Algorithm and Model Development for Innovative High Power AC Transmission

by

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of the Requirements for the Degree
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ABSTRACT

This thesis presents research on innovative AC transmission design concepts and focused mathematics for electric power transmission design. The focus relates to compact designs, high temperature low sag conductors, and high phase order design. The motivation of the research is to increase transmission capacity with limited right of way.

Regarding compact phase spacing, insight into the possibility of increasing the security rating of transmission lines is the primary focus through increased mutual coupling and decreased positive sequence reactance. Compact design can reduce the required corridor width to as little as 31% of traditional designs, especially with the use of inter-phase spacers. Typically transmission lines are built with conservative clearances, with difficulty obtaining right of way, more compact phase spacing may be needed. With design consideration significant compaction can produce an increase by 5-25% in the transmission line security (steady state stability) rating. In addition, other advantages and disadvantages of compact phase design are analyzed. Also, the next two topics: high temperature low sag conductors and high phase order designs include the use of compact designs.

High temperature low sag (HTLS) conductors are used to increase the thermal capacity of a transmission line up to two times the capacity compared to traditional conductors. HTLS conductors can operate continuously at 150-210°C and in emergency at 180-250°C (depending on the HTLS conductor). ACSR conductors operate continuously at 50-110°C and in emergency conditions at 110-150°C depending on the utility, line, and location. HTLS conductors have decreased sag characteristics of up to 33% compared to
traditional ACSR conductors at 100°C and up to 22% at 180°C. In addition to what HTLS has to offer in terms of the thermal rating improvement, the possibility of using HTLS conductors to indirectly reduce tower height and compact the phases to increase the security limit is investigated. In addition, utilizing HTLS conductors to increase span length and decrease the number of transmission towers is investigated. The phase compaction or increased span length is accomplished by utilization of the improved physical sag characteristics of HTLS conductors.

*High phase order* (HPO) focuses on the ability to increase the power capacity for a given right of way. For example, a six phase line would have a thermal rating of approximately 173%, a security rating of approximately 289%, and the SIL would be approximately 300% of a double circuit three phase line with equal right of way and equal voltage line to line. In addition, this research focuses on algorithm and model development of HPO systems. A study of the impedance of HPO lines is presented. The line impedance matrices for some high phase order configurations are circulant Toeplitz matrices. Properties of circulant matrices are developed for the generalized sequence impedances of HPO lines. A method to calculate the sequence impedances utilizing unique distance parameter algorithms is presented. A novel method to design the sequence impedances to specifications is presented. Utilizing impedance matrices in circulant form, a generalized form of the sequence components transformation matrix is presented. A generalized voltage unbalance factor in discussed for HPO transmission lines. Algorithms to calculate the number of fault types and number of significant fault types for an *n*-phase system are presented. A discussion is presented on transposition of HPO transmission
lines and a generalized fault analysis of a high phase order circuit is presented along with an HPO analysis program.

The work presented has the objective of increasing the use of rights of way for bulk power transmission through the use of innovative transmission technologies. The purpose of this dissertation is to lay down some of the building blocks and to help make the three technologies discussed practical applications in the future.
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NOMENCLATURE

\[
\begin{align*}
\alpha & = \frac{\pi}{360} \text{ phases} \\
\text{AC} & = \text{Alternating Current} \\
\text{ACCC} & = \text{Aluminum Conductor Composite Core} \\
\text{ACCR} & = \text{Aluminum Conductor Composite Reinforced} \\
\text{ACIR/AW} & = \text{Aluminum Conductor Invar Reinforced / Aluminum clad steel core} \\
\text{ACSR} & = \text{Aluminum Conductor Steel Reinforced} \\
\text{ACSS/AW} & = \text{Aluminum Conductor Steel Support / Aluminum clad steel core} \\
\text{ACSS/TW} & = \text{Aluminum Conductor Steel Support / Trapezoidal shaped aluminum strands} \\
A_{\text{wind}} & = \text{Cross-sectional area seen by perpendicular winds for one span} \\
b & = \text{Six phase angle operator } e^{j2\pi/3} = 1\angle 60^\circ \\
\text{BIL} & = \text{Basic Impulse Level} \\
C & = \text{Capacitance or coefficient matrix for sequence impedance calculation} \\
c & = \text{Twelve phase angle operator } e^{j2\pi/6} = 1\angle 30^\circ \\
\text{CFO} & = \text{Critical Flashover Voltage} \\
\text{CT} & = \text{Circulant Toeplitz matrix} \\
\text{CVUF} & = \text{Complex voltage unbalance factor} \\
d & = \text{Phase spacing distance} \\
d_c & = \text{Diameter of the conductor} \\
\text{DC} & = \text{Direct Current} \\
d_{c,\text{ice}} & = \text{Diameter of the conductor with ice around the conductor} \\
d_{eq} & = \text{Equivalent phase spacing distance} \\
d_{i,\text{BIL}} & = \text{Phase spacing required by voltage, BIL, and switching surges} \\
d_{p,m} & = \text{Phase spacing distance between conductors } p \text{ and } m \\
D_{\text{swing}} & = \text{Distance the conductor can swing horizontally} \\
D_{X0} & = \text{Distance parameter to calculate the zero sequence reactance} \\
D_{X1} & = \text{Distance parameter to calculate the positive sequence reactance} \\
D_{Xq} & = \text{Distance parameter to calculate the } q \text{ sequence reactance} \\
\vec{E} & = \text{Electric field vector}
\end{align*}
\]
\( f \)  
Frequency

\( F_{\text{horizontal}} \)  
Horizontal force on the span

\( F_{\text{vertical}} \)  
Vertical force on the span

GMD  
Geometric mean distance

GMR  
Geometric mean radius

GUI  
Graphical user interface

\( H \)  
Horizontal tension strength

\( \vec{H} \)  
Magnetic field intensity

HPO  
High phase order

HTLS  
High temperature low sag

HVDC  
High voltage direct current

\( I, I_1, I_{\text{line}} \)  
Current, fault current, line current

\( I_a, I_b, I_c \)  
Phase current on phase A, B, and C

IEEE  
Institute of Electrical and Electronics Engineers

\( L \)  
Inductance

\( l \)  
Length

\( M \)  
Mutual reactance

\( n \)  
Number of phases

\( n_t \)  
Number of transposition sections

\( n_{ft} \)  
Number of transposition sections to attain ‘fully transposed’

\( N-1 \)  
Single line outage contingency

\( N-2 \)  
Double line outage contingency

NEMA  
National Electrical Manufacturers Association

NESC  
National Electrical Safety Code

\( P_{12} \)  
Active power flow between bus 1 and 2

\( \phi \)  
The Euler’s totient function also known as the phi function

PSLF  
Positive Sequence Load Flow

pu  
Per unit

\( Q \)  
Reactive power

\( Q_{\text{per_ph}} \)  
Reactive power per phase
$R$ Resistance
RAS Remedial Action Scheme
$r_e$ Equivalent radius of a conductor
$r_{ice}$ Radius of ice on a conductor
ROW Right of way
$S$ Conductor sag
SCT Symmetrical Circulant Toeplitz
SIL Surge impedance loading
$T$ Transformation matrix between sequence components and phase components
TSAT Transient Stability Analysis Tool
$U_{3ph}$ Three phase unbalance factor
$U_{nph}$ $n$-phase unbalance factor
$V$ Voltage
$V_{lb}, V_{ln}$ Voltage line to line and voltage line to neutral
$v^+ v^- v^0$ Positive, negative, and zero sequence voltage
$V_0, V_1, V_q$ Zero sequence, positive sequence, $q$ sequence voltage
$v_{an}, v_{bn}, v_{cn}$ Phase A, B, and C voltages
VAr Volt-Ampere reactive
$V_{post}$ Postfault voltage
$V_{pre}$ Prefault voltage
$v_q$ Eigenvector
$V_{rated}$ Rated voltage
$V_{spike}$ Voltage spike
VUF Voltage unbalance factor
$w$ Weighting matrix or weight of conductor
$w_c$ Weight of conductor
$W_{ice}$ Weight of ice on a span
WECC Western Electricity Coordinating Council
WECC-09-SP Western Electricity Coordinating Council 2009 summer peak case
$X$ Reactance

$X^+ , X_I$ Positive sequence reactance

$X, X^0$ Negative and zero sequence reactance

$X_{3ph}$ Reactance matrix for a three phase transmission line

$X_m , X_s$ Mutual and self reactance

$Z$ Sequence impedance matrix of untransposed line

$Z_0, Z_I, Z_q$ Zero sequence impedance, positive sequence impedance, sequence impedances

$Z_c$ Characteristic impedance of a transmission line

$Z_m$ Mutual impedance

$Z_{m,c,k}$ Mutual impedance between conductor $c$ and $k$

$Z_{ph}$ Line impedance matrix

$Z_{ph,c,k}$ Impedance at row $c$ column $k$ of the line impedance matrix

$Z_s$ Self impedance

$Z_{seq}$ Sequence impedance matrix $diag(\lambda_0, \lambda_1, \ldots \lambda_{n-1})$

$Z_u$ Line impedance matrix of an untransposed line

$\Delta d$ Change in phase spacing distance

$\delta_{max}$ Maximum allowable bus voltage phase angle difference between bus 1 and bus 2

$\varepsilon_0$ Permittivity of free space $8.854 \times 10^{-12}$ F/m

$\lambda$ Eigenvalues

$\mu_0$ Permeability of free space $4\pi \times 10^{-7}$ H/m

$\omega$ Frequency in r/s

$\rho_{ice}$ Density of ice

$\tau$ Toeplitz matrix form

$\tau_c$ Circulant matrix form

$\theta$ Angle of conductor swing

$\phi, \varphi$ Phase

$\zeta$ Impedance vector $[Z_s, Z_m, \ldots]'$ of the first row of the transmission line impedance matrix
CHAPTER 1
INTRODUCTION TO HIGH POWER TRANSMISSION TECHNOLOGIES

1.1 Motivation and Statement of the Research Area

Electric energy demand in the long term is increasing and in the U.S. from 2012 to 2040 it is estimated that growth will be approximately 29% [1]. The increase in worldwide population especially in urban areas causes difficulties obtaining rights of way for transmission assets. Much of the transmission infrastructure is a half century to a century old and in need of upgrading. One reference states that 70% of transmission lines and transformers are more the 25 years old [2]. There is an increase in transmission and distribution congestion due to many factors including deregulation of the power industry which deferred transmission and distribution investments [2, 3]. In addition, there is an increase in natural gas and renewable generation sites causing an increase in transmission investments. Renewable portfolio standards will increase the renewable generation sites located far from load centers causing additional transmission to be constructed [4]. There are also regulations such as the Energy Policy Act of 2005 [5] and the American Recovery and Reinvestment Act of 2009 [6] which aim to promote transmission infrastructure with tax credits and methods to ease the transmission planning process. Overall between 2010 and 2030 the U.S. electric utility industry will put $1.5 to $2 trillion dollars in infrastructure investment [2].

The aim of this research is to determine innovative transmission designs to upgrade the contemporary transmission system and use new overhead transmission assets to transfer bulk power. Included in this research are three main design possibilities:
A. Compact phase spacing,

B. High temperature low sag (HTLS) conductors

C. High phase order (HPO) designs.

In addition, studies analyze possible combinations of the three concepts. The objective is to develop mathematical models, algorithms, representative designs, and applications to render these technologies to practice. A block diagram highlighting the focus of this dissertation is in Fig. 1.1.

![Block Diagram](image)

**Figure 1.1 Dissertation Emphasis**

1.2 Phase Compaction

   The basis of compact design transmission line design is to reduce the spacing between the phases. This decreases the right of way (ROW) for an overhead transmission line and results in many advantages which are explained below. However, lines can only
be compacted to a certain level. To determine the minimum allowed phase spacing for a transmission line, a number of variables need to be taken into consideration including:

- The phase to phase voltage
- Lightning surges
- Switching surges
- Maintenance issues
- The permissible sag
- Insulator configuration
- Tension vs. sag towers
- Altitude above sea level
- Span length
- Wind levels
- Icing levels
- Environmental issues.

References [7, 8] discuss these factors further and the phase spacing is often limited by local codes and standards. The National Electrical Safety Code (NESC) [9, 10] gives minimum conductor spacing for lower voltages. For higher voltages greater than 50 kV, there are minimum requirements due to the basic impulse level (BIL) and switching-surge factors as seen in Table 1.1. The minimum spacing must be found during the maximum sag and during wind and ice conditions. Table 1.2 shows typical phase spacing from existing transmission lines referenced in the Transmission Line Reference Book [8]. Many operating companies and some jurisdictions (e.g., California [11], or the U. S. Department of Agriculture [12]) have additional requirements. Realizing the legal implications of these codes and standards, it is nonetheless instructive to examine the engineering tradeoffs of compacting the phases. For example, if spacers between phases were used, or spacing down to the minimum NESC standard was utilized, it may be possible to fully realize the benefits of compact designs. Additional surge arrestors may also be beneficial to a compact transmission line.
Table 1.1 NESC Minimum Conductor Spacing Based on Switching-surge Factors
(abstracted from [9])

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Minimum conductor spacing*</th>
</tr>
</thead>
<tbody>
<tr>
<td>765 kV</td>
<td>20.8 ft</td>
</tr>
<tr>
<td>500 kV</td>
<td>11.2 ft</td>
</tr>
<tr>
<td>345 kV</td>
<td>6.4 ft</td>
</tr>
<tr>
<td>230 kV</td>
<td>6.3 ft</td>
</tr>
</tbody>
</table>

*At elevations under 1500 ft. For higher elevations, add 3% spacing for every 1000 ft above 1500 ft From NESC Table 235-4 minimum values.

Table 1.2 Typical Phase to Phase Spacing for Existing Transmission Lines
(Data taken from [8])

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Typical phase to phase spacing from existing lines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>1500 kV***</td>
<td>N/A</td>
</tr>
<tr>
<td>1200 kV***</td>
<td>N/A</td>
</tr>
<tr>
<td>765 kV**</td>
<td>45 ft</td>
</tr>
<tr>
<td>735 kV*</td>
<td>39.4 ft</td>
</tr>
<tr>
<td>500 kV</td>
<td>28.5 ft</td>
</tr>
<tr>
<td>345 kV</td>
<td>15 ft</td>
</tr>
</tbody>
</table>

*Line data from only 3 existing lines listed. ** Line data from only 4 existing lines listed. *** Directly from [8] for horizontal spacing and maximum voltage.

