].

With the advancement in technology several new types of conductors have been developed. These new conductors called High Temperature Low Sag conductors (HTLS) are able to carry large current with higher thermal and lower sag limits.

In 1970s Barnes and Barthold developed the high phase order system consisting of six, nine or twelve phase instead of the conventional three phase system [28]. A test line was developed in Saratoga, New York as well as a double circuit

115 kV line was converted to a 93 kV (line-to-ground) six phase line [29][30]. The advantage of high phase order system is that the line-to-line voltage is less than or equal to line-to-ground voltage. This reduces the phase-to-phase and the phase-to-tower clearance requirements, increasing the possibility of line compaction.

This chapter discusses in detail these three techniques that aid in increasing power transfer capability, relieving congestion in the system and effectively using the right-of-way.

4.2 Line compaction

It is known that power transfer capability is inversely proportional to the positive sequence reactance of the line. Equation 2.10 provides the positive sequence reactance of the line, which depends on the self and mutual reactance [7]. For a given line, X_s depends on the conductor properties and is constant and X_m depends on the inter-phase distance and mutual coupling between the phases. Line compaction reduces the phase-to-phase distance causing higher mutual coupling. This results in higher X_m , reducing the positive sequence reactance of the line. Hence, the power transfer capability is higher for compact line as compared to conventional uncompact configuration.

In order to understand the effect of line compaction three different tower configurations were studied. The towers include three phase single circuit horizontal, vertical configurations and three phase double circuit vertical configuration. Figure 4.1 shows a typical 230 kV single circuit horizontal, vertical and double circuit vertical tower configurations which were studied [31].

Figure 4.1 Various configurations (230 kV) [31]

Table 4-1 provides detail of various configurations and the comparison between the actual clearances of the tower with the minimum NESC requirement [18]. Since the clearances (phase-to-phase and phase-to-tower) are higher than the NESC requirement, the line is compacted until a NESC criterion is not violated. For example, in configuration - 1, line compaction is carried out such the phase-to-tower clearances is reduced to the minimum requirement of 1.24 m, causing a phase-to-phase clearances of 2.48 m. Figures 4.2, 4.3 and 4.4 indicate the change in positive and zero sequence reactance for all three configurations using the Bluebird conductor.

Table 4-1 Comparison of clearances with the minimum NESC requirement

Clearances	Horizontal configuration	Vertical configuration	Three phase double circuit (Vertical configuration)	Minimum requirement as per NESC
Phase to phase (m)	6.70	5.48	5.48	1.6
Phase to tower (m)	3.04	1.75	1.75	1.24
Height of the lower conductor (m)	15.54	21.10	21.10

Figure 4.2 Change in reactance for configuration - 1

Figure 4.3 Change in reactance for configuration - 2

Figure 4.4 Change in reactance for configuration - 3

The results indicate 8 – 16% reduction in reactance that increases the power transfer capability of the line.

Another advantage of line compaction is the reduction in electric and magnetic field values at the edge of right of way. As shown in Chapter 3 the elec-

tric and magnetic field are becoming more stringent. Line compaction reduces the values of electric and magnetic field at edge of right of way. Thus reducing the right of way requirement of the line. Figures 4.5, 4.6 and 4.7 indicate the comparison of electric and magnetic field between standard and compact configurations calculated at 1 m above the ground level, across the right of way at mid-span, with a sag of 7.4 m.

Figure 4.5 Electric and magnetic field plots for configuration - 1

Figure 4.6 Electric and magnetic field plots for configuration – 2

Figure 4.7 Electric and magnetic field plots for configuration – 3

Another important point of interest in compact configurations mentioned above is that even though the phase-to-tower clearance has reached its minimum value as per NESC requirements, the phase-to-phase distance is still higher than the minimum value. Hence, new compaction techniques are developed using inter-phase spacers with composite insulators. For example, configuration – 1 in Figure 4.1, the configuration obtained by compacting it to minimum NESC requirement is shown as the compact configuration – 1a in Figure 4.8. The new compaction technique using inter-phase spacers is shown as the compact configuration – 1b and 1c in Figure 4.8. In compact configuration - 1b using inter-phase spacers the phase-to-phase distance is gradually reduced to 1.6 m at mid-span. While in compact configuration - 1c, the phase-to-phase distance of 1.6 m was attained closer to the tower and was kept unchanged for the major portion of the line.

Figure 4.8 Various compact configurations

Figure 4.9 shows the comparative line reactance for all four configurations (1, 1a, 1b and 1c) over the span of the line. The net reactance of the line over its span was obtained by integrating the areas under the line reactance curves.

Figure 4.9 Change in reactance for various horizontal compact configurations

Similarly compaction was carried out for configuration 2 and 3 and Figures 4.10 and 4.11 show the comparative line reactance over the span of line.

Figure 4.10 Change in reactance for various vertical compact configurations

Figure 4.11 Change in reactance for various double circuit vertical compact configurations

It was observed that 15 – 35% reduction in line reactance was achieved, when compared to standard configurations. The maximum reduction was obtained by compaction with inter – phase spacers. Theoretically, this would result in increasing the power transfer capability in the range of 17 – 53%. However, as discussed in Chapter 2 various limitations affects the power transfer capability in the larger interconnected system. These factors affect the actual power transfer capability achieved in the system.

As shown in Figure 4.5, line compaction aides in reduction of electric and magnetic field at the edge of right of way. Figure 4.12 indicates the comparison of electric and magnetic field using configuration 1, 1a, 1b and 1c.

Figure 4.12 Electric and magnetic field comparisons

The other advantages of line compaction are:

- Increasing the peak of power angle curve causing increase in system stability.
- Improved voltage regulation and stability.