Compact phase design research has been focused on the need to decrease right of way, increase power transfer for a limited ROW, and decrease overall transmission line costs. The magnitude of the magnetic fields at ground level and at the edge of the right of way decrease with phase compaction [13]. The electric field for compact transmission lines decrease at the edge of the right of way (ROW) and ground level, however there is an increase in the electric field at the surface of the conductors [14, 15]. This causes an increase in the possibility of corona. The increased corona is reduced by using a high number of conductors in a bundle [16, 14] or grading ring and corona rings [17]. The corona can be further decreased with use of optimal bundle configuration and spacing [18]. In addition, phase to phase spacers at the mid-span and
V-type insulators may be utilized to prevent conductor swinging and flashovers [19]. Compact transmission lines also increase capacitance, decrease inductance, increase surge impedance loading, and increase the security rating of the transmission lines [14, 15].

A compact 500 kV transmission line was built and tested in China in 1999 [16]. The compact line used phase spacing of 19 ft vs. the traditional 35 ft (traditional range of 28 - 45 ft) and 6 bundled conductors. The line is 1.12 miles long [14]. The compact line is compared to a traditional horizontal configured 500 kV transmission line with 42 ft phase to phase spacing and a four conductor bundle. The compact line exhibits lower surge impedance, higher power transfer, uses approximately a third of the corridor width, lower electric and magnetic fields at the edge of the ROW and ground level, and has lower current and voltage unbalance. However the compact line has increased electric fields on the conductor surface, increased radio and audible noise, and increased corona and corona losses [14].

In addition, research has been done for a compact double circuit 750 kV line in China [17, 19]. A compact 500 kV transmission line was constructed in Brazil with phase spacing of 19.75 ft arranged in a triangle [14]. A compact double circuit 10 kV, one km transmission line was built in the Ukraine with 6-bundled conductors on each phase. A 115 kV compact transmission line was constructed by the Niagara Mohawk Power Corporation in 1995 [13]. All of the compact transmission lines mentioned use a delta or inverted delta conductor configuration to maximize the use of ROW and increase power density. In 1991-1992 short pilot compact transmission lines of 500 kV
and 330 kV horizontally configured using 26 ft and 18 ft phase to phase spacing and 6 and 4 bundled conductors were built in Russia after extensive research [15].

1.3 High Temperature Low Sag Technologies Literature Survey

High temperature low sag (HTLS) conductors have been installed worldwide to increase the thermal capacity of transmission lines and are typically used when reconductoring a transmission line. The first HTLS aluminum conductor composite reinforced (ACCR) conductors were commercially installed in 2005 [20]. The first U.S. installation of the HTLS aluminum conductor steel supported (ACSS) conductor was in 2007 [21]. The main difference between HTLS conductors and traditional conductor is the material used in the core of the conductor. The purpose of the different core is to improve heat handling capabilities. The different core allows for an increase in the current carrying capabilities. There are multiple types of HTLS conductors, each use different materials. Some use composite cores as discussed in [22-24], others utilize alloy reinforced metals [25, 26], and others use a steel supported gap method [27].

A typical HTLS conductor can handle 150 – 210°C continuously [23, 24, 28-30], whereas typical ACSR conductors have continuous temperature ratings of 50 - 100°C [31]. The temperature limit increase allows HTLS conductors to continuously operate at 1.6 to 3 times the current of a similar conventional conductor [32]. This increase in current is proportional to the increase in the thermal power rating. However, this increase in current comes at a dollar cost of 1.2 to 6.5 times that of a conventional conductor (see Table 1.3). In addition, HTLS conductors have an increased emergency rating where the conductors can operate at 180 – 250°C [23, 24, 28-30] vs. the emergency rating for
ACSR conductors of 100 - 150° C [31]. This allows for emergency ratings greater than the cited 1.6 to 3 times rated ampacity of ACSR conductors.

Comparing the alternatives of a single HTLS circuit versus a double circuit conventional line, HTLS may have higher $I^2R$ losses as a consequence of the higher current and slightly higher resistance. HTLS conductor operating temperatures can be in the range 80° to 250° C [33], and consequently the conductor resistance can be higher than that seen for conventional conductors when operated at higher temperatures. As an example, [33] quotes a lower conductivity of HTLS conductors in the range of 60 to 63% of that for conventional aluminum conductors (i.e., the resistance increase over conventional conductors is 1.59 to 1.67). As a further example, 3M ACCR Drake conductors have resistance of 0.1116 Ω/mi at 75°C and 0.1613 at 210°C [24]. CTC Global’s ACCC Drake conductors have resistance of 0.1065 Ω/mi at 75°C and 0.1428 at 180°C [23]. Typical ACSR Drake conductor has resistance of 0.1422 Ω/mi at 75°C and should not operate at temperatures similar to the HTLS conductors due to loss of strength and possible permanent damage to the conductor [34]. Therefore typically, HTLS conductors have lower resistance than its ACSR counterpart during equal operating conditions.

Table 1.3 Current Capacity, Cost, and Resistance for HTLS Conductors Compared to Conventional Conductors*

<table>
<thead>
<tr>
<th>Conductor type</th>
<th>Relative ampacity</th>
<th>Relative cost</th>
<th>Relative Resistance**</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCC</td>
<td>2.0</td>
<td>2.5-3.0</td>
<td>0.85</td>
<td>CTC Cable [23]</td>
</tr>
<tr>
<td>ACCR</td>
<td>2.0-3.0</td>
<td>5.0-6.5</td>
<td>0.82</td>
<td>3M [24]</td>
</tr>
<tr>
<td>ACSS/AW</td>
<td>1.5-2.0</td>
<td>1.1-1.5</td>
<td>0.98</td>
<td>Southwire [27]</td>
</tr>
<tr>
<td>ACSS/TW</td>
<td>1.7-2.0</td>
<td>1.2-1.5</td>
<td>0.90</td>
<td>Southwire [27]</td>
</tr>
<tr>
<td>GTACSR</td>
<td>1.3-2.0</td>
<td>2.0-3.0</td>
<td>0.95</td>
<td>J-Power [35]</td>
</tr>
<tr>
<td>ACIR/AW</td>
<td>1.5-2.0</td>
<td>3.0-5.0</td>
<td>1.00</td>
<td>LS Cable [26]</td>
</tr>
</tbody>
</table>

*Compared to conventional ACSR conductors [15, 28] **Comparison at 75°C
1.4 High Phase Order Transmission

High phase order was initially considered at the inception of AC power generation and transmission. Three phase designs have a distinct advantage in that with the addition of a single phase conductor over single phase counterparts, triple power transmission is possible. The general concept is attributed to Nikola Tesla [36].

High phase order, although not in use, has been significantly studied for overhead AC transmission. The literature of the field in the area of six phase technology is copious including (as examples) the economics of six phase [37], fault detection and analysis [38-43], and electromagnetic impact [44, 45]. An experimental six phase line was constructed in the 1990s in Saratoga NY, and [46-50] describes results. Brief work is also shown on an economic break-even distance for new construction and upgrading to six phase lines [47, 51]. The general study of HPO for higher phase order is less voluminous. Perhaps the seminal work on high phase order is that of Barnes [52], and reference [53] is an example of other literature.

The main advantage of HPO is the reduction of line-line (phase to phase) voltages. The advantage of HPO low phase to phase voltage is illustrated for the six phase case in which the phase to phase voltage magnitude is equal to the phase to neutral voltage magnitude. The lower phase to phase voltage allows the individual phases to be compacted, i.e., located closer together in space. The ultimate spacing limitations of the phase conductors are determined by codes (e.g., the NESC [9]), consideration of the basic impulse level (BIL), switching surges, the spacing required for live line maintenance, and physical interaction of the phase conductors. The compacted phases incur advantages
such as the increase in mutual coupling between the phases and sequence impedances shall be evaluated. Sequence impedances are evaluated for fault studies, and unbalance calculations.

It should be noted that comparison of HPO lines with three phase (3φ) circuits is complicated by issues of what parameters are to remain constant in the comparison. These parameters include the phase to phase voltage, phase to ground voltage, conductor size and ampacity, and cost. For purposes of this dissertation, voltage phase to phase, voltage phase to neutral, and phase to phase spacing are the control parameters that are varied.

As indicated above, phase to phase spacing is nominally limited by code requirements. The approach taken in the literature has been to examine modest compaction. As examples, references [16] and [54] relate to phase compaction in transmission engineering and Chapter 2 describes phase compaction in details.

The topic of HPO frequently is raised when high power level transmission with limited ROW is investigated and this is likely the most prominent use of HPO transmission. HPO should also be discussed when considering long bulk power transmission. HPO is known to have increased costs at the terminal ends of the transmission line due to extra transformer and protection considerations. However, the HPO transmission line itself is typically cheaper than that of a three phase or multicircuit three phase line. For this reason, HPO would likely be used in long line applications. The subject of high phase order transmission may also have value for cases in which the high phase order AC is applied directly to large polyphase rectifiers [55] and induction motors [56, 57]. In addition, HPO may be useful in wind farm transmission since conversion is often used between
DC and three phase AC and wind farms are often far from a load center requiring long transmission lines.

1.5 Other High Power Density Transmission Technologies

Only three technologies are discussed in detail in this thesis. However, other useful technologies should be considered when discussing high power density applications in power transmission. Several additional alternative technologies are discussed briefly in this section.

Perhaps one of the most practical technologies for high power density is high voltage direct current (HVDC). In the past two decades, HVDC has been installed worldwide for long line high power density applications [58, 59]. One of the biggest advantages for HVDC is the ability to use HVDC to connect asynchronous systems together and allow for somewhat of a firewall from cascading outages [60]. In addition, HVDC has been utilized in long distance transmission and cable applications [58]. The biggest disadvantage of HVDC is the increased cost at the terminal ends of the transmission line due to DC to AC converters, and limited technology for HVDC circuit breakers [61, 62].

Another technology to improve power transmission capacity with limited ROW is the use of flexible alternating current transmission systems (FACTS). FACTS devices are a power electronic based system that enhances the control of AC networks. In addition, FACTS devices can improve power transfer. FACTS devices typically are made of up power electronic devices to provide series or shunt compensation [63]. The biggest disadvantage of using FACTS devices is the increased cost to the system and possibly increasing the transients and harmonics in the system due to switching devices [63, 64].
Dynamic line ratings may improve the capacity of transmission lines. The basic idea is to install monitoring equipment on transmission lines of interest; the monitoring equipment takes measurements of conductor sag, temperature, wind, and other conditions to determine a more accurate real time thermal rating of the transmission line [65]. This rating is typically higher than the conservative general rating given to the transmission line during all conditions [66, 67].

Non-standard frequencies could be utilized to improve power transmission capacity. Typically power frequencies are in the range of 50-60 Hz. If lower frequencies were utilized, the transmission line reactance is reduced, capacitive charging current would decrease, and transmission line length can be increased for AC transmission. This has been specifically proposed for off-shore wind farms [68, 69], where typically underwater HVDC or AC standard frequency cables are used to connect the wind turbines to the shore. If lower frequencies, such as 20 Hz were utilized, the AC underwater cable could be approximately three times as long as typical 60 Hz cables [69]. The main disadvantage of this technology is a use of a converter is needed at the shore to convert back to standard frequency. In addition, the transformers for low frequency transmission are larger, heavier, and more expensive; however this also leads to lower core loss [69].

Transmission lines with superconducting cables are rarely used. The rudimentary idea is that liquid nitrogen system or other super cooling system would cool the conductors below their critical temperature. At this low temperature the conductors would exhibit low resistivity and incur approximately zero losses. However, the cost for the cooling system, the cooling agent, containment, the exotic conductors of sufficient cross sec-
tion to maintain superconductivity, and losses in the cooling system generally outweigh the savings [70]. In addition, the superconducting cable could potentially increase up to five times the current carrying capabilities of the conductor [71].

The idea of bulk wireless power transmission technology is to use laser transmitters or microwave transmission to send power through the air to a rectenna. The rectenna would receive the power and convert it to usable AC or DC power [72]. This has been specially proposed for solar power satellite projects, where solar panels in space would produce electricity and wirelessly send the power to a rectenna on earth [72-75].

1.6 Organization of this Dissertation

This dissertation is organized into six chapters with four chapters of research related importance. Chapters 2, 3, and 4 explain the three main ideas: phase compaction, high temperature low sag conductors, and high phase order. Chapter 5 includes an application that has been designed to help with high phase order fault analysis, transposition analysis, and electric and magnetic field analysis. The program developed in Chapter 5 was verified with mathematics and other power system analysis tools, such as PowerWorld and OpenDSS. The thesis closes with conclusions and recommendations in Chapter 6.

Appendix A contains the use cases for all the examples in the dissertation. Each use case in Appendix A contains the objective, parameters, and a brief conclusion of the example. Appendix B contains MATLAB code for the optimization program to design sequence impedances to specification using conductor arrangement and phase spacing. Appendix C contains power flow and fault simulation results for the IEEE 30 bus exam-
ple case with a comparison of double circuit three phase to six phase. Appendix D contains MATLAB code for the HPO analysis program and graphical user interface (GUI).

1.7 Overall Dissertation Contributions

This dissertation describes contributions to power transmission engineering in the area of three technologies: HTLS conductor applications, compact phase spacing for overhead transmission, and high phase order AC analysis and design. The main contributions are:

- Numerical analysis of the increase in phase angle security rating (steady state stability rating) for decrease in phase spacing for compact phase designs
- Analysis to use HTLS conductors to their full potential, including emergency operation at high current and also long term operation at high current
- Analysis to use HTLS conductors in combination with compact phase spacing
- Analysis of the increased span length afforded by HTLS technologies
- Identification of line lengths that benefit from HTLS and/or compact designs
- Numerical analysis of the sequence impedances of HPO transmission lines
- A generalized n-phase modal matrix of the line impedance matrix, written in modern notation, as a generalized symmetrical component transformation
- New innovative algorithms to calculate n-phase generalized sequence impedances
- A new optimization method to design sequence impedances to specifications for an n-phase overhead transmission line
- A generalized n-phase fault analysis method with illustrations
• New algorithms to calculate the number of fault types and number of significant fault types for \( n \)-phase systems
• A new voltage unbalance factor suitable for HPO systems, and the application of that unbalance factor to measure transposition effectiveness
• Analysis of HPO transposition, with transposition design suggestions
• An \( n \)-phase analysis of a high phase order line under open phase, steady state operation (for the purpose of reliability enhancement)
• A comparison of double circuit three phase and six phase overhead technologies, with an IEEE networked illustration
• An \( n \)-phase steady state analysis program (and GUI application) to study any fault type and any simultaneous faults on \( n \)-phase systems.
CHAPTER 2
PHASE COMPACTION

2.1 Objectives of Phase Compaction in Overhead Power Transmission

The objective of research in phase compaction is to present a method to increase power transfer capabilities without increase in ROW. An analysis of the transmission line limits is presented. Compaction allows for an increase in the surge impedance loading, increase in the steady state stability limit, while maintaining the same thermal line limit as conventionally spaced transmission lines. The aim is to show the advantages of decreasing the phase spacing to the minimal phase spacing requirements due to switching surge factors and BIL. In addition, the disadvantages are presented.

2.2 Increased Phase Angle Security Rating due to Phase Compaction

Compaction decreases the positive sequence reactance which increases the phase angle security rating of a transmission line. For purposes of this thesis, security limit (phase angle steady state stability limit) refers to

\[
P_{12} = \frac{|V_1||V_2| \sin(\delta_{max})}{X_{12}^+}. \tag{2.1}
\]

This limit does not account for voltage magnitude out of limits and it does not account for the loss of synchronism of an interconnected network upon appearance of a disturbance. Reference [76] refers to this limit as the steady state stability limit. Note that (2.1) applies to a short (i.e., lumped parameter), lossless, three phase transmission line, where \( |V_1| \) and \( |V_2| \) are the voltage magnitudes at the line terminals and \( \delta_{max} \) is the maximum tolerable voltage phase angle difference. The parameter \( X_{12}^+ \) is the positive sequence reactance.
tance of the transmission line between bus 1 and 2. The exact value of a transmission active power limit (in megawatts) that insures retention of synchronism would need to be determined by a dynamic stability study. It is possible to estimate a transmission line loading limit by specifying a conservative bus terminal voltage phase angle difference across each transmission element. This is the approximate approach taken in (2.1). The security limit is often calculated using $30^\circ$ as $\delta_{\text{max}}$ as a conservative estimate to avoid loss of synchronism [76]. In (2.1), only the active power flow due to the positive sequence voltages and currents is calculated. Unbalanced operation is not considered. The assumption is made that the only active power is attributed to positive sequence voltages and currents. In (2.1), a short, lumped, lossless model is used. It is possible to include circuit resistance to capture losses, and it is also possible to use a long line (‘hyperbolic’) model that is accurate at one frequency (e.g., 60 Hz) to calculate the power transmitted in the line. Let $P_s$ denote the power ‘sent’ for a single transmission line, and $P_R$ is used to denote the power ‘received’. The lossy long line model can be seen in Fig. 2.1 and is mathematically modeled as,

$$P_s = Re\{V_s I_s^*\} \quad \text{and} \quad P_R = Re\{V_R I_R^*\}$$

$$V_s = V_R \cosh(\gamma l) + Z_C I_R \sinh(\gamma l)$$

$$I_s = V_R \frac{\sinh(\gamma l)}{Z_C} + I_R \cosh(\gamma l)$$

$$Z_C = \sqrt{\frac{z}{y}} \quad \text{and} \quad \gamma = \sqrt{zy}$$
where $\gamma$ is the propagation constant, $Z_C$ is the characteristic impedance, $z$ is the series impedance per unit length, $y$ is the shunt admittance per unit length, and $l$ is the line length in consistent units [76]. For purposes of this section the lossless short line model is used.

\[(2.1)\]

Figure 2.1 Transmission Long Line Model

The security limit of a transmission line may also be written in terms of the SIL,

\[
SIL = \frac{|V_{\text{rated}}|^2}{\sqrt{\frac{L}{C},}}
\]

where $V_{\text{rated}}$ is the voltage rating of the transmission line and $L$ and $C$ are the inductance and capacitance of the transmission line respectively. The importance of the SIL is that if a line is loaded to its SIL rating, then the sending end voltage is equal to the receiving end. If a line is loaded over its SIL, the receiving end voltage is lower than the sending end. If a line is loaded under its SIL rating, then the receiving end voltage is higher than
the sending end. Therefore a loading level window can be determined where the receiving end voltage does not go above or below typical limits of 1.05 pu and 0.95 pu.

The security limit can also been written as,

$$P_{12} = \frac{|V_1||V_2|(SIL)\sin(\delta_{max})}{\sin(2\pi f\sqrt{LC})}$$

(2.3)

where $P_{12}$ is the maximum power flow on the transmission line, $V_1$ is the sending end voltage in per unit, $V_2$ is the receiving end voltage in per unit, and SIL is the surge impedance loading. The limit $\delta_{max}$ is the maximum allowed voltage phase angle between the terminals of the transmission line and is theoretically 90 degrees for continuous operation. In practice, the continuous operational limit is 30-35 degrees [76]. The system frequency is $f$, $L$ is the total inductance of the transmission line, and $C$ is the total capacitance of the transmission line.

Generally, long lines are limited by security constraints, whereas short lines are limited by thermal constraints, as seen in Fig. 2.2 (offered as a typical characteristic for a 3φ 500 kV horizontally configured Drake circuit). Parameters for the example in Figure 2.2 can be found in Appendix A denominated as Use Case A. Throughout this thesis all examples are attached to a Use Case, which can be found in Appendix A. In Fig. 2.2, the line is thermally limited before line length of 100 miles, but security limited for lines longer than 100 miles.
The security rating of a lossless, short transmission line is inversely proportional to the positive sequence reactance of the line. The sequence impedances of a transposed transmission line can be found from the eigenvalues of the line impedance matrix, $Z_{3ph}$. The $Z_{3ph}$ matrix is formed from the basic principle of the voltage drop in a segment of the line. $V_{line}$ is given by

$$V_{line} = \begin{bmatrix} V_{an,s} - V_{an,r} \\ V_{bn,s} - V_{bn,r} \\ V_{cn,s} - V_{cn,r} \end{bmatrix}, \quad (2.4)$$

and $I_{line}$ is simply the phase currents $\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$. For the fully transposed case, $Z_{3ph}$ is,

Figure 2.2 Line Length vs. Security and Thermal Rating Using Short Lossless Line Model: Exemplary Parameters Shown for a 3φ Drake 500 kV Line
where $Z_m$ is the mutual impedance between two conductors and $Z_S$ is the self impedance. Typically there may also be ground conductors included in the line impedance matrix in (2.5), however, using Kron reduction [77] the ground wire rows / columns in (2.5) are eliminated. The line voltage can also be calculated with,

$$V_{\text{line}} = Z_{3ph} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}. \quad (2.6)$$

The sequence impedances are determined from the eigenvalue of $Z_{3ph}$ as,

$$Z^+ = Z^- = Z_S - Z_m \quad (2.7)$$

$$Z^0 = Z_S + 2Z_m. \quad (2.8)$$

The approximate self impedance for a 60 Hz conductor can be calculated using modified Carson’s equations [77],

$$Z_S = R + j0.00202237f \left( \ln \left( \frac{1}{GMR} \right) + 7.6786 + \frac{1}{2} \ln \left( \frac{\rho}{f} \right) \right) \frac{\Omega}{\text{mile}}, \quad (2.9)$$

where $R$ is the resistance of the conductor, $f$ is the frequency in Hertz, and $\rho$ is the Earth resistivity. The geometric mean radius (GMR) is in feet and depends on the number of conductors in a bundle. The calculation of GMR depending on the number of conductors in the bundle is given in reference [76]. The approximate mutual impedance for a 60 Hz line can be calculated using modified Carson’s equations [77],

$$Z_m = j0.00202237f \left( \ln \left( \frac{1}{GMD} \right) + 7.6786 + \frac{1}{2} \ln \left( \frac{\rho}{f} \right) \right) \frac{\Omega}{\text{mile}} \quad (2.10)$$
where the geometric mean distance (GMD) is in feet and is the phase spacing equivalent. The geometric mean distance is,

\[ GMD = \sqrt[3]{d_{ab}d_{bc}d_{ac}}, \]  \hspace{1cm} (2.11)

where the distances, \( d \), are in feet. However, the positive sequence reactance in the balanced transposed 60 Hz case can be found using a simplified equation [76],

\[ Z^+ = Z_S - Z_m = R + j f \mu_0 \ln \left( \frac{GMD}{GMR} \right) = R + j 0.121314 \ln \left( \frac{GMD}{GMR} \right), \]  \hspace{1cm} (2.12)

where \( f \) is the transmission line frequency and \( \mu_0 \) is the permeability of free space. Therefore, for a 60 Hz line, to illustrate the typical reduction in positive sequence line reactance, if \( d = 30 \) ft, the nominal 0.8110 \( \Omega/\text{mi} \) decreases to 0.7269 \( \Omega/\text{mi} \) at 15 ft spacing. Using the lossless short line model \( X^+ \) is inversely proportional to active power flow in a transmission line with fixed terminal voltage phases. If a line were security rated at 500 MW and the line spacing was decreased from 30 ft to 15 ft the rating would increase by \~10.37\% to 551.85 MW. The percent decrease in positive sequence reactance for decrease in phase spacing is seen in Fig. 2.2 for parameters given in Use Case B.

Table 2.1 shows the percent increase in security rating resulting from a decrease in phase spacing for a specific design. If restrictions on phase spacing were relaxed, the line security rating would increase. In the subsequent section, the drawbacks and advantages of phase compaction are discussed.
Table 2.1 Percent Increase in Active Power Security Limit vs. Change in Phase Spacing for Different Original Phase Spacing *

<table>
<thead>
<tr>
<th>Original phase spacing</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 ft</td>
<td>4.13%</td>
<td>9.94%</td>
<td>19.88%</td>
</tr>
<tr>
<td>35 ft</td>
<td>4.21%</td>
<td>10.14%</td>
<td>20.27%</td>
</tr>
<tr>
<td>30 ft</td>
<td>4.30%</td>
<td>10.37%</td>
<td>20.74%</td>
</tr>
<tr>
<td>25 ft</td>
<td>4.42%</td>
<td>10.66%</td>
<td>21.32%</td>
</tr>
<tr>
<td>20 ft</td>
<td>4.58%</td>
<td>11.04%</td>
<td>22.08%</td>
</tr>
<tr>
<td>15 ft</td>
<td>4.80%</td>
<td>11.57%</td>
<td>23.14%</td>
</tr>
<tr>
<td>10 ft</td>
<td>5.15%</td>
<td>12.41%</td>
<td>24.82%</td>
</tr>
</tbody>
</table>

*Assumed GMR of conductor 0.0375 ft. As GMR rises, the percent increase in power transfer due to compaction rises.

In order to assess the impact of reduced spacing, note that the rate of change of positive sequence reactance $X^+$ with respect to spacing $d$ in ft is found,

$$X^+(d + \Delta d) = X^+(d) + \int_{d}^{d+\Delta d} \frac{0.121316}{d} dd$$  \hspace{1cm} (2.13)
\[ \Delta X^+ = X^+(d + \Delta d) - X^+(d) = 0.121316 \ln \left( \frac{d + \Delta d}{d} \right) \]  

(2.14)

\[ \Delta X^+ = 0.121316 \ln \left( 1 + \frac{\Delta d}{d} \right) \frac{\Omega}{m}. \]  

(2.15)

Using a Taylor series expansion for \( \ln \) around \( \Delta d = 0 \),

\[ \Delta X^+ = 0.121316 \left[ \frac{\Delta d}{d} - \frac{1}{2!} \left( \frac{\Delta d}{d} \right)^2 - \frac{1}{3!} \left( \frac{\Delta d}{d} \right)^3 - \frac{1}{4!} \left( \frac{\Delta d}{d} \right)^4 - \cdots \right] \frac{\Omega}{m}. \]  

(2.16)

Using (2.13)-(2.16), Fig 2.4 shows the change in positive sequence line reactance, illustrating reduced \( X^+ \), with decreasing phase separation. If 30 foot spacing is reduced by a certain amount in Fig. 2.4, the \( X^+ \) would decrease as depicted in this figure for parameters in Use Case B. However, the spacing is limited by the NESC standards as depicted in Table 1.1 [9].

![Figure 2.4 The Change in Positive Sequence Line Reactance, Illustrating Reduced \( X^+ \), With Decreasing Phase Separation](image-url)
2.3 Loading of Adjacent Transmission Assets

There is a potential benefit of reducing loading on critical parallel transmission circuits by phase compaction through the use of lower reactance parallel paths. There is a disadvantage in that some nearby circuits (e.g., transformers) may experience increased loading, and this increase must be accommodated.

The real example below shows the possibility of reducing loading on adjacent transmission from the use of compaction. The example is from the Western Electricity Coordinating Council (WECC) peak summer 2009 case. The example is taken from the southern California transmission network. A study is performed using PowerWorld. The three main lines under analysis are located in the Los Angeles area and power flows from buses Northridge and Rinaldi to Tarzana. During a line outage there is a transformer overload and a line near its capacity as seen in Fig. 2.5. However, if the line that is operating well under rating is compacted, more flow occurs on that line reducing the overload and the highly loaded line as seen in Fig. 2.6. Figures 2.5 – 2.6 are from the summer 2009 peak. The parameters for this example are seen in Use Case C (see Appendix A).

Note that line compaction can help alleviate congestion of an adjacent line. Compaction can be used to shift load. If the shifted load does not overload adjacent components, or if the system loading is considered in line design, compaction can be used advantageously.
Figure 2.5 Overloaded Area During Line Outage of One of the Parallel Circuits Between Rinaldi and Tarzana.