4.3 High temperature low sag conductors (HTLS)

Present Aluminum Conductor Steel Reinforced (ACSR) conductors are capable of carrying rated capacity at 75°C (167°F) [19][32]. However, due to high atmospheric temperature and thermal heating of conductors the current carrying capacity is limited. Moreover, excessive heating causes elongation of conductors which increases sagging. These may jeopardize the safe and reliable operation of the line. To overcome these issues of thermal and sag limits, new types of conductors have been developed that can sustain high current carrying capacity at higher temperature range with lower sagging. These conductors could be used in lines which are thermal and sag limited. Different types of HTLS conductors are developed like Aluminum Conductor Composite Core (ACCC), Aluminum Conductor Steel Supported (ACSS), Aluminum Conductor Composite Reinforced (ACCR) and Aluminum Conductor Alloy Reinforced (ACAR). Table 4-2 shows the comparison of various HTLS conductors with conventional ACSR conductors for Drake type conductor [32].

Table 4-2 Comparison of HTLS conductor with ACSR conductor (Drake)

Conductor type	Diameter (in)	Resistance (AC@75°C) (Ω /mile)	X_1 (Inductive reactance @ 1 ft) (Ω /mile)	Current capacity (A)
ACSR	1.108	0.1389	0.399	900@75°C
ACCC	1.11	0.1085	0.401	1695@180°C
ACCR	1.128	0.1300	0.3999	1813@210°C
ACSS	1.108	0.1368	0.4012	1697@200°C
ACAR	1.108	0.1261	0.405	

It can be seen that even though the mechanical characteristic of various HTLS conductors are similar with ACSR conductor the current carrying capacity and temperature limits are higher. Hence, there is a significant amount of increase in power transfer with the same positive sequence reactance.

4.4 High phase (six phase) order system

Barnes and Barthold pioneered the development of high phase order system to satisfy future load demand and effectively utilizing the right of way [28]. As mentioned in Section 4.1 the line to line voltage is less than or equal to line to ground voltage. Table 4-3 indicates the relationship between line to line and line to ground voltage for high phase order system [30].

Table 4-3 Relationship between line to line and line to ground voltage in high phase order system

Three phase system	$V_{LL} = V_{LG} * \sqrt{3}$
Six phase system	$V_{LL} = V_{LG}$
Twelve phase system	$V_{LL} = 0.517 * V_{LG}$

In this study, improvement in present infrastructure was considered. Hence, a conversion of three phase double circuit to six phase single circuit was studied as it would not require any additional right of way requirement. In order to achieve the conversion of three phase circuit to six phase circuit various techniques were available. They are: 1) Three phase to six phase transformer 2) Power electronics convertor [33].

Power transfer capability is an important factor while comparing a three phase double circuit to a six phase circuit. Equation 4.1 indicates the power transfer capability for a n - phase system with line to ground voltage.

$$P = \frac{nV_{L-G}^2}{Z_s} \quad (4.1)$$

Hence, keeping the same line to ground voltage the power transfer capability of the line is inversely proportional to the surge impedance. Surge impedance for a three phase circuit is studied in Section 2.2. Similar procedure could be applied for six phase system resulting in a 6 X 6 impedance and capacitance matrix corresponding to six sequences of a six phase system. Considering the same 132.8

kV (line to ground voltage) three phase double circuit (Configuration – 3) as in Section 4.2 having the surge impedance of 180.28Ω when converting it to a 132.8 kV six phase single circuit becomes 352.18Ω . Hence the power transfer capability of a 132.8 kV three phase double circuit is nearly equal to a 132.8 kV six phase single circuit. However, upgrading the insulator string for 230 kV (line to ground voltage) a six phase system has a power transfer capability of 1.732 times as compared to three phase double circuit. Based on this, using Falcon conductor having a current carrying capacity of 1000 A. Figure 4.13 compares the line-to-line voltage required to transfer equal amount of power in a three phase double circuit to a six phase single circuit.

Figure 4.13 Voltage requirement for three phase double circuit and six phase single circuit for same amount of power transfer

From Figure 4.13 it is clear that in order to transfer equal amount of power higher voltages are required in case of three phase double circuit as compared to six phase single circuit. Thus, reduces the right of way requirement in six phase lines as compared to a three phase lines.

Chapter 5. Validation of techniques

5.1 Objective and description

The objective of this chapter is to implement the techniques discussed in Chapter 4. The IEEE 9 and 118 bus test systems are used to validate the results. An IEEE 9 bus test system representing three areas system is shown in Figure 5.1. It consists of three generating stations at buses 1, 2 and 3 and loads at buses 5, 6 and 8. The line MVA ratings are shown in Table 5-1. Further details regarding the generator, transformer and line parameters can be found in [20][34]. The study was carried out in Power World.

Figure 5.1 Nine bus test system

Table 5-1 Line limits for nine bus test system

Line no.	Line ratings (MVA)
7 - 8	90
7 - 5	150
5 - 4	80
4 - 6	100
6 - 9	100
8 - 9	60

5.2 Base case

Figure 5.1 indicates the base case. The pie – chart on the top of transmission line represents the percentage of the line MVA loading. Power flow results were that the line connecting bus 7 and 8 was the most congested line of the system.

5.3 Case – 1: Line compaction

The line compaction technique mentioned in Section 4.2 was applied to all transmission lines in the system. It is assumed that the line compaction technique reduces 30% of line reactance. Table 5-2 shows various cases of line compaction, affecting the power flow on line 7- 8.

Table 5-2 Effect of compaction techniques on congested line 7 - 8

Case no.	Compaction technique applied to line	Change in power flow on line 7-8 (as percentage of line rating)
1a	7-8	+2%
1b	7-5	-7%
1c	8-9	-2%
1d	5-4	+1%
1e	9-6	+5%
1f	6-4	-2%

It was interesting to note that if the line compaction technique was applied to the congested line (Case 1a), it worsened the situation. To ease the congestion, the compaction technique should be applied to the neighboring lines, as depicted in Case 1b and 1c.