Figure 2.6 Reduced Loading Between Rinaldi and Tarzana with Compaction of the Line Between Northridge and Tarzana (see Fig. 2.5)
2.4 Additional Issues

*Increased capacitance of overhead circuits*

Phase compaction in overhead transmission circuits results in higher phase to phase capacitance. The phase to phase capacitance is proportional to the inverse of the logarithm of the spacing and geometric mean distances of the phase conductors and their images, and therefore compaction results in higher equivalent capacitance. For example,

\[
Q_{\text{per,ph}} = \omega |V_{in}|^2 \frac{2 \pi \varepsilon_0}{\ln \left( \frac{GMD}{r_e} \right)}
\]

where \( r_e \) is the equivalent radius of the conductor, GMD is the geometric mean distance of the conductors, \( \varepsilon_0 \) is the permittivity of free space, \( \omega \) is the radian frequency, and \( |V| \) is the rms line to ground voltage. The additional capacitance in a compact phase design is illustrated as follows: a transposed three phase 500 kV line with three-bundled Bluebird conductor at 18 inch bundle spacing (the original phase spacing of 40 ft horizontally configured is compacted by a factor of \( \sqrt{3} \) to 23.1 ft) and the revised transmission design is delta configured instead of horizontally configured. This reconfiguration adds 21% additional kVAR per mile to the line charging. This example is listed as Use Case D. The reliance of line charging to generate system reactive power is not a usual function of the transmission system, and therefore the Use Case D is offered only as an interesting observation. Note too that any reconfiguration of this type would require changing the disconnect switches at line terminals to accommodate the higher line charging. There is a potential resetting of protective relays and also updating of circuit breaker capability.
The increased reactive power injection into the system buses generally raises the operating voltage magnitude because most systems are operated at lagging power factor. The higher per phase capacitance effectively affords added reactive power. In some cases this is an advantage and in some cases this is a disadvantage. The increased capacitance causes higher inrush current when the line is energized. Also, the higher line charging requires additional capability in disconnect switches, and perhaps in circuit breakers.

*Higher surge impedance loading*

The increased mutual coupling increases the line capacitance and decreases the line inductance. Overall this results in lower surge impedance, and therefore higher surge impedance loading (SIL) of the line [16]. Although the higher SIL may not result in actual operating point change (note that SIL is simply an *index* or *yardstick* of the loadability of the line, and not a measure of the actual operating point), there may be advantages in long line applications. References [14, 16] state that for 500 kV compact transmission lines, the surge impedance loading is approximately 133% of similar conventionally spaced lines.

*Decreased ROW and construction benefit*

Phase compaction results in obvious reduced ROW and possible reduction of tower size. The disadvantages of reduced phase spacing include more difficult or preclusion of live line maintenance and circuit maintenance in general [13, 78]. The decreased phase spacing may be unacceptable to some operating companies and in some jurisdi-
tions – regardless of the benefits (e.g. state regulations in California [11]). The next paragraph addresses the percent decrease of ROW width further.

*Decreased electric and magnetic fields at ground level*

The electric and magnetic fields of an overhead line at ground level and at the edge of the ROW may be decreased using phase compaction [13, 16]. Reference [14] states the electric field for compact 500 kV lines reduces to 75% of conventional designs. Tower height is related to the electric and magnetic field strengths at ground level. Therefore, there may be implications of permissible lower tower height. In addition, the ROW needed to be acquired can be reduced due the reduction of the high field region (i.e. the electric field magnitude at ground level dissipates closer to the tower for compact designs) [13]. The decrease corridor width required for a compact 500 kV line in China was reduced to 31% of a conventional line, and a 500 KV compact line in Brazil allowed for a reduction to 59% of a conventional line [14].

*Corona levels and electric fields at the surface of the conductors*

Many parameters affect corona level, and compaction of conductors results in higher electric field strength between conductors, and there is simultaneous increase in corona, corona losses, and audible noise. Reference [14, 15] shows an increase in electric field at the surface of the conductor for compact 300 kV and 500 kV designs to approximately 110-113% of conventional designs. In addition, the audible noise increases to 105-114% for the compact designs [14]. This is especially important in high voltage designs. References that discuss corona implications for compact lines are [14, 15].
Voltage and current unbalance

Reference [16] reports better charging current balance among the phases for a compact 3φ experimental 500 kV line vs. a traditionally spaced line. This potentially allows lines of hundreds of kilometers to be untransposed. In addition, [14] reports less voltage unbalance for theoretical calculations of compact transmission lines and an existing 500 kV compact line in Brazil compared to traditionally spaced lines.

Decreased lightning exposure

The smaller cross-sectional footprint of the transmission circuit in the landscape view results in less lightning exposure [78].

Use of phase spacers

Phase compaction results in an obvious increase for the potential interaction between adjacent phases. The use of interphase (insulating) spacers may be used to avoid this difficulty. The design of span length may also assist in controlling phase spacing. It is often thought that an effective way to compact the spacing is to decrease the span length. This would cause the need for more towers, which companies try and minimize due to cost. Instead of adding more towers, phase spacers in the middle of the span could be utilized for the closest possible phase separation [79]. However phase spacers add expense and weight. An example is provided to show how the use of phase spacers affects the interaction between phases and allows for phase spacing reduction. The example seen in Table 2.2 is for a 345 kV transmission line with Drake conductors and a span of 900 ft in the heavy wind and ice district of the U.S. The line data for this example are taken from a representative line discussed in [8]. The heavy loading district defined by the
NESC [9] sets the horizontal wind pressure to 4 lb/ft$^2$ and the max thickness of ice on the conductor to 0.5 in. The parameters and results for this example are seen in Table 2.2. Calculations will show the maximum conductor swing with and without phase spacers and the required phase spacing.

Table 2.2 Parameters Needed to Calculate Conductor Swing and Phase Spacing

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Span</th>
<th>900 ft</th>
<th>Sag</th>
<th>45 ft</th>
<th>$w_c$</th>
<th>1.075 lb/ft</th>
<th>$d_c$</th>
<th>1.108 in</th>
<th>$r_{ice}$</th>
<th>0.5 in</th>
<th>$d_{c&amp;ice}$</th>
<th>2.108 in</th>
<th>$\rho_{ice}$</th>
<th>57 lb/ft$^3$</th>
<th>$BIL_{spacing}$</th>
<th>6.4 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated spacing</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max conductor swing without mid span phase spacers</td>
<td>$D_{swing}$</td>
<td>14.4 ft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase spacing required without mid span spacers</td>
<td></td>
<td>35.2 ft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max conductor swing with mid span phase spacers</td>
<td>$D_{swing}$</td>
<td>7.5 ft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase spacing required with mid span spacers</td>
<td></td>
<td>21.4 ft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

The cross-sectional area ‘seen’ by perpendicular wind is,

$$A_{wind} = d_{c&ice}(Span).$$  \hspace{1cm} (2.18)

However, with mid span phase spacers this area is reduced by half. The horizontal force from the wind on the span is,

$$F_{horizontal} = F_{wind} = Wind_{pressure}(A_{wind}).$$  \hspace{1cm} (2.19)
The weight of the ice on the span is,

\[ W_{\text{ice}} = \pi (\rho_{\text{ice}}) (\text{Span}) \left[ \left( \frac{d_{\text{c}} \text{ & ice}}{2} \right)^2 - \left( \frac{d_{\text{c}}}{2} \right)^2 \right]. \] (2.20)

Therefore the total weight of the span, (i.e. the downward force on the span) is,

\[ F_{\text{vertical}} = w_c (\text{Span}) + W_{\text{ice}}. \] (2.21)

The angle of conductor swing is,

\[ \theta = \tan^{-1} \left( \frac{F_{\text{horizontal}}}{F_{\text{vertical}}} \right). \] (2.22)

Therefore the distance horizontally the conductors can swing is,

\[ D_{\text{swing}} = (Sag) \sin(\theta), \] (2.23)

and the required phase spacing is,

\[ \text{Phase spacing} = 2D_{\text{swing}} + BIL_{\text{spacing}}. \] (2.24)

The phase spacers at the mid span reduce the max conductor swing to 52% of the swing without spacers. This allows for a substantial decrease in phase spacing to 61% of the phase spacing without mid span spacers. Phase spacers allow for substantial compaction without violating the NESC requirements.

Possible increase in flashovers

A disadvantage of a compact line is the possibility that the line may have more flashovers, causing more outages and reduced reliability [78]. There may be fewer lightning strikes on the line, but if lightning does strike, there is a higher chance of flashover.
For this reason more vibration dampers, phase spaces, and surge arrestors may be utilized as compared to a traditionally spaced transmission line [78]. Critical flashover voltage (CFO) is the voltage level at which 50% of the applied surges (of equal wave shape) result in flashover. The CFO is dependent on many conditions, such as weather. These variations can cause the CFO to vary by 4-5% [8]. For example, a horizontal rod to rod test [8] with spacing of 26 ft has a CFO of 2300 kV, whereas spacing of 13 ft has a CFO of 1600 kV [8].

2.5 Applications

Compact transmission designs should be considered when right of way is expensive or difficult to obtain. In addition, compact designs should be considered for long transmission lines that are security limited. Compact designs can also be used to decrease electric and magnetic fields at ground level and the edge of the right of way. Compaction can be used to increase the surge impedance loading of a transmission line. Also, compaction can be used to adjust power flow in a system. The following references give specific applications for phase compaction [13-16].

2.6 Conclusions

Compact phase spacing may provide a useful method to increase overhead transmission line power flow, SIL, and security rating while simultaneously using limited ROW. Compact designs can decrease the necessary corridor width to 31% of traditional spaced designs and decrease the positive sequence reactance to as little as 73% compared to traditionally spaced lines [14]. In addition, calculations show an increase in line capacitance to 121% of traditionally spaced lines. Phase compaction can allow for an increase
in security rating by 5-20%. In addition, compaction can allow for an increase in the SIL of a transmission line to 133% of that compared to traditionally spaced lines [14, 16]. Compaction can also be used to redirect power flow in a more advantageous way to reduce loading of certain assets. The electric field at ground level can be decreased to 74% of a traditionally spaced line. In addition, the magnetic fields may be reduced. There are at least two references [13, 14] that purpose that voltage and current unbalance decrease with phase compaction. Phase compaction affords reduced lightning exposure and smaller tower size. In addition, an increase in line capacitance from compaction causes higher charging current. Also, compact designs are discussed in both Chapters 3 and 4. Chapters 3 and 4 analyze technologies that may allow for phase compaction.
3.1 Increased Thermal Rating Using HTLS Conductors

High temperature low sag (HTLS) conductors can tolerate increased temperatures without excessive sag as compared to ACSR conductors. This directly increases the current handling capabilities of the transmission line and therefore increases the thermal rating of a transmission line. HTLS conductors increase the continuous rating and the emergency rating compared to ACSR conductors. HTLS conductors can operate continuously at 150-210°C and in emergency at 180-250°C (depending on the HTLS conductor). ACSR conductors operate continuously at 50-110°C and in emergency conditions at 110-150°C depending on the utility, line, and location [31]. These ratings can be seen in Table 3.1. Most HTLS conductors are used in the U.S. because the ACSR conductor does not have high enough emergency ratings for contingencies, and the utility may violate N-1. Therefore the utility may reconductor to HTLS to boost the emergency rating. The line still operates regularly at 75-110°C, but now has an emergency rating of 180-250°C. However, the line could operate at 150-210°C continuously if need be. In the U.S. operating at high temperatures is unusual because the losses increase substantially [80]. However, in other countries that have a more difficult time acquiring new ROW for overhead transmission; they operate the HTLS conductors at high temperatures continuously [81].

Usually there is an emergency rating 1 (E1) and emergency rating 2 (E2) and these ratings and concomitant permissible durations of operation can vary between operating companies. Some HTLS manufacturers give temperature ratings for continuous operation
and emergency operation (only one emergency temperature is usually given by the manufacturer). These operating temperatures are higher than those permitted for ACSR conductors (see Table 3.1). Some (perhaps many) HTLS manufacturers appear not to specify emergency ratings in terms of ampacity, but instead, in terms of operating temperature. When emergency operating temperatures are specified, the permissible duration of operation at elevated temperature is often not specified. Some references state that the emergency temperature rating is allowed for a certain number of hours cumulative over the life of the conductor, e.g., 1000 hours for ACCR [24], 10000 hours for ACCC [23].


Table 3.1 Thermal Continuous and Emergency Rating for Different Conductors

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Continuous rating</th>
<th>Emergency rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACSR [31]</td>
<td>50-110°C</td>
<td>80-150°C</td>
</tr>
<tr>
<td>ACCC [23]</td>
<td>180°C</td>
<td>200°C</td>
</tr>
<tr>
<td>ACCR [24]</td>
<td>210°C</td>
<td>240°C</td>
</tr>
<tr>
<td>ACSS [29, 28]</td>
<td>200°C</td>
<td>230-250°C</td>
</tr>
<tr>
<td>ACSS/TW-HMS [28]</td>
<td>200°C</td>
<td>240°C</td>
</tr>
<tr>
<td>GTACSR [28]</td>
<td>150°C</td>
<td>180°C</td>
</tr>
<tr>
<td>STACIR [28, 30]</td>
<td>210°C</td>
<td>240°C</td>
</tr>
<tr>
<td>TACIR [28]</td>
<td>150°C</td>
<td>180°C</td>
</tr>
</tbody>
</table>

3.2 HTLS with Compact Designs

Consider a line that is reconducted using HTLS. Once reconducted to HTLS, it is possible that the limiting factor for the transmission line will no longer be the thermal limit, but instead the steady state stability limit (defined as the ‘security limit’ for purposes of this thesis). Further, the line that was reconducted with HTLS technology will sag less, and there is the opportunity to use phase compaction to further raise the line rat-
ing. The cited advantage would be a salient advantage in case that the artifact line is the limiting element in an N-1 security assessment.