5.4 Case – 2: HTLS conductor on line 7 – 8

The existing ACSR conductor on line 7 – 8 was replaced with the new HTLS conductor explained in Section 4.3. The rating of the new line was increased by 90 MVA and the corresponding loading was 41%. This eliminated the line congestion and enhanced the overall power transfer capability of the system. Further increase in system load resulted in congestion on other lines. Table 5-3 lists the most congested lines due to increase in load at various buses.

Table 5-3 Impact of load increment on line congestion

Case	Bus number	Increase in load (MW)	Congested line	Line Flow (as percentage of line rating)
2a	5	50	5 - 4	117%
2b	8	50	5 - 4	93%
			8 - 9	88%
2c	6	60	4 - 6	84%
			5 - 4	76%

5.5 Case – 3: Converting line 7 – 8 to high phase order system (six phase)

The study was carried out by converting line 7 – 8 to a six-phase line and the impact on congestion was investigated. The line to ground voltage of six-phase line was kept at 132 kV, equal to the line to ground voltage of a three-phase double circuit line. The study was carried out by converting six-phase impedance to equivalent three-phase single circuit impedance. Converting the line to six-phase system increased the capacity to 180 MVA. The results indicated that the power flow on line 7 – 8 was reduced to 44% from 83%. Table 5-4 indicates the congested line in the system if the load is increased.

Table 5-4 Impact of load increment on line congestion

Case	Bus number	Increase in load (MW)	Congested line	Percentage flow of maximum rating
1	5	50	5 - 4	121%
2	8	50	5 - 4	98%
3	6	60	4 - 6	79.7%
			5 - 4	79.5%

Similar results were obtained when converting line 7 – 8 to a three-phase double circuit line. Hence, maintaining the same line to ground voltage does not increase the power transfer capability of the line. However, upgrading it to 230 kV six-phase line enables it to carry power equivalent to a 400 kV three-phase line.

5.6 Case – 4: Transient stability analysis

A transient stability analysis was performed on the system with and without line compaction. The generators were modeled as GENCLS and details of the parameters are shown in Appendix – B. Table 5-5 shows the critical clearing time (CCT) for both the uncompact and compact cases when there was a three-phase fault on various transmission lines. The table indicates the increase in critical clearing time because of line compaction.

Table 5-5 Critical clearing time with and without line compaction

Fault on line	CCT without line compaction (cycle)	CCT with line compaction on 5 - 7 (cycle)	CCT with line compaction on 5 - 4 (cycle)	CCT with line compaction on 4 - 6 (cycle)	CCT with line compaction on 6 - 9 (cycle)	CCT with line compaction on 7 - 8 (cycle)	CCT with line compaction on 8 - 9 (cycle)
5 to 7	14	9	13	14	14	14	14
5 to 4	11	11	11	11	11	11	11
4 to 6	11	11	11	11	11	11	11
6 to 9	16	18	17	16	17	17	16
7 to 8	8	9	8	8	8	8	8
8 to 9	11	12	12	11	12	11	11

5.7 Objective and description of the 118 bus test system

As discussed in the above sections application of various techniques for increasing power transfer capability results in reducing congestion of the system. The objective of this study was to illustrate few cases explaining the application of these techniques in transmission planning and system improvement.

In order to study the application of techniques in planning and system improvement, an IEEE 118 bus test system was used [34][35]. A detail of the system is available in Appendix – C. The test system was divided into three zones as shown in Figure 5.2 [35]. Zone – 1 is the area of study consisting of 53 generators, 63 transmission lines and 91 loads. Figure 5.3 indicates the congestion on the lines in 118 bus system. The test system used is not $N - 1$ contingency satisfied. $N - 1$ contingency is a NERC requirement in which a system should remain stable even if a single element is lost in the electric grid. In this study, loss of transmission line was considered.

Table C – 3 in Appendix – C indicates the lists of contingency achieved when a transmission line was lost in the system. The techniques studied in Chapter 4 are applied on the system in order to make it $N - 1$ satisfied.

Figure 5.2 118 bus test system [35]

Figure 5.3 Line limit monitoring of IEEE 118 bus test system

5.8 Case – 5: Line compaction

During normal operating conditions, a few of the congested lines were 8 - 30 and 23- 32 with loading of 99% and 91% respectively. As seen in Appendix – B line 23 – 32 violates 9 contingency. The maximum flow on line 23 -32 is 163% during contingency. Line compaction technique was used on lines 20 - 21, 21- 22, 22- 23, 26- 30 and 17 - 31 reduced the reactance by 30%. As a result of line compaction the normal power flow on lines 8 - 30 and 23 - 32 were reduced to 96% and 82% respectively. The maximum flow on line 23 – 32 was reduced to 145% during contingency.

5.9 Case – 6: Application of HTLS conductors

Few lines like 23 – 24, 17 – 18 and 5 – 11 were thermally limited lines having a power flow of 19%, 83% and 78% respectively. The maximum flow passing through the lines during various contingencies are 115%, 130% and 130% respectively. In order to increase the power transfer capability on these lines HTLS conductors can be used.

Chapter 6. Conclusions and future work

6.1 Conclusions

It has been shown that various techniques applied on the test system have improved the power transfer capability and reduced congestion on the system. The following results were obtained from the test systems.

- Line compaction helps in the reduction of line reactance. A 30% line compaction is possible aiding in increasing power transfer capability and reducing congestion on various lines in the system. This helps in effectively using the existing right of way and satisfying a portion of future load demand. The other advantages of line compaction is the reduction in electric and magnetic field values at the edge of right of way required and could be installed in areas requiring stringent electric and magnetic field restrictions.
- Replacing the present ACSR conductor with the new HTLS conductors on a thermally limited transmission line increases the power transfer capability of the system. The advantage of HTLS conductors over ACSR conductors includes similar line impedance, mechanical properties, better thermal capability and lower sag. As seen in Case – 2 in Chapter – 4, for system that make use of HTLS conductors, an increase in load results in the second most congested line becoming the most congested line of the system. The disadvantage of HTLS conductors is their price being much higher than the present ACSR conductors.

- High phase (6 phase) order system was studied and it has been found that for the same line to ground voltage the power transfer capability of a three phase double circuit is nearly equal to six phase single circuit. Moreover, the voltage requirement for equal amount of power transfer is lower in a six-phase circuit as compared to a three-phase circuit. This aids in reducing the right of way requirement and increases line compaction. Since the voltage in a six-phase circuit is lower than three-phase, the electric field is lower at the edge of right of way.

6.2 Future work

This thesis focuses on techniques for increasing the power transfer capability of the system using the existing right of way. Further studies are required for implementing these techniques on the existing electric grid.

- Line compaction reduces the phase-to-phase and phase-to-tower distance. This might result in the phase to phase and phase to tower flash over during lightning and switching surges. Hence studies and tests are required to verify the Basic insulation Impulse Level (BIL) and Basic Switching insulation Level (BSL) for the compacted transmission line. Lightning arresters installed on transmission towers could aide in maintaining the BIL and BSL of the line.
- Inter-phase spacers made of composite insulators are used in line compaction. Effects of contamination caused due to pollution, water, ice and other factors need to be studied.

- High Phase (Six phase) order systems have several advantages such as lower voltage requirement to transfer higher amount of power when compared with three phase system. The line voltage determines the clearances distance and hence more line compaction is possible in high phase system. However, future research has to be conducted in line protection as 24 different faults are possible for six phase system. This could be solved with the development of various numerical relays.
- Application of the aforementioned techniques on a larger system and understanding the effects on electric grid need to be studied.
- Transmission planning includes building new transmission line and upgrading voltage of the line. However application of the discussed techniques could reduce the number of lines required.

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motor.ece.iit.edu/data/JEAS_IEEE118.doc

- [36] ICNIRP Guidelines, “For limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz),” 1998.

APPENDIX A

STANDARDS FOR ELECTRIC AND MAGNETIC FIELD

Table A-1 Electric and magnetic field standards established by various states in the United States [8]

Various States in the United States	Electric field at the edge of right of way (kV/m)	Magnetic field at the edge of right of way (mG/m)
New York	1.6	200
Florida	3	150
Montana	1	--
New Jersey	3	--

Table A-2 Occupational and public exposure by ICNIRP [36]

Exposure	Electric field (kV/m)	Magnetic field (G/m)
Occupational exposure	8.4	4.167
Public exposure	4.167	0.833

APPENDIX B

PARAMETERS FOR IEEE 9 BUS SYSTEM

Table B-1 Generator parameters for IEEE 9 bus test system

Generator parameters	Per unit (P.U.) on 100 MVA base
H (Inertia)	6.4
D (Damping)	1.28
R_a	0
X_d	0.8958
X_q	0.8645
X'_d	0.1198
$X''_d = X''_q$	0.1198
X_l	0.0599
T'_{d0}	6.0
$T''_{d0} = T''_{q0}$	0.5350

APPENDIX C

DATA FOR 118 BUS TEST SYSTEM

Table C-1 Bus data

No	No- minal kV	PU	Volt (kV)	Angle (Deg)	Load MW	Load MVar	Gen MW	Gen MVar	Switched Shunts MVar	Zone
1	1.00	0.95	0.957	-18.2	51.00	27.00				1
2	1.00	0.97	0.972	-17.7	20.00	9.00				1
3	1.00	0.96	0.969	-17.3	39.00	10.00				1
4	1.00	0.99	0.998	-13.6	30.00	12.00	-9	-15.5		1
5	1.00	1.00	1.002	-13.2					-40.17	1
6	1.00	0.99	0.99	-15.9	52.00	22.00	0	15.8		1
7	1.00	0.98	0.989	-16.3	19.00	2.00				1
8	1.00	1.01	1.015	-8.13			-28	61.6		1
9	1.00	1.04	1.043	-0.87						1
10	1.00	1.05	1.05	6.71			450	-50.9		1
11	1.00	0.98	0.985	-16.2	70.00	23.00				1
12	1.00	0.99	0.99	-16.7	47.00	10.00	85	88.3		1
13	1.00	0.96	0.968	-17.5	34.00	16.00				1
14	1.00	0.98	0.984	-17.4	14.00	1.00				1
15	1.00	0.97	0.97	-17.7	90.00	30.00	0	2.71		1
16	1.00	0.98	0.984	-17	25.00	10.00				1
17	1.00	0.99	0.995	-15.2	11.00	3.00			0	1
18	1.00	0.97	0.973	-17.4	60.00	34.00	0	25.3		1
19	1.00	0.96	0.963	-17.8	45.00	25.00	0	-8		1
20	1.00	0.95	0.958	-17	18.00	3.00				1
21	1.00	0.95	0.959	-15.4	14.00	8.00				1
22	1.00	0.96	0.97	-12.9	10.00	5.00				1
23	1.00	0.99	1	-7.99	7.00	3.00				1
24	1.00	0.99	0.992	-8.23			-13	-13.9		1
25	1.00	1.05	1.05	-1			220	49.6		1
26	1.00	1.01	1.015	0.78			314	9.49		1
27	1.00	0.96	0.968	-13.5	62.00	13.00	-9	2.34		1
28	1.00	0.96	0.962	-15.1	17.00	7.00				1
29	1.00	0.96	0.963	-16	24.00	4.00				1
30	1.00	0.98	0.986	-10.2						1
31	1.00	0.96	0.967	-15.8	43.00	27.00	7	3.96		1
32	1.00	0.96	0.964	-14	59.00	23.00	0	-14		1
33	1.00	0.97	0.972	-18.1	23.00	9.00				1
34	1.00	0.98	0.986	-17.3	59.00	26.00	0	-8	13.61	1