As stated earlier, long lines are generally limited by security constraints, whereas short lines are often limited by thermal constraints. For discussion purposes, consider that a transmission upgrade decision has been made for a given line. Perhaps an N-1 security analysis was used to identify the line for upgrading; however, further consider that only HTLS and possibly a combination of HTLS and phase compaction shall be used for the upgrade. To illustrate the approximate line lengths that favor HTLS and compact designs or a combination of the two, see Fig. 3.1 and Table 3.1. For example purposes, typical line data were used from examples in [8]. Voltages of 230, 345, and 500 kV are analyzed. A Drake conductor is illustrated. The HTLS Drake conductor current rating is twice that of the ACSR Drake. Bundles of 2, 2, and 3 are used respectively for the three voltages illustrated. A bundle spacing of 1.5 ft and a conventional (not compacted) phase spacing of 20, 25, and 35 ft are used. Let the compacted phase spacing be one-half of conventional spacing. For this example, let the security limit be calculated using 30° bus voltage phase angle difference. This example is Use Case E (see Appendix A). Figure 3.1 illustrates the limits for a 500 kV line. The graph includes the thermal and security limits for the conventional conductors, the HTLS design thermal limit, and the compact design security limit. From Fig. 3.1, Table 3.2 is obtained indicating the line lengths at which HTLS and compact designs are favored. Much of this section was published in [82].
Figure 3.1 Normal Limits and Limits with HTLS or Compact Designs for a Typical Triple Bundle Drake at 18 in. 500 kV Line

Table 3.2 Line Length Favoring HTLS and / or Compact Designs *

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Lengths favoring HTLS (mi)</th>
<th>Lengths favoring HTLS / compact designs (mi)</th>
<th>Lengths favoring compact designs (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>$l &lt; 33$</td>
<td>$33 &lt; l &lt; 77$</td>
<td>$77 &lt; l$</td>
</tr>
<tr>
<td>345</td>
<td>$l &lt; 47$</td>
<td>$47 &lt; l &lt; 108$</td>
<td>$108 &lt; l$</td>
</tr>
<tr>
<td>500</td>
<td>$l &lt; 48$</td>
<td>$48 &lt; l &lt; 112$</td>
<td>$112 &lt; l$</td>
</tr>
</tbody>
</table>

*Under the assumed conditions of Use Case E and as stated in the text above

HTLS conductors can benefit compact designs; for example an ACCC conductor sags approximately 31% compared to that of an ACSR conductor at 100°C [22]. In addition, if the ACSR conductor operates at a max of 100°C and the ACCC conductor oper-
ates at a max of 180°C the ACCC conductor will still sag approximately 35% compared to the ACSR conductor. This reduction in sag applied to the example in Section 2.4, Table 2.2, and equations (2.18)-(2.24) allows for a reduction in phase spacing from 35.4 ft to 16.6 ft, a reduction to 47% of the traditional spacing.

Several transmission operating companies have used HTLS conductors, reconductoring old circuits identified for higher power capacity and higher emergency ratings. Alternatives for raising the line thermal rating include:

A. Add an additional conductor to the tower
B. Add a second circuit on a separate tower
C. Reconductor to a higher ampacity (larger) conductor
D. Reconductor the old circuit to HTLS
E. Raise the voltage.

A total network reconfiguration is also possible. These options are compared in Table 3.3. Note that in Option D, reconductor to HTLS could be a good option to improve the thermal rating because reconductoring to HTLS can use the existing towers and the line would be out of service for a short period. As an example, Southern Company reconducted a 16 mile line to HTLS. Construction took ten weeks [80]. In that case, the cost of the HTLS conductor was assessed as tolerable considering labor costs, outage time (and costs), tower costs, and ROW cost. The line was reconducted to be able to handle the increases current on the line during N-1 contingencies.
Table 3.3 A Comparison of Four Options for Overhead Transmission Upgrades

<table>
<thead>
<tr>
<th>Option</th>
<th>Favorable to this option</th>
<th>Unfavorable to this option</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Lowers circuit $X^+$, higher power transfer</td>
<td>Added weight may not be tolerated by structure or clearances</td>
</tr>
<tr>
<td>B</td>
<td>May retain original circuit in service during construction</td>
<td>High cost, longer construction time, wide ROW</td>
</tr>
<tr>
<td>C</td>
<td>Short reconductoring time, low cost ACSR</td>
<td>Potential problem in supporting a larger conductor, and clearances</td>
</tr>
<tr>
<td>D</td>
<td>Allows use of same towers, short reconductoring time</td>
<td>High cost for HTLS conductor</td>
</tr>
<tr>
<td>E</td>
<td>Lowers the line losses</td>
<td>Cost for upgrading equipment at the terminal ends of the line (especially transformers) and possible need to change towers, insulators, and phase spacing</td>
</tr>
</tbody>
</table>

3.3 HTLS to Increase Span Length

HTLS conductors have decreased sag compared to ACSR conductors. If a transmission line utilizes HTLS conductors, and is no longer thermally limited, but steady state stability limited, the conductors will not be operated at high currents or high temperatures. Therefore the transmission line sags less with the HTLS conductor than a traditional conductor. In Section 3.2, it states that decreased sag could allow for compaction of the phases. In this section instead of compacting the phases, the span length is increased due to the conductors decreased sag as seen in Fig. 3.2. This subject is briefly discussed in [83]. This is especially interesting because one of the largest costs of a new transmission line is the towers, so increasing the span length may decrease the required number of towers built. This idea may show an economic advantage that all new long transmission lines should use HTLS conductors. The economic trade off in question is
whether the increase cost of the conductor would be less than the decreased cost from fewer towers.

![Diagram of HTLS conductor and ACSR conductor with equal sag](image)

*Figure 3.2 Utilizing HTLS Reduced Sag Characteristics to Increase Span Length*

A case study is formed to show this idea and discuss building a new high voltage long transmission line with HTLS conductors instead of traditional ACSR conductors. The data for the case study is in shown in Table 3.4 and is Use Case F. The HTLS conductor analyzed in this example will be the aluminum conductor composite core (ACCC). Three cases will be compared and can be seen in Table 3.4.

Note that typically clearance is the limiting factor for span length [83]. However, span length could also be limited by phase spacing (blowout and interaction of phases), or conductor weight and strength. The foregoing results assume the limiting factor is clearance and do not include the potential impact of ‘blowout’ or lateral swing of conductors due to wind loading, or tower violations of conductor strength and weight.

The three cases shown in Table 3.4 are chosen because Cases 1 and 3 have the same cross sectional area and nearly the same resistance and Case 2 and 3 have the nearly the same diameter and weight.
Table 3.4 Conductor Parameters for HTLS Span Length Comparisons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (in)</td>
<td>1.246</td>
<td>1.108</td>
<td>1.110</td>
</tr>
<tr>
<td>Cross section area (in²)</td>
<td>0.916</td>
<td>0.727</td>
<td>0.916</td>
</tr>
<tr>
<td>Resistance @75°C (Ω/mi)</td>
<td>0.1114</td>
<td>0.1389</td>
<td>0.1065</td>
</tr>
<tr>
<td>Resistance @180°C (Ω/mi)</td>
<td>NA</td>
<td>NA</td>
<td>0.1428</td>
</tr>
<tr>
<td>Ampacity (A)</td>
<td>1047</td>
<td>907</td>
<td>1706</td>
</tr>
<tr>
<td>Tensile strength (lbs)</td>
<td>36,600</td>
<td>31,500</td>
<td>41,200</td>
</tr>
<tr>
<td>Conductor weight (lb/ft)</td>
<td>1.331</td>
<td>1.093</td>
<td>1.052</td>
</tr>
<tr>
<td>Linear coefficient of expansion (°C)</td>
<td>$19.4 \times 10^{-6}$</td>
<td>$18.9 \times 10^{-6}$</td>
<td>$1.61 \times 10^{-6}$</td>
</tr>
<tr>
<td>Elastic modulus (psi)</td>
<td>$9.7 \times 10^6$</td>
<td>$10.9 \times 10^6$</td>
<td>$16.3 \times 10^6$</td>
</tr>
</tbody>
</table>

An illustrative example will show numeric values for the increased span length using HTLS conductors. A long flat transmission line is to be designed for normal operation of 900 A per phase ampacity. The maximum allowed sag is 30 ft and the transmission line will be built with 18% horizontal tensile strength.

The calculated spans for the three cases are 1091, 1117, and 1303 feet (seen in Table 3.5) using,

$$span \ length = \frac{2H}{w} \cosh^{-1}\left(\frac{Sw}{H} + 1\right),$$

where $S$ is the maximum allowed sag, $H$ is the horizontal tension, and $w$ is the weight per foot. This means that the HTLS ACCC transmission line (Case 3) will require 16.2% fewer towers than Case 1 and 14.2% fewer towers than Case 2.
Table 3.5 Results of HTLS vs. ACSR to Increase Span Study

<table>
<thead>
<tr>
<th></th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conductor type</strong></td>
<td>ACSR Curlew</td>
<td>ACSR Drake</td>
<td>ACCC Drake</td>
</tr>
<tr>
<td>Span length needed for maximum 30 ft sag</td>
<td>1091</td>
<td>1117</td>
<td>1303</td>
</tr>
<tr>
<td><strong>% of towers needed in construction</strong></td>
<td>116.3 %</td>
<td>114.3 %</td>
<td>100 %</td>
</tr>
<tr>
<td>% losses when operated at equal current</td>
<td>104.6 %</td>
<td>130.4 %</td>
<td>100 %</td>
</tr>
<tr>
<td><strong>Continuous ampacity (A)</strong></td>
<td>1047</td>
<td>907</td>
<td>1706</td>
</tr>
<tr>
<td>Emergency rating temperature</td>
<td>~110°C</td>
<td>~110°C</td>
<td>200°C</td>
</tr>
<tr>
<td><strong>Conductor cost</strong></td>
<td>~1.25</td>
<td>1.0</td>
<td>~2.75</td>
</tr>
</tbody>
</table>

Table 3.5 shows a significant decrease in the losses for HTLS, significant decrease in the towers needed, and a significant increase in the emergency rating of the conductor. However, there is a significant increase in cost for HTLS over the ACSR counterparts. A lifetime conductor cost comparison would need to be completed similar to work using reference [84] and [85].

3.4 Illustrative Applications

The software PowerWorld [86] for the WECC 2009 summer peak case (WECC-09-SP) was used to simulate steady state cases with HTLS, compact designs, and a mixture of the two. For example purposes, two separate circuits will be analyzed; one is a short line in the Los Angeles area, Rinaldi – Tarzana seen in Appendix A as Use Case C; and one is a long line in Wyoming and Idaho, Bridger – West called Use Case G. In practice, HTLS has been used primarily on short lines for thermal rating upgrade. However, a long line is also considered for study purposes. For these lines, two cases were analyzed: the case that the lines are reconductored to HTLS, and the case that the lines are reconductored to HTLS with compact phase spacing.
Short line in Southern California, North - Tarzana.

The double circuit line between buses Rinaldi and Tarzana is approximately 9.7 miles long, and 230 kV. The line is located in Los Angeles, CA seen in Figure 3.2. In addition, a similar 230 kV line from Northridge to Tarzana will be reconductored. These three lines service a 693 MW load at the Tarzana bus (WECC-09-SP). In Table 3.6 – 3.8 the maximum acceptable load at Tarzana is indicated. These load levels are the highest load Tarzana can attain without voltage or line load violations. It is observed that in the N-2 case, North – Tarzana is not the limiting element: instead, Sylmar – Northridge, a nearby 230 kV line is the first to exhibit a violation, namely a line load thermal limit. For this reason the maximum acceptable load at Tarzana is approximately 205 MW for all three cases under N-2 analysis.

1. **Base case** (existing construction)

   In the base case there are no voltage or line load violations with all circuits in service, and the three lines (double circuit Rinaldi - Tarzana and Northridge-Tarzana) are loaded to a maximum of 62%. However, under N-1 conditions, a bus tie at Rinaldi is overloaded and the 230 kV circuits from Rinaldi to Tarzana are loaded 92%. Under N-2 conditions, the double circuit Rinaldi - Tarzana is far above thermal rating at 141%.

2. **Reconductored to HTLS**

   Once the three lines are reconductored, the violations are alleviated in the N -1 case. This allows for a potential increase in the load at Tarzana, namely from 693 to 1583 MW.
3. HTLS and compact spacing

The Rinaldi – Tarzana 230 kV double circuit and Northridge - Tarzana are recon ductored to HTLS and the phases are compacted. The thermal rating will increase by 1.5 times that of the conventional conductor (as compared with the double ampacity rating if compact design is not used). This is such that the line will sag 50% less than that of a conventional conductor and still have 50% increased ampacity. Since the line sags less, the phases can be compacted. The phases will be compacted from ~30 ft to 22.5 ft. This will increase the power flow on the lines by 3.6%, or 25 MW at peak summer 2009 load.
The results of reconductoring these lines are shown in Tables 3.6 – 3.8. Reconductoring these three lines would increase the power consumption capacity of Tarzana by 380% in the N-1 case for no violations (i.e. no bus voltages out of ±5% and no lines
overloaded). However, the most benefit comes from HTLS plus compact design. Once reconductored to HTLS and compacted, the line has almost all the benefits of a purely HTLS line, with many other benefits such as: increased power transfer on the compacted lines and reduced thermal loading on neighboring lines. If new towers were built, there may be some advantages in smaller towers and narrower ROW.

*Long line in Wyoming and Idaho, Bridger - West*

From the WECC critical path report [87] approximately 60 circuit paths were identified as bottlenecks in the WECC system. One of these paths is selected here for simulation to study the potential HTLS and / or compact design enhancements utilizing the WECC-09-SP case. For example purposes, the 345 kV lines between the Jim Bridger Generating Station in Wyoming, and the Populus and 3 Mile Knoll substations in Idaho were chosen for reconductoring seen in Figure 3.4. This circuit path is identified in [87] as a critical path that is a bottleneck in the western interconnection because under line outage contingencies, the phase angle stability may be compromised. The solution to the stability problem has been the design and use of a remedial action scheme (RAS). The RAS takes system actions to retain phase angle stability during line outages. Utilizing the RAS allows the Jim Bridger plant to operate at its maximum output of 2,200 MW, without the RAS, the plant would need to reduce to 1,300 MW. The RAS is described in [88]. The three lines in the cited path are approximately 190 miles long seen in Figure 3.3, are assumed to be heavily loaded, and have caused problematic operating conditions in the past [89].
Figure 3.4 Transmission Path ~190 Miles Long From Jim Bridger Plant in Wyoming to Populus Substation in Idaho

For example purposes, the HTLS conductor will result in twice the ampacity of the conventional conductor presently in place. The values in Table 3.9 – 3.11 illustrate the results of reconductoring and utilization of phase compact design. Note the following:

1. **Base case** (present construction)

   During the base summer peak 2009 case, the Bridger – Populus lines are loaded approximately 78% of rating. However, in an $N$-1 case (one of the three 345 kV lines is out), the lines are thermally loaded to approximately 113% of rating. In the case where two of the three 345 kV lines are out of service (the $N$-2 case), the remaining line is loaded 229% with voltage as high as 1.41 pu at the Bridger bus.