No	No- minal kV	PU	Volt (kV)	Angle (Deg)	Load MW	Load MVar	Gen MW	Gen MVar	Switched Shunts MVar	Zone
35	1.00	0.98	0.981	-17.8	33.00	9.00				1
36	1.00	0.98	0.98	-17.8	31.00	17.00	0	-1.73		1
37	1.00	0.99	0.992	-16.9					-24.61	1
38	1.00	0.96	0.963	-12.1						1
39	1.00	0.97	0.971	-19.5	27.00	11.00				1
40	1.00	0.97	0.97	-20.1	20.00	23.00	-46	25.3		1
41	1.00	0.96	0.967	-20.2	37.00	10.00				1
42	1.00	0.98	0.985	-17.7	37.00	23.00	-59	21.9		1
43	1.00	0.97	0.979	-17.5	18.00	7.00				1
44	1.00	0.98	0.985	-15.2	16.00	8.00			9.71	1
45	1.00	0.98	0.987	-13.5	53.00	22.00			9.74	1
46	1.00	1.00	1.005	-10.7	28.00	10.00	19	-5.68	10.1	1
47	1.00	1.01	1.017	-8.58	34.00	0.00				1
48	1.00	1.02	1.021	-9.27	20.00	11.00			15.63	1
49	1.00	1.02	1.025	-8.26	87.00	30.00	204	108		1
50	1.00	1.00	1.001	-10.1	17.00	4.00				1
51	1.00	0.96	0.968	-12.5	17.00	8.00				1
52	1.00	0.95	0.958	-13.4	18.00	5.00				1
53	1.00	0.94	0.946	-14.2	23.00	11.00				1
54	1.00	0.95	0.955	-13.1	113.0	32.00	48	-29		1
55	1.00	0.95	0.952	-13.5	63.00	22.00	0	1.11		1
56	1.00	0.95	0.955	-13.3	84.00	18.00	0	-8		1
57	1.00	0.97	0.971	-12.3	12.00	3.00				1
58	1.00	0.95	0.96	-13.1	12.00	3.00				1
59	1.00	0.98	0.985	-10.4	277.0	113.00	155	83.3		1
60	1.00	0.99	0.993	-6.95	78.00	3.00				1
61	1.00	0.99	0.995	-6.06			160	-41.6		1
62	1.00	0.99	0.998	-6.79	77.00	14.00	0	0.6		1
63	1.00	0.96	0.969	-7.22						1
64	1.00	0.98	0.984	-5.56						1
65	1.00	1.00	1.005	-2.55			391	78.8		1
66	1.00	1.05	1.05	-3.3	39.00	18.00	392	16.8		1
67	1.00	1.01	1.02	-5.69	28.00	7.00				1
68	1.00	1.00	1.003	-2.62						1
70	1.00	0.98	0.984	-7.11	66.00	20.00	0	6.6		1
71	1.00	0.98	0.987	-7.49						1
72	1.00	0.98	0.98	-8.42			-12	-11.2		1

No	No- minal kV	PU	Volt (kV)	Angle (Deg)	Load MW	Load MVar	Gen MW	Gen MVar	Switched Shunts MVar	Zone
73	1.00	0.99	0.991	-7.7			-6	9.63		1
74	1.00	0.95	0.959	-8.08	68.00	27.00	0	-6	11.03	1
75	1.00	0.96	0.968	-6.83	47.00	11.00				1
76	1.00	0.94	0.943	-7.86	68.00	36.00	0	0.78		1
77	1.00	1.01	1.012	-2.91	61.00	28.00	0	-20		1
78	1.00	1.00	1.008	-3.3	71.00	26.00				1
79	1.00	1.01	1.013	-3.16	39.00	32.00			20.53	1
80	1.00	1.04	1.04	-1.38	130.0	26.00	477	126		1
81	1.00	0.99	0.997	-2.13						1
82	1.00	1	1	-3	54.00	27.00	0	21.9	20	1
83	1.00	0.99	0.994	-2.07	20.00	10.00			9.88	1
84	1.00	0.98	0.985	0.07	11.00	7.00				1
85	1.00	0.98	0.988	1.44	24.00	15.00	0	-8		1
86	1.00	0.98	0.989	0.1	21.00	10.00				1
87	1.00	1.01	1.015	0.37			4	9.95		1
88	1.00	0.98	0.989	4.2	48.00	10.00				1
89	1.00	1.00	1.005	8			607	-19.8		1
90	1.00	0.98	0.985	3.46	78.00	42.00	-85	44.4		1
91	1.00	0.98	0.98	3.7			-10	-19.1		1
92	1.00	0.99	0.998	4.43	65.00	10.00	0	-3		1
93	1.00	0.99	0.991	1.21	12.00	7.00				1
94	1.00	0.99	0.994	-1.14	30.00	16.00				1
95	1.00	0.98	0.985	-2.23	42.00	31.00				1
96	1.00	0.99	0.998	-2.55	38.00	15.00				1
97	1.00	1.01	1.014	-2.32	15.00	9.00				1
98	1.00	1.02	1.024	-2.72	34.00	8.00				1
99	1.00	1.01	1.01	-2.89			-42	-17.6		1
100	1.00	1.01	1.017	-1.73	37.00	18.00	252	75.4		1
101	1.00	0.99	0.995	0.02	22.00	15.00				1
102	1.00	0.99	0.995	2.86	5.00	3.00				1
103	1.00	1.00	1.006	-5.37	23.00	16.00	40	40		1
104	1.00	0.98	0.988	-8.26	38.00	25.00	0	23		1
105	1.00	0.98	0.982	-9.35	31.00	26.00	0	23	19.3	1
106	1.00	0.97	0.973	-9.5	43.00	16.00				1
107	1.00	0.95	0.952	-12.1	28.00	12.00	-22	-8.71	5.44	1
108	1.00	0.97	0.977	-10.4	2.00	1.00				1
109	1.00	0.97	0.975	-10.8	8.00	3.00				1