2. **Reconductored to HTLS**

   Again consider the same Bridger – Populus circuits. If the lines were reconductored using HTLS conductors, reconductoring would double the thermal ratings. HTLS
design reduces the thermal loading to levels of 56% and 114% during the N-1 and N-2 cases respectively; much improved as compared to the base case with corresponding thermal loads 113% and 229% respectively. However, reconductoring to HTLS on such a long line would be extremely expensive and the cost would likely outweigh the advantages.

3. HTLS and compact spacing

Consider the case where the three lines are reconductored to HTLS and the phases are compacted. The thermal rating of the HTLS line increases by 1.5 times that of the conventional conductor (as opposed to double the thermal rating which would be expected in a conventionally spaced HTLS line). The 150% thermal rating is applied such that the line sags 50% less than that of a conventional conductor and has 50% increased ampacity. Since the line sags less in the HTLS construction, the phases can be compacted. For this study, the phases are compacted from ~35 ft to 26 ft. In the study case, compaction decreases the positive sequence reactance of the line by 3.6%.

Table 3.9 Base Case WECC-09-SP Results for Lines From Bridger – West

<table>
<thead>
<tr>
<th></th>
<th>No outage</th>
<th>N-1</th>
<th>N-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridger voltage</td>
<td>1.07 pu</td>
<td>1.15 pu</td>
<td>1.41 pu</td>
</tr>
<tr>
<td>End of line voltage</td>
<td>1.03 pu</td>
<td>1.01-99 pu</td>
<td>0.89 pu</td>
</tr>
<tr>
<td>Bridger line MVA</td>
<td>78%</td>
<td>113%</td>
<td>229%</td>
</tr>
<tr>
<td>End of line MVA</td>
<td>74%</td>
<td>98%</td>
<td>152%</td>
</tr>
<tr>
<td>Security angle difference</td>
<td>17.2°</td>
<td>21.3°</td>
<td>29.5°</td>
</tr>
</tbody>
</table>
Table 3.10 HTLS Case WECC-09-SP Results for Lines From Bridger – West

<table>
<thead>
<tr>
<th></th>
<th>No outage</th>
<th>N-1</th>
<th>N-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridger voltage</td>
<td>1.07 pu</td>
<td>1.15 pu</td>
<td>1.39 pu</td>
</tr>
<tr>
<td>End of line voltage</td>
<td>1.03 pu</td>
<td>1.01-99 pu</td>
<td>0.88 pu</td>
</tr>
<tr>
<td>Bridger line MVA</td>
<td>39.0%</td>
<td>56.4%</td>
<td>114.4%</td>
</tr>
<tr>
<td>End of line MVA</td>
<td>37.1%</td>
<td>49.2%</td>
<td>75.8%</td>
</tr>
<tr>
<td>Security angle difference</td>
<td>16.1</td>
<td>21.3</td>
<td>29.6</td>
</tr>
</tbody>
</table>

Table 3.11 HTLS Compact Designs Case WECC-09-SP Results for Lines From Bridger – West

<table>
<thead>
<tr>
<th></th>
<th>No outage</th>
<th>N-1</th>
<th>N-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridger voltage</td>
<td>1.07 pu</td>
<td>1.15 pu</td>
<td>1.45 pu</td>
</tr>
<tr>
<td>End of line voltage</td>
<td>1.03 pu</td>
<td>1.02 pu</td>
<td>0.91 pu</td>
</tr>
<tr>
<td>Bridger line MVA</td>
<td>53.2%</td>
<td>76.6%</td>
<td>158.2%</td>
</tr>
<tr>
<td>End of line MVA</td>
<td>50.6%</td>
<td>66.6%</td>
<td>103.9%</td>
</tr>
<tr>
<td>Security angle difference</td>
<td>18.2</td>
<td>22.4</td>
<td>31.2</td>
</tr>
</tbody>
</table>

Reconductoring to HTLS helps the thermal rating of the line extensively. However, with HTLS and compact designs, the line receives much of the benefit from HTLS with an increased power flow on the lines, reduced thermal loading on neighboring lines, smaller towers, and less use of ROW.

3.5 Thermal vs. Dynamic Improvements Afforded by HTLS Conductors and Compact Phase Spacing

Consideration now turns to the dynamic response of systems with overhead transmission for the cases of reconductoring with HTLS and / or compact phase spacing. Note that the illustration in Section 3.4 for the Rinaldi -Tarzana 230 kV line is a case of a short line. As shown in Fig. 3.1, short lines are generally thermally limited. To illustrate the dynamic consequences of reconductoring, consider only the Bridger West critical
The Bridger West critical path is illustrated in Figure 3.4 with the path location illustrated in Figure 3.3. Note the series compensated segment of the Bridger – Three Mile Knoll line.

![Diagram of Bridger – West Critical Path in Idaho and Wyoming]

Figure 3.5 Pictorial of the Bridger – West Critical Path in Idaho and Wyoming

Consider three cases in which alteration of the present design occurs in the Bridger to Three Mile Knoll 345 kV circuit. This is one of three critical circuits from the Jim Bridger power plant, and this circuit is series compensated. The three cases considered are: (1) present construction; (2) HTLS plus compaction of spacing by 25%; and (3) HTLS plus compaction to 50% spacing as compared to the original design plus the addition of a new Bridger – Three Mile Knoll circuit as shown in Figure 3.5. In Case 3, it is assumed that the use of HTLS allows the compaction of the phase spacing so that the original ROW need not be widened. For purposes of evaluating the dynamic response, two double line outage contingencies are studied. The two double line outage contingencies are:

- Bridger to Three Mile Knoll 345 kV plus Bridger to Populus (1)
- Bridger to Three Mile Knoll 345 kV plus Bridger to Populus (2).
The cases studied have an actual power transfer along this critical WECC path of 1181 MW from East to West. The cases studied are for the 2020 summer peak load condition. In these cases, the calculated transfer limit along the Bridger West critical path is 2200 MW from East to West. This critical path is studied using the Positive Sequence Load Flow (PSLF) and Transient Security Assessment Tool (TSAT) analysis packages, commercially available software tools in common use in the electric power industry today. The case study results are shown in Table 3.12.

**Table 3.12 Results of Dynamic Studies for Three Cases of Double Line Outage Contingencies (Bridger West Critical Path) [90]**

<table>
<thead>
<tr>
<th>Double line outage contingency #1</th>
<th>Limitation</th>
<th>Transient voltage dips and voltage violations</th>
<th>Transient voltage dips and voltage violations</th>
<th>Transient voltage dips and voltage violations</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSAT solution characteristics</td>
<td>Case 1: present construction</td>
<td>Bus voltage oscillations: 0.93 Hz mode damped at 2.9%; 1.67 Hz mode damped at 5.5%</td>
<td>Bus voltage oscillations: 0.93 Hz mode damped at 2.9%; 1.67 Hz mode damped at 5.5%</td>
<td>Bus voltage oscillations: 0.93 Hz mode damped at 3.14%; 1.67 Hz mode damped at 6.28%</td>
</tr>
<tr>
<td>Case**</td>
<td>Case 2: HTLS reconductoring plus compact phase spacing by 25%*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3: HTLS + compact phase spacing to 50% plus new circuit addition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note that the HTLS construction does not materially modify the circuit reactance, and therefore the dynamic response is about the same as for the present construction.
**The contingency #2 gives the same results as contingency #1.

Note that in the results shown in Table 3.12 do not include the actions of RASs. For this circuit, a triple modular redundant programmable logic controller is used to obtain a generator trip or capacitor insert / bypass signal. These control actions would obviate the instability and poor damping shown in Table 3.12. Because the RASs are not implemented in TSAT and PSLF simulations, the problematic conditions shown in the table
occur. The purpose of the RASs in this application is to make the circuit IEC 61131-3 compliant. A full description of the RASs used for Bridger West appears in [88]. Note that the two double line outage contingencies are nearly identical because the circuit reactance is very similar. Inspection of Table 3.12 shows that two critical modes that occur during a line outage contingency are better damped in Case 3. It appears that the advantages of Case 3 are that the damping of critical modes is enhanced and the addition of a new 345 kV circuit can be accomplished without widening the existing ROW.

The foregoing example relates to a long line of 190 miles. The issue of high cost of HTLS conductors needs to be recognized as a serious consideration in a practical transmission engineering environment. While the high cost of HTLS may be quantified from presently available data, it is more difficult to quantify the benefits such as increased line capacity. Tokombayev in [91] does this cost / benefit analysis assuming the value of power marketing and representative transmission construction costs. Uncertainty in the data used for this cost / benefit analysis is high, and in view of present transmission practice in the United States, it is unlikely that a 190 mile circuit would be reconducted with HTLS.

3.6 Applications

The prominent application for high temperature low sag conductors is to reconductor existing lines to improve N-1 system performance. In addition, HTLS may be used to reconductor to increase the continuous and the emergency rating of a transmission line. In the present environment, HTLS conductors will be used mostly on short thermally limited lines. HTLS can also be used for specific spans where sag and clearance are the main
issues. Another application for HTLS conductors is to increase the emergency rating of a transmission line while simultaneously increasing the span length and/or decreasing sag. In addition, HTLS conductors can be used in compact line designs to help prevent blow-out.

HTLS conductors could be used for economic reasons to increase power capacity to a certain location for power marketing. If a transmission line thermal rating is a limiting factor in economic dispatch, an upgrade to HTLS may improve the operating cost. Thus HTLS conductors could be used to relax thermal constraints of selected transmission lines to allow for a decrease in overall operating costs. A method to determine which transmission lines are identified for upgrading would be to run an $N$-1 security assessment, determine if transmission congestion is a limiting factor, and perform a cost to benefit study [131].

3.7 Conclusions

High temperature low sag conductors are advantageous in increasing the thermal capacity of a transmission line up to twice that of traditional conductors. HTLS conductors can be advantages in reconductoring applications due to short reconducting time and use of the existing towers, in addition to increased power marketing capabilities [91]. HTLS conductors have decreased sag characteristics of up to 33% compared to traditional ACSR conductors at 100°C and up to 22% at 180°C [22]. HTLS conductors can also be advantageous to indirectly increase the security (steady state stability) rating of a transmission asset by utilizing the decreased sag to compact the phases. Using HTLS conductors to compact phases depends on many factors, however for typical high voltage con-
struction (existing lines with data given in [8]), the phase spacing can be reduced to approximately 47% using ACCC conductors compared to traditional designs with ACSR conductors. HTLS conductors may be used to increase the span length for new transmission construction up to approximately 115% of that of an ACSR conductor, and therefore decrease the number of towers necessary. Line lengths beneficial for HTLS, HTLS plus compaction, and compaction are presented for exemplary cases. For typical lines (e.g., existing 230 – 500 kV lines with data given in [8]), lengths under 48 miles can benefit from upgrade to HTLS; lengths between 33 and 112 miles can benefit from HTLS with compact designs; and lengths longer than 77 miles can benefit from compact designs. The line lengths cited are dependent on a number of application factors, and the conclusions are for illustration only. In addition, examples are analyzed using PowerWorld and TSAT for the use of HTLS and compaction where advantages and disadvantages for both the static and dynamic cases are studied. The dynamic damping improvement from compaction with HTLS was found to be minor.
CHAPTER 4
HIGH PHASE ORDER TRANSMISSION DESIGNS

4.1 Basic Voltage Relationships

For a balanced polyphase system of \( n \)-phases, the phase to phase and phase to neutral voltage magnitudes, \( |V_{ll}|, |V_{ln}| \) are given by,

\[
|V_{ll}| = |V_{ln}| \sqrt{2 \left(1 - \cos \left(\frac{360}{n}\right)\right)}
\]  

(4.1)

where \( n \) is the number of phases. Equation (4.1) is a consequence of the application of the law of cosines to the triangle in Fig. 4.1.

![Figure 4.1 The Relationship between \( V_{ll} \) and \( V_{ln} \) For \( n \)-phase Systems](image)

Useful phase line to line and line to neutral relationships are shown in Table 4.1. The lower phase to phase voltage magnitude at higher phase orders allows for reduced insulation requirements between phases. In this sense, for HPO, a more compact line can be constructed.

With the use of HPO the lower phase to phase voltage leads to a compaction benefit and/or power transfer benefit. For the same phase ampacity in comparison circuits, a 500 kV double circuit 3\( \phi \) line will carry the same power as a 288.7 kV 6\( \phi \) line. In addi-
tion, the 6φ line can be compacted by \(\sqrt{3}\) thus decreasing the required ROW. It can be also be noted that a 230 kV (\(V_{ll}\)) double circuit 3φ line could be converted to a 398 kV 6φ line allowing for a 73% increase in power capacity on that line using the same ROW.

Table 4.1 Comparison Equations for Voltage Line to Line vs. Voltage Line to Neutral

<table>
<thead>
<tr>
<th>Phases</th>
<th>Voltage line to line and line to neutral comparison*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>(V_{ll} = \sqrt{3}V_{ln} \leq 30^\circ)</td>
</tr>
<tr>
<td>6</td>
<td>(V_{ll} = V_{ln} \leq 60^\circ)</td>
</tr>
<tr>
<td>12</td>
<td>(V_{ll} = 0.5176V_{ln} \leq 75^\circ)</td>
</tr>
<tr>
<td>18</td>
<td>(V_{ll} = 0.3473V_{ln} \leq 80^\circ)</td>
</tr>
</tbody>
</table>

\[ V_{ll} = V_{ln} \sqrt{2 \left(1 - \cos \left(\frac{360}{n}\right)\right)} \angle \left(90^\circ - \frac{180^\circ}{n}\right) \]

*The phase angle indicates for the line to line voltage between phases 1 and 2 where \(V_{ln}\) in phase 1 is the reference phasor.

4.2 Converting Multicircuit Three Phase to HPO

If a multicircuit three phase transmission line is in need of increase power capacity, one viable option is to convert from multicircuit three phase to HPO. Additional transformers may be needed to upgrade from multicircuit three phase to HPO. The additional transformers add obvious expense; however there is a significant increase in power capacity on the transmission line due to an increase in the voltage line to neutral. The increase in voltage line to neutral is permissible without increasing the voltage line to line. The increase in voltage line to neutral causes an increase in the transmission line power capacity (see Table 4.2). The increase in voltage line to neutral increases both the thermal limit and the security limit of the transmission line.
Table 4.2 Increase in Transmission Power Capacity for HPO vs. Multicircuit Three Phase

<table>
<thead>
<tr>
<th>Phases</th>
<th>Percent increase in transmission line power capacity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>6φ vs. 2 - 3φ</td>
<td>73.2%</td>
</tr>
<tr>
<td>9φ vs. 3 - 3φ</td>
<td>153.2%</td>
</tr>
<tr>
<td>12φ vs. 4 - 3φ</td>
<td>234.6%</td>
</tr>
<tr>
<td>18φ vs. 6 - 3φ</td>
<td>398.8%</td>
</tr>
<tr>
<td>nφ vs. n/3 - 3φ</td>
<td>( \left( \frac{1}{\sqrt{\frac{2}{3} \left( 1 - \cos \left( \frac{360}{n} \right) \right)} - 1} \right) \times 100% )</td>
</tr>
</tbody>
</table>

*The increase in power capacity is from an equivalent increase in voltage line to neutral.

The increase power capacity in Table 4.2 should not require any extra right of way (or minimal extra ROW [92]), which is the main advantage. However, the phase to structure insulators on the towers will likely need to be of higher voltage rating, and there is the possible use of V-style insulators needed to prevent blowout to the tower. In addition, the line to ground capacitance will increase. Also the electric fields at ground level will increase due to an increase in voltage line to neutral (the electric field is also depended on multiple other parameters, e.g. phase order and configuration). In designs in which the increase in electric field at ground level results in field strengths above code [8], the design may require an increase in tower height. The conversion between three phase and six phase and certain other HPO designs generally does not require specially manufactured transformers since the voltage ratings for wye and inverted wye transformers all fall into standardized designs. However, HPO designs of high order are likely to require transformers with specially manufactured voltage ratings. This is discussed at the start of Section 4.3. An example for the comparison between double circuit three phase and six phase in done in Section 4.16.
Perhaps the greatest impediment to HPO designs is the lack of familiarity of practicing engineers with these technologies, and the reluctance to ‘break new ground’ with innovative designs.

4.3 Operation and Design Features in High Phase Order Applications

*Transformer configurations*

Significant research has been done on transformer implementation for six phase designs in [93, 94] and a useful summary is in [51]. The general idea behind the transformers to change between three phase and six phase designs can be seen in Table 4.3. Six phase designs may utilize two three phase transformers (i.e. the two three phase transformers in row one column one or row one column two in Table 4.3) and twelve phase designs may utilize four three phase transformers (i.e. all four transformers in row one of Table 4.3). Basically in a six phase design an inverted-Y configuration is used to shift three of the six phases by sixty degrees. The multiple transformers to convert to HPO add extra cost and size compared to three phase designs. This is one of the greatest disadvantages of HPO power transmission designs.

The six phase design could also use six phase transformers (Table 4.3 row two and three) which are basically a combination of two three phase transformers using one core. In addition, a twelve phase design could use two six phase transformers. Other HPO transformers have been proposed e.g. [95-97].

According to some studies, autotransformers are also a possibility for conversion to HPO and are less costly to build for high phase order designs, but are hard to transport for high voltage designs [51, 95]. An autotransformer provides no ohmic isolation be-
tween windings. Therefore, in HPO high voltage designs, it is more likely the transformer design to convert from three phase to six phase would use two three phase units with a three leg core, wound in a *delta-Y* and *delta-inverted Y* connection as shown in Table 4.3 [51]. Further high phase order could utilize an autotransformer [98] or power electronics (especially at lower power levels) for the conversion between three phase and HPO.

Table 4.3 Transformers Configurations for Three Phase to Six or Twelve Phase Designs

<table>
<thead>
<tr>
<th>Two 3-phase transformers</th>
<th>Equivalent six phase transformer</th>
<th>Six phase transformer wye - mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram" /> Y – Y</td>
<td><img src="image2" alt="Diagram" /> Δ – Y</td>
<td><img src="image3" alt="Diagram" /> Y – Hexagon</td>
</tr>
<tr>
<td><img src="image1" alt="Diagram" /> Y – inverted Y</td>
<td><img src="image2" alt="Diagram" /> Δ – inverted Y</td>
<td></td>
</tr>
<tr>
<td><img src="image1" alt="Diagram" /> Y – Star</td>
<td><img src="image2" alt="Diagram" /> Δ – Star</td>
<td></td>
</tr>
</tbody>
</table>
**HPO compaction benefit**

In this section, attention turns to the integration of phase compaction and HPO technologies. A notable benefit of the decreased $V_{ll}$ in a HPO transmission line is the ability to increase the power density of the transmission line. The decreased $|V_{ll}|$ allows for compaction of the phase to phase spacing. Table 4.4 shows how much closer the phases can be brought together.

**Table 4.4 Decrease in Phase Spacing for a Representative Number of Phases Compared to a Multicircuit 3φ Construction**

<table>
<thead>
<tr>
<th>Number of phases</th>
<th>% of typical spacing*</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>100 %</td>
</tr>
<tr>
<td>6</td>
<td>57.75 %</td>
</tr>
<tr>
<td>9</td>
<td>39.49 %</td>
</tr>
<tr>
<td>12</td>
<td>29.89 %</td>
</tr>
<tr>
<td>18</td>
<td>20.05 %</td>
</tr>
</tbody>
</table>

$n = \sqrt{\frac{2}{3}} \left(1 - \cos \left(\frac{360}{n}\right)\right) \times 100$

*Assumption that voltage line to line is linearly related to phase spacing

Note that the advantages and disadvantages of compaction are discussed in Chapter 2 of this thesis:

- Loading of adjacent transmission assets
- Increased capacitance
- Decreased ROW and construction benefit
- Decreased electric and magnetic fields at ground level and at edge of ROW
- Increased corona levels, however, note that HPO lower voltage line to line decreases the corona
- Decreased lightning exposure
- Decreased voltage and current unbalance
- Increased surge impedance loading.

**Protection design**

Protection of HPO lines is more complex than three phase counterparts. Many methods have been proposed to address HPO designs, e.g., [49, 50]. One of the main difficulties is the increased number of possible faults, which is revisited in Section 4.10, along with the increased range of possible fault current. Fault analysis for HPO is revisited in Section 4.11. Relay configuration for HPO is dependent on whether single pole switching, three phase switching, or all phase switching would be implemented. One protection method is to use segregated phase comparison (differential relaying), i.e. measure the current on each phase at both ends of the transmission line [99, 100]. When a phase current magnitude is vastly different on the two ends of the transmission line, the phase is tripped. Using unbalance measurements and a transient stability study, it can be determined whether single phase tripping, three phase tripping, or complete line trip is utilized for every possible fault combination.

**Design of insulators and phase spacers**

Alternative phase spacer configurations were studied in [45, 51] for circularly configured transmission lines. Four designs were considered seen in Fig. 4.2 from [51]. The cheapest and lightest design is the hexagon design and is suggested for use at the towers and if phase spacers are needed at the mid-span.
Substation design considerations

The substation design to accommodate HPO transmission lines may require more space than typical designs. As mentioned before, six phase designs may utilize two three phase transformers, and twelve phase designs may utilize four three phase transformers. The additional transformer(s) will increase space requirements at each substation [51]. Also, the phase conductors on the HPO side of the transformers need to be transposed to adjust the configuration to allow $n/360^\circ$ degree angle separation between phase and adjacent phases [101]. Appropriate (often increased) phase-phase clearances are required during the transposition. If single pole switching is utilized, additional land space will be needed for additional protection equipment and circuit breakers. Overall, substations that support HPO power transmission will be more expensive, and require more land than traditional substations.

Corona

The decreased voltage line-to-line and decrease in electric field on the surface of the conductors cause the corona on the line to be less. One source even states the corona
is approximately six times less on a 6-phase line *per conductor* over a 3-phase line for 80 kV ($V_{in}$) [51]. This in turn also decreases the radio frequency interference and audible noise, and reference [51] states the radio noise is decreased by 6.2 dB and audible noise by 4.8 dB for six phase vs. three phase. However, note that if the spacing between the conductors is decreased due to lower voltage line to line, the closer phase spacing increases corona [16].

*Current unbalance*

Apart from unbalance arising in the HPO voltage source, and apart from load unbalance, high phase order transmission circuits have a minimal current unbalance when arranged circularly due to the symmetry of the conductors [47]. This decreases the need for transposition. Reference [51] reports a study in which an 80 mile simplified modeled line had a current unbalance of 4% with 3-phase and 0.5% with 6-phase.

4.4 Consequences of HPO and Circuit Impedance

The circuit impedance has a direct impact on the power flow on the transmission line and the transmission line security rating. In Section 2.2, compaction causes the $X^+$ to decrease, and $X^+$ is directly proportional to the steady state stability rating (i.e., security rating) by,

$$P_{12} = \frac{|V_1||V_2| \sin(\delta_{max})}{X_{12}^+},$$

using the lossless short line approximation. The lossy long line calculation is discussed in Section 2.2.
To calculate \( X^+ \) in a HPO line versus the three phase multicircuit counterpart, the sequence impedance equations are calculated in terms of self and mutual impedances. To calculate sequence impedances, properties of circulant matrices are discussed. Note that HPO lines add additional transformer impedance to the circuit but the significance of this impedance decrease dramatically as line length increases [47].

At this point consider the use of the term ‘mutual impedance’. The term self impedance of a transmission line is \( Z_s = R + jX_s \) and is dependent on the conductor. When mutual reactance is present, then there is a term \( I'jX_m \) which describes the voltage induced in the artifact element from an adjacent current \( I' \). Then

\[
V = (R+jX_s)I + jX_mI'.
\]

For compactness of notation, it is useful to introduce the notation \( Z_m = 0 + jX_m \) as a mutual impedance,

\[
V = Z_sI + Z_mI'.
\]

This notation is used throughout this chapter.

Perhaps the simplest HPO technology is the 6φ case. Consider a 6φ transmission line on which the phases are arranged in a regular hexagon as shown in Figure 4.3. Consider the line impedance matrix as a lumped parameter, untransposed, lossless 6φ transmission line model,
The notation $Z_S$ refers to the self impedance of a given phase, and $Z_m$ is the mutual impedance with an adjacent phase, and $Z_{m1}$ and $Z_{m2}$ are the mutual impedances with more distant phases related to $d_i$ shown in Figure 4.3. Note that in (4.2) and similar line impedance matrices in this chapter could also include rows/columns for the ground wires (overhead protection wires); however, using Kron reduction [77] those rows / columns can be eliminated.

Figure 4.3 Configurations for a Double Circuit 3φ and 6φ Line

4.5 Sequence Components and Sequence Impedances

*Traditional calculation of power system sequence impedances*

The method of sequence components (symmetrical components) and sequence impedances was proposed in Fortescue’s classic paper, [102]. The basic concept is that the phases of an AC polyphase network are decoupled into several single phase circuits.
These decoupled circuits are solved for power flow analysis and fault analysis, and subsequently the several symmetrical components are inverse transformed back to phase variables. The sequence components method has been applied for nearly a century and relevant research is still on-going, e.g. [103-106]. This shows the importance of sequence components in power system analysis. This section as well as Sections 4.6 and 4.7 focuses on the calculation of sequence impedances and much of these sections were presented in [107, 108].

The sequence impedances are the eigenvalues of the line impedance matrix. The line impedance matrix is implicitly defined as,

\[ V_1 - V_2 = Z_{ph}I, \]

where \( V_1 \) and \( V_2 \), are the line terminal voltage vectors in phase notation, \( I \) is the line current vector also in phase variable notation. The line impedance matrix, \( Z_{ph} \), is an \( n \times n \) matrix of the self and mutual impedances of the polyphase transmission line. The polyphase impedance matrix is readily used with known network combination and modelling to obtain a model of an interconnected polyphase AC transmission system.

In theory, one method to calculate sequence impedances is with the use of a similarity transformation – and this is always guaranteed to decouple a polyphase system into many decoupled single phase systems. In the case of three phase systems, the required similarity transformation is the symmetrical component transformation.

The symmetrical component transformation for three phase circuits is well known [102].
where \( a = e^{j\frac{2\pi}{3}} \). The \( \frac{1}{\sqrt{3}} \) coefficient in (4.3) insure that the inverse transform is the hermitian of \( T_3 \). Any non-zero complex coefficient could be used in the forward transform, and the coefficient 1.0 is often used. A corresponding generalized transformation can be found for any \( n \)-phase system and this was proposed in [102]. The transformation matrix is simplified and presented in modern matrix notation for the general \( n \)-phase case,

\[
T_n = \frac{1}{\sqrt{n}} \begin{bmatrix}
  a^{-0+0} & a^{-0+1} & \cdots & a^{-0+(n-1)} \\
  a^{-1+0} & a^{-1+1} & \cdots & a^{-1+(n-1)} \\
  \vdots & \ddots & \ddots & \vdots \\
  a^{-(n-1)+0} & a^{-(n-1)+1} & \cdots & a^{-(n-1)+(n-1)}
\end{bmatrix}
\]

(4.4)

where \( a = e^{j\frac{2\pi}{n}} \). Note that \( T_n \) is symmetric and its inverse is \( T_n^H \) where \((.)^H\) denotes the hermitian. Using conventional terminology, the first row / column of \( T_n \) corresponds to the zero sequence; the next row / column corresponds to positive sequence and the last row / column corresponds to the negative sequence. The other rows / columns of \( T_n \) correspond to sequences that do not exist in the three phase case; however some researchers have proposed terminology for the six phase case [109].

The transformation matrix in (4.4) is used to diagonalize (decouple) the line impedance matrix (\( Z_{ph} \)) into the sequence impedances (\( Z_{seq} \)). The \( Z_{ph} \) matrix is decoupled with a similarity transformation,

\[
Z_{seq} = T^{-1}Z_{ph}T,
\]

(4.5)

where \( Z_{seq} \) is a symmetric \( n \times n \) matrix in the form,
where the sequence impedances are on the diagonal, $Z_0, Z_1, \ldots, Z_{n-1}$, and $Z_0$ is the zero sequence impedance, $Z_1$ is the positive sequence impedance and $Z_{n-1}$ is the negative sequence impedance. The other diagonal entries in (4.6) are the sequence impedances that do not exist in the three phase case. The result of (4.5) for the three phase case is,

$$Z_{3\text{seq}} = \text{diag} \begin{bmatrix} Z_0 \\ Z_1 \\ Z_2 \end{bmatrix} = \text{diag} \begin{bmatrix} Z_s + 2Z_m \\ Z_s - Z_m \\ Z_s - Z_m \end{bmatrix},$$

(4.7)

where $Z_s$ is the self impedance and $Z_m$ is the mutual impedance.