No	No- minal kV	PU	Volt (kV)	Angle (Deg)	Load MW	Load MVar	Gen MW	Gen MVar	Switched Shunts MVar	Zone
110	1.00	0.97	0.973	-11.5	39.00	30.00	0	-7.48	5.68	1
111	1.00	0.98	0.98	-9.87			36	-1.84		1
112	1.00	0.97	0.975	-14.6	25.00	13.00	-43	41.5		1
113	1.00	0.99	0.993	-15.3			-6	34.4		1
114	1.00	0.96	0.96	-14.3	8.00	3.00				1
115	1.00	0.96	0.96	-14.3	22.00	7.00				1
116	1.00	1.00	1.005	-3.06			-184	50.3		1
117	1.00	0.98	0.982	-16.7	20.00	8.00				1
118	1.00	0.94	0.95	-7.77	33.00	15.00				1

Table C-2 Transmission line data

From No.	To No.	Cir- cuit	Branc h	MW From	MVar From	MVA From	Line MVA	% of MVA Limit (Max)	MW Loss
12	117	1	Line	20.1	4.6	20.7	100	21.5	0.15
11	12	1	Line	34.2	-35	48.9	100	48.9	0.14
8	30	1	Line	74.5	27.1	79.3	100	105.1	0.35
24	70	1	Line	-3.9	-2.1	4.4	100	8.7	0.02
6	7	1	Line	35.4	-4.7	35.8	100	35.8	0.06
27	28	1	Line	31.2	-0.3	31.2	100	31.2	0.2
19	34	1	Line	-5.4	-10.1	11.4	100	11.4	0.06
17	31	1	Line	11.3	12.6	16.9	100	19.4	0.16
30	38	1	Line	62.8	16.3	64.9	0	0	0.25
23	32	1	Line	90.7	5.1	90.9	100	90.9	2.65
25	27	1	Line	142.2	30	145.3	500	29.1	6.28
15	19	1	Line	11	12.4	16.6	100	17.2	0.04
1	2	1	Line	-12.3	-11.8	17.1	100	17.1	0.09
23	24	1	Line	12.1	10	15.6	100	19	0.04
22	23	1	Line	-52.9	-6.6	53.3	100	54.4	1.03
23	25	1	Line	-163	-25.4	165.7	500	34.5	4.25
70	75	1	Line	0	9.3	9.3	100	12.5	0.05
17	113	1	Line	8.8	4.4	9.8	100	10.1	0.01
32	113	1	Line	6	-18	19	100	19	0.18
15	33	1	Line	5.4	-4.4	7	100	7	0.02

From No.	To No.	Circuit	Branch Type	MW From	MVar From	MVA From	Line MVA	% of MVA Limit (Max)	MW Loss
29	31	1	Line	-10	-8.2	12.9	100	12.9	0.02
4	5	1	Line	-103.	-27.3	106.7	500	21.4	0.21
14	15	1	Line	4	3.2	5.1	100	8.9	0.03
3	12	1	Line	-9.8	-11.6	15.2	100	15.2	0.1
16	17	1	Line	-17.4	-3.8	17.8	100	17.8	0.14
26	30	1	Line	223.8	-12.1	224.2	500	44.8	3.98
27	32	1	Line	12.8	0.8	12.8	100	13	0.04
71	73	1	Line	6	-10.7	12.3	100	12.3	0.01
20	21	1	Line	-28.3	4.8	28.7	100	29.1	0.17
114	115	1	Line	1.2	0.7	1.4	100	1.5	0
5	6	1	Line	88.4	4.3	88.5	100	88.5	0.93
8	5	1	Transformer	338.2	124.4	360.3	0	0	0
12	14	1	Line	18.1	2.7	18.3	100	18.5	0.07
1	3	1	Line	-38.7	-15.2	41.6	100	41.7	0.24
74	75	1	Line	-51.9	-7	52.3	100	52.7	0.37
71	72	1	Line	9.1	-0.6	9.1	100	9.7	0.04
70	71	1	Line	15.2	-12	19.4	100	19.4	0.03
9	10	1	Line	-445	-24.6	445.9	500	90.6	4.78
30	17	1	Transformer	231.2	94.1	249.6	0	0	0
32	114	1	Line	9.2	2.3	9.5	100	9.9	0.01
113	31	1	Line	8.6	25.9	27.2	1000	2.7	0
31	32	1	Line	-26.4	10.5	28.4	100	29.2	0.27
12	16	1	Line	7.6	4.2	8.7	100	9.8	0.02
5	11	1	Line	77.1	3.1	77.2	100	77.2	1.21
27	115	1	Line	20.9	4.6	21.4	100	21.7	0.08
7	12	1	Line	16.4	-6.5	17.6	100	17.6	0.03
2	12	1	Line	-32.4	-18.7	37.4	100	37.4	0.27
3	5	1	Line	-68.1	-13.4	69.4	100	71.2	1.23
24	72	1	Line	2.9	2.9	4.2	100	8.2	0.02
28	29	1	Line	14	-6.2	15.3	100	15.3	0.06
8	9	1	Line	-440	-89.8	449.7	500	89.9	4.54
26	25	1	Transformer	90.2	21.6	92.7	0	0	0
13	15	1	Line	0.6	-3.8	3.9	100	3.9	0

From No.	To No.	Circuit	Branch	MW From	MVar From	MVA From	Line MVA	% of MVA Limit (Max)	MW Loss
17	18	1	Line	79.2	25.3	83.2	100	83.2	0.86
4	11	1	Line	64.1	-0.2	64.1	100	64.1	0.86
18	19	1	Line	18.4	14.2	23.3	100	23.7	0.07
70	74	1	Line	16.3	12.4	20.5	100	22	0.19
15	17	1	Line	-101	-25.3	105	500	21.3	1.53
75	77	1	Line	-36.2	-11.4	37.9	100	38.2	0.89
75	118	1	Line	39	24.8	46.2	100	46.2	0.33
11	13	1	Line	34.9	11.4	36.7	100	36.7	0.32
21	22	1	Line	-42.5	-2	42.5	100	42.9	0.41
19	20	1	Line	-10.3	5.3	11.6	100	13	0.04
37	40	1	Line	33.2	0.2	33.2	100	33.2	0.67
69	77	1	Line	55.3	2.7	55.4	100	55.4	0.9
37	39	1	Line	43.7	6.3	44.2	100	44.2	0.64
38	37	1	Transformer	226.4	114.2	253.5	0	0	0
68	116	1	Line	184.1	-65.4	195.4	500	39.1	0.11
68	81	1	Line	-39.1	-5	39.4	100	84.8	0.05
35	37	1	Line	-33.9	-15.4	37.3	100	37.3	0.16
35	36	1	Line	0.9	6.4	6.5	100	6.7	0
65	66	1	Transformer	39.9	72.5	82.7	0	0	0
34	43	1	Line	2.7	1.5	3.1	100	6.2	0.01
34	37	1	Line	-97.3	-38	104.4	500	21	0.29
62	67	1	Line	-19.9	-15.6	25.3	100	25.3	0.15
62	66	1	Line	-32.7	-18.6	37.6	100	37.6	0.64
34	36	1	Line	30.2	11.8	32.4	100	32.4	0.09
33	37	1	Line	-17.6	-10.4	20.4	100	20.4	0.17
60	62	1	Line	-6.3	-7.8	10	100	10	0.01
60	61	1	Line	-112	8.6	112.3	500	22.5	0.33
59	61	1	Line	-48.3	4	48.5	100	49.3	0.8
59	60	1	Line	-39.8	2.5	39.9	100	40.5	0.52
56	59	2	Line	-20.1	-7.1	21.3	100	21.3	0.38
56	59	1	Line	-20.1	-7.1	21.3	0	0	0.38
56	58	1	Line	-3.8	-4.8	6.1	100	6.1	0.01
56	57	1	Line	-19.3	-10.6	22	100	22	0.17

From No.	To No.	Circuit	Branch	MW From	MVar From	MVA From	Line MVA	% of MVA Limit (Max)	MW Loss
55	59	1	Line	-25.3	-10.9	27.6	100	27.6	0.37
55	56	1	Line	-27.9	-7.4	28.9	100	28.9	0.05
54	59	1	Line	-20.8	-10.2	23.2	100	23.2	0.27
54	56	1	Line	27.6	-4	27.9	100	27.9	0.02
47	69	1	Line	-52.4	10	53.3	100	55.6	2.39
53	54	1	Line	-14.4	-4.9	15.2	100	15.2	0.06
51	58	1	Line	15.8	4.2	16.4	100	16.8	0.08
49	69	1	Line	-43	9	43.9	100	46.3	1.9
99	100	1	Line	-26.1	-3.8	26.4	100	26.4	0.12
49	54	1	Line	33	13.8	35.8	0	0	0.97
49	66	1	Line	-101	-4.9	102	500	20.8	1.78
49	54	2	Line	33	13.8	35.8	100	36.4	0.97
49	54	1	Line	33.1	12.1	35.3	100	35.6	1.12
49	66	1	Line	-101	-4.9	102	0	0	1.78
49	66	2	Line	-101	-4.9	102	500	20.8	1.78
56	59	1	Line	-21.1	-7	22.3	100	22.3	0.41
49	51	1	Line	61.6	21.3	65.2	100	65.2	2
49	50	1	Line	49.7	14.2	51.7	100	51.7	0.69
48	49	1	Line	-35	3.2	35.2	100	35.5	0.21
63	59	1	Transformer	143.2	67.9	158.5	0	0	0
50	57	1	Line	32	10.2	33.6	100	33.6	0.55
98	100	1	Line	-8.72	3.3	9.3	100	11.9	0.04
61	62	1	Line	30.8	-14.9	34.2	100	34.2	0.1
64	61	1	Transformer	32.2	14.6	35.4	0	0	0
52	53	1	Line	8.6	2.6	9	100	10.5	0.04
47	49	1	Line	-12.1	-9.7	15.5	100	15.5	0.04
63	64	1	Line	-143	-67.9	158.5	500	31.7	0.43
64	65	1	Line	-175	-66.9	188.2	500	37.6	0.93
46	48	1	Line	-14.9	-5.8	16	100	16	0.14
65	68	1	Line	7.9	-21.5	22.9	100	43.5	0
66	67	1	Line	48.6	19.9	52.5	100	52.5	0.57
68	69	1	Transformer	-137	113.1	177.8	0	0	0
46	47	1	Line	-30.1	-1.7	30.2	100	30.5	0.34
54	55	1	Line	9.8	0.8	9.8	100	10.1	0.02