For the system to be decoupled using the transformation $T$, the off-diagonals in (4.6) should be zero. The off-diagonals are zero as long as the transmission line is circularly configured or transposed. Circularly configured transmission line examples are shown in Fig. 4.4, i.e., the conductors are located on a circumscribed circle at points $360/n$ degrees apart; where $n$ is the number of phases throughout this dissertation.

There is an interesting property of the similarity transformation $T$. Consider two line impedance matrices: the total line impedance matrix of a transposed transmission line, and the line impedance matrix of just one section of the transmission line (or the same line untransposed). If the similarity transform $T$, using (4.4), is applied to both cases, the diagonal elements will be equal. The difference is the off-diagonal elements. The transposed case will have zeros on the off-diagonals; the one section (i.e. the untransposed case) will have non-zero off-diagonal elements.
The calculation of most interest is the calculation of the diagonal elements in (4.6), the sequence impedances. The following sections present alternative calculations of the sequence impedances to model polyphase systems. Methods to calculate the sequence components are useful in the fault analysis of HPO transmission circuits.

4.6 Symmetrical Circulant Toeplitz Matrices Connection to Sequence Impedances

*Circulant calculation method of sequence impedances*

Properties of circulant matrices are used to determine the sequence impedances of a transmission line. The line impedance matrix will be shown to be in the circulant form. A circulant matrix is a subset of the Toeplitz matrices. A Toeplitz matrix is a square matrix of the form [110],

\[
\tau = \begin{bmatrix}
    t_0 & t_1 & t_2 & \cdots & t_{n-1} \\
    t_n & t_0 & t_1 & \cdots & \vdots \\
    t_{n+1} & t_n & t_0 & \cdots & t_2 \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    t_{2n-2} & \cdots & t_{n+1} & t_n & t_0
\end{bmatrix},
\] (4.8)
where \( n \) is the size of the matrix, or for the purpose of this dissertation, \( n \) is the number of phases. A circulant matrix is a Toeplitz matrix of the form,

\[
\tau_c = \begin{bmatrix}
t_0 & t_1 & t_2 & \cdots & t_{n-1} \\
t_{n-1} & t_0 & t_1 & \cdots & t_2 \\
& & \ddots & & \\
t_2 & & \ddots & \ddots & \ddots \\
t_1 & t_2 & \cdots & t_{n-1} & t_0
\end{bmatrix}.
\] (4.9)

**Line impedance matrices in the circulant form**

If the conductors of an AC polyphase transmission line are arranged circularly symmetric, e.g. as seen in Fig. 4.4, or the transmission line is transposed, \( Z_{ph} \) is in the circulant form (4.9) with symmetry imposed due to the reciprocity theorem,

\[
Z_{ph} = \begin{bmatrix}
Z_s & Z_{m1} & Z_{m2} & \cdots & Z_{m\frac{n}{2}} & \cdots & Z_{m2} & Z_{m1} \\
Z_{m1} & Z_s & Z_{m1} & \ddots & \ddots & \ddots & \ddots & \ddots \\
Z_{m2} & Z_{m1} & Z_s & \ddots & \ddots & \ddots & \ddots & \ddots \\
& & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
& & & Z_{m\frac{n}{2}} & & & \ddots & \\
& & & \ddots & \ddots & \ddots & \ddots & \ddots \\
& & & Z_{m2} & & & \ddots & \ddots \\
Z_{m1} & Z_{m2} & \cdots & Z_{m\frac{n}{2}} & \cdots & Z_{m2} & Z_{m1} & Z_s
\end{bmatrix}.
\] (4.10)

for even \( n \). For odd \( n \), \( Z_{ph} \) is,
where $Z_s$ is the self impedance and $Z_{mi}$ is the mutual impedance related to the distance between conductors, $d_i$, e.g. as in Fig. 4.4. Note that a line impedance matrix in the form,

$$
Z_{ph} = \begin{bmatrix}
Z_s & Z_{m1} & Z_{m2} & \ldots & Z_m & Z_{n-1} & Z_{n-1} & \ldots & Z_m & Z_{m1} \\
Z_{m1} & Z_s & Z_{m1} & \ldots & & & & \vdots & \vdots & \vdots \\
Z_{m2} & Z_{m1} & Z_s & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
Z_{m1} & Z_{m2} & \ldots & Z_m & Z_{n-1} & Z_{n-1} & \ldots & Z_m & Z_{m1} & Z_s
\end{bmatrix}
$$

(4.11)

is a sub-matrix of the circulant matrix (4.9).

Eigenvalues (sequence impedances) of circulant matrices

The $n$ eigenvalues of a circulant matrix are [110],

$$
Z_q = \sum_{p=1}^{n} Z_{ph,1,p} e^{-j2\pi(p-1)q/n} \quad q = 0, 1, ..., n - 1.
$$

(4.13)

where $Z_{ph,1,p}$ is the $p$th column entry of the first row of the $Z_{ph}$ matrix. The eigenvalues, $Z_q$ in (4.13) are the sequence impedances. For zero sequence, $q = 0$, positive sequence, $q = 1$, negative sequence, $q = n-1$ which gives the same value as positive sequence. The other sequences $1 < q < n-1$ are sequences that do not exist in the three phase case. Note that
the $Z_q$ values in (4.13) are the discrete Fourier transform (DFT) of the sequence \{Z_{ph,1,1}, Z_{ph,1,2}, \ldots, Z_{ph,1,n}\}, i.e. the first row of the line impedance matrix.

In addition, if any row of the circulant line impedance matrix is known, the sequence impedances can be calculated from,

$$Z_q = \sum_{p=1}^{n} Z_{ph,k,p} e^{-j2\pi(p+k-2)q/n} \quad q = 0, 1, \ldots, n - 1,$$

where $k$ is the row of the circulant line impedance matrix (i.e. 1, or 2, or \ldots $n$), and $p$ is the column of the circulant line impedance matrix.

The method in (4.13) can be used to find the equations for the sequence impedances of any phase order transmission line when the line impedance matrix is known in the circulant form. For example, for six phase and twelve phase respectively,

$$Z_{6seq} = \text{diag} \left[ \begin{array}{c} Z_s + 2Z_{m1} + 2Z_{m2} + Z_{m3} \\ Z_s + Z_{m1} - Z_{m2} - Z_{m3} \\ Z_s - Z_{m1} - Z_{m2} + Z_{m3} \\ Z_s - 2Z_{m1} + 2Z_{m2} - Z_{m3} \\ Z_s - Z_{m1} - Z_{m2} + Z_{m3} \\ Z_s + Z_{m1} - Z_{m2} - Z_{m3} \end{array} \right]$$

(4.14)
where the top row is the zero sequence impedance, the second and last rows are equal and are the positive and negative sequence impedance.

It should be noted that a circulant matrix has the special property that all circulant matrices of size \(n \times n\) share the same \(n\) eigenvectors \([110]\),

\[
v_q = \frac{1}{\sqrt{n}} \left[ e^{0}, e^{\frac{j2\pi q}{n}}, ..., e^{\frac{j2\pi q(n-1)}{n}} \right]^t \quad q = 0, 1, ..., n-1, \quad (4.16)
\]

The \(n\) eigenvectors \(v_q\) can be arranged in columns to form the modal matrix \(T_n\), in (4.4). This modal matrix is used in the similarity transformation to decouple an \(n\)-phase system when the transmission line is circularly configured or transposed.

**Sequence impedances of a transposed transmission line**

The fundamental element of any model of an interconnected AC system is the model of each transmission line in the network. If the transmission line were arbitrarily configured, and transposed in segments to balance the transmission line, the resulting total line impedance matrix is circulant. Consider such a line: the impedance matrix for one section of the line is,
where $Z_s$ is the self impedance, and $Z_{m,c,k}$ is the mutual impedance between conductors $c$ and $k$. The sequence impedances can be directly calculated from (4.17) using,

$$
Z_{ph} = \begin{bmatrix}
Z_s & Z_{m,1,2} & Z_{m,1,3} & \cdots & Z_{m,1,n-1} & Z_{m,1,n} \\
Z_{m,1,2} & Z_s & Z_{m,2,3} & \cdots & Z_{m,2,n-1} & Z_{m,2,n} \\
Z_{m,1,3} & Z_{m,2,3} & \ddots & \vdots & \vdots & \vdots \\
\vdots & \vdots & \ddots & Z_s & Z_{m,n-1,n} \\
Z_{m,1,n-1} & Z_{m,2,n-1} & \cdots & Z_s & Z_{m,n-1,n} \\
Z_{m,1,n} & Z_{m,2,n} & \cdots & Z_{m,n-1,n} & Z_s
\end{bmatrix}, \quad (4.17)
$$

and when a numerical subscript on $Z_{ph}$ is greater than $n$, that is,

$$
Z_{ph_{c,k}} \text{ while } k > n, \text{ then } k = k - n. \quad (4.18)
$$

Assuming that the mutual terms are purely imaginary and that all the sequence impedances contain the same real component, $R$, the resistance of the conductor, then,

$$
Z_q = R + j \sum_{p=1}^{n} X_{ph,1,p} \cos(2\pi (p - 1)q/n), \quad (4.19)
$$

and when $q = 0, 1, \ldots, n-1$ and $X_{ph}$ is the imaginary part of $Z_{ph}$. Equation (4.19) is for circularly configured transmission lines or when the line impedance matrix is circulant; and (4.20) is for transposed transmission lines when the line impedance matrix is known for only a section of the line, i.e. $Z_{ph}$ is not circulant.

$$
Z_q = R + j \sum_{p=1}^{n} \sum_{c=1}^{n} X_{ph,c,(c+p)} \cos(2\pi pq/n), \quad (4.20)
$$
4.7 The Direct Calculation of Sequence Impedances from Conductor Spacing

In this section new distance parameters similar to the GMD are presented and used to calculate the exact sequence reactances of circular or transposed polyphase transmission lines. That is, instead of using the line impedance matrix to calculate the sequence impedances, the distances between each conductor are used directly to calculate the sequence impedances.

_GMD positive sequence reactance calculation_

GMD is the geometric mean distance between the conductors and is well defined [111]. If GMD is generalized for any number of phases, where $n$ is the number of phases,

$$GMD = \sqrt[n]{(d_{1n}d_{1(n-1)} \cdots d_{12})(d_{2n}d_{2(n-1)} \cdots d_{23}) \cdots (d_{(n-2)(n-1)}d_{(n-2)n})(d_{(n-1)n})},$$

where $d_{p,m}$ is the distance between conductors $p$ and $m$, which can be written in a product form,

$$GMD = \prod_{p=1}^{n-1} \prod_{m=p+1}^{n} d_{p,m}^{\frac{2}{(n-1)n}}. \quad (4.21)$$

This introduces the new distance parameter form, i.e. using a double product notation. GMD is used in transmission line reactance calculations and the positive sequence reactance for a three phase transmission line is well known,

$$X_{1}^{3ph} = 0.062844 \frac{f}{50} \ln \left( \frac{GMD}{GMR} \right), \quad (4.22)$$
where GMR is the geometric mean radius of the conductor, \( ln \) is the natural logarithm, and \( X \) and the frequency \( f \) are in Ohm/km and Hz. However, when there is more than three phases \((n > 3)\), the positive sequence reactance can no longer be calculated with (4.22). If (4.22) were used to calculate the positive sequence reactance of a high phase order transmission line, the value will be off by an amount that is not negligible. The error between actual positive sequence reactance and the GMD calculation method in (4.22): increases as phase order increases, increases as phase spacing decreases, and increases as GMR increases. For example consider a 50 Hz transmission line with Drake conductors circularly configured at three different ‘phase to nearest phase’ spacing, 1, 4, and 10 meters. This example is Use Case H and shown in Fig. 4.5; displaying the error that occurs when using GMD in the calculation of HPO positive sequence reactance,

\[
\text{percent error when using GMD} = \left| \frac{X_1 - X_{1,GMD,approx}}{X_1} \right| \times 100\%
\]

For this reason, a new value to be used instead of GMD shall be presented for \( n \)-phase systems termed \( D_{Xq} \), \( D_{XI} \) for positive sequence, and \( D_{X0} \) for zero sequence. These are distance parameters to use instead of GMD, for HPO systems, which exactly calculate the sequence reactances of circular or transposed transmission lines.
Any sequence reactance distance parameter

Any sequence reactance for an $n$-phase transmission line with any configuration, but is transposed, can be calculated using a newly presented $D_{Xq}$ in the calculation instead of GMD in equation (4.22). The distance parameter used to calculate any sequence reactance is,

$$D_{Xq} = \prod_{p=1}^{n-1} \left[ \prod_{c=1}^{n} d_{c,(c+p)} \right]^{-\frac{1}{n} \cos \frac{2\pi pq}{n}}, \quad (4.23)$$

where $q = 0, 1, 2\ldots n-1$. For zero sequence, $q = 0$, positive sequence, $q = 1$, negative sequence, $q = n-1$ which gives the same value as positive sequence. The other distance pa-
Parameters for other sequences that do not exist in the three phase case are when \( q \) is in between 1 and \( n-1 \). When distances arise where the second subscript number on \( d \) is greater than \( n \), that is,

\[
d_{c,k} \quad \text{while} \quad k > n, \quad \text{then} \quad k = k - n.
\]

The parameter \( d_{c,k} \) is the distance between conductors \( c \) and \( k \). Using (4.23) any sequence impedance can be found from,

\[
Z_q = \begin{cases} 
R + j0.062844 \frac{f}{50} \ln \left( \frac{D_{Xq}}{GMR} \right) & q \neq 0 \\
R + j0.062844 \frac{f}{50} \left[ \ln \left( \frac{D_{X0}}{GMR} \right) + n \left( 7.6786 + \frac{1}{2} \ln \frac{\rho}{f} \right) \right] & q = 0 
\end{cases}, \quad (4.24)
\]

which is derived from Carson’s equations, [77], where \( X \) is in \( \text{Ohm/km} \), \( f \) is in \( \text{Hz} \), \( \rho \) is the resistivity of Earth, and \( R \) is