From No.	To No.	Circuit	Branch	MW From	MVar From	MVA From	Line MVA	% of MVA Limit (Max)	MW Loss
69	70	1	Line	104.7	16.5	106	500	21.2	3.22
69	75	1	Line	106.7	20.4	108.6	500	21.7	4.58
45	49	1	Line	-49.3	-2	49.3	100	51	1.7
45	46	1	Line	-35.5	-3.5	35.7	100	36.1	0.52
80	99	1	Line	16.1	8.8	18.3	100	21.1	0.17
80	98	1	Line	25.4	9	27	100	27.7	0.17
80	97	1	Line	23.3	22.9	32.7	100	33.7	0.19
43	44	1	Line	-15.4	-1.4	15.4	100	16	0.15
51	52	1	Line	26.8	6.8	27.6	100	27.7	0.17
42	49	2	Line	-50.4	-1	50.4	100	52.3	1.88
78	79	1	Line	-13.4	-16.4	21.2	100	21.2	0.02
42	49	1	Line	-50.4	-1	50.4	100	52.3	1.88
77	82	1	Line	6	7.6	9.7	100	16.8	0.05
77	80	2	Line	-70	-36.1	78.7	500	15.7	1
42	49	1	Line	-50.4	-1	50.4	0	0	1.88
77	80	1	Line	-31.9	-19.1	37.2	500	7.4	0.38
77	80	1	Line	-70	-36.1	78.7	0	0	1
41	42	1	Line	-32	-4.3	32.3	100	32.6	0.45
77	78	1	Line	57.7	8.7	58.4	100	58.4	0.13
79	80	1	Line	-52.4	-27.4	59.2	100	59.8	0.52
81	80	1	Transformer	-39.1	75.3	84.8	0	0	0
80	96	1	Line	15.8	18.3	24.2	100	27.2	0.23
76	118	1	Line	-5.7	-10.9	12.3	100	12.3	0.03
40	42	1	Line	-22.4	-2.9	22.6	100	22.7	0.3
76	77	1	Line	-62.3	-24.3	66.9	100	70.4	2.2
44	45	1	Line	-31.5	5.5	32	100	32.5	0.24
40	41	1	Line	5	4.6	6.8	100	7.6	0.01
39	40	1	Line	16.1	-4.2	16.6	100	16.6	0.05
38	65	1	Line	-163	-60.7	174.7	500	34.9	2.62
110	112	1	Line	69.5	-30.6	75.9	100	75.9	1.46
110	111	1	Line	-35.7	1	35.7	100	36	0.3
108	109	1	Line	21.8	-10.4	24.2	100	24.2	0.06
106	107	1	Line	24	-3.4	24.2	100	24.2	0.33
105	108	1	Line	24	-10.6	26.2	100	26.2	0.19
105	106	1	Line	8.7	4.6	9.8	100	10.4	0.02

From No.	To No.	Circuit	Branch	MW From	MVar From	MVA From	Line MVA	% of MVA Limit (Max)	MW Loss
104	105	1	Line	48.7	0.1	48.7	100	48.7	0.25
103	110	1	Line	60.6	3.2	60.6	100	60.6	1.44
103	104	1	Line	32.3	7.9	33.3	100	33.3	0.53
101	102	1	Line	-41.8	8.2	42.5	100	43.2	0.46
100	106	1	Line	60.6	9.2	61.3	100	61.3	2.24
100	104	1	Line	56.4	10.6	57.4	100	57.4	1.47
100	103	1	Line	121.1	-4.3	121.2	500	24.2	2.27
100	101	1	Line	-19.5	20.9	28.6	100	30.5	0.24
96	97	1	Line	-8	-17.7	19.5	100	19.5	0.06
95	96	1	Line	2.6	-24.6	24.7	100	24.7	0.1
94	100	1	Line	5.4	-43.8	44.2	100	44.2	0.31
94	96	1	Line	24.4	-13	27.7	100	27.7	0.2
94	95	1	Line	44.9	6.2	45.3	100	45.3	0.28
93	94	1	Line	49.7	-18.8	53.2	100	53.2	0.63
92	102	1	Line	47.5	-6.2	47.9	100	47.9	0.28
92	100	1	Line	34.3	-15.9	37.8	100	37.8	0.86
92	94	1	Line	57.3	-14.1	59	100	59	1.66
92	93	1	Line	62.8	-10.6	63.6	100	63.6	1.04
91	92	1	Line	-12.8	-11.3	17.1	100	17.1	0.1
91	90	1	Line	2.8	-7.7	8.2	100	8.2	0.01
89	92	2	Line	122.4	-8.6	122.7	500	24.5	1.47
89	92	1	Line	38.5	-5.9	39	500	7.8	0.58
89	92	1	Line	122.4	-8.6	122.7	0	0	1.47
89	90	2	Line	41.9	-1.9	42	500	8.4	0.9
89	90	1	Line	79.7	-1.1	79.7	500	15.9	1.5
89	90	1	Line	41.9	-1.9	42	0	0	0.9
103	105	1	Line	42.98 2	6.5	43.4	100	43.4	1.02
88	89	1	Line	-92.8	-1.8	92.8	500	18.8	1.22
86	87	1	Line	-4	-14.1	14.7	0	0	0.05
85	89	1	Line	-65.2	0.9	65.2	100	66.2	1.04
105	107	1	Line	26.7	-1.8	26.8	100	26.8	0.41
85	88	1	Line	-44.4	7.7	45	100	45.5	0.42
85	86	1	Line	17.2	-6.4	18.3	100	18.3	0.11
84	85	1	Line	-31.3	9.8	32.8	100	33.3	0.34
109	110	1	Line	13.7	-12.9	18.8	100	18.8	0.1

From No.	To No.	Circuit	Branch	MW From	MVar From	MVA From	Line MVA	% of MVA Limit (Max)	MW Loss
83	85	1	Line	-36.1	13.8	38.6	100	39.6	0.67
83	84	1	Line	-19.9	15.2	25	100	26.4	0.42
82	96	1	Line	-12.4	4.6	13.2	100	15.9	0.03
82	83	1	Line	-35.7	26	44.2	100	46.2	0.23

Table C-3 Violations in IEEE 118 bus test system

Sr.No	From Number	To Number	Circuit	Xfrmr	Violations	Max % Loading Cont.
1	4	11	1	NO	1	100.27
2	5	6	1	NO	7	113.96
3	5	11	1	NO	5	130.32
4	8	30	1	NO	57	419.78
5	11	12	1	NO	1	107.31
6	12	14	1	NO	1	106.83
7	12	16	1	NO	1	142.04
8	13	15	1	NO	1	106.76
9	14	15	1	NO	1	119.47
10	16	17	1	NO	1	166.25
11	17	18	1	NO	3	130.26
12	23	24	1	NO	2	109.25
13	23	32	1	NO	9	163.27
14	47	69	1	NO	2	103.59
15	65	68	1	NO	2	291.49
16	68	81	1	NO	2	112.45
17	69	77	1	NO	2	107.4
18	76	77	1	NO	1	115.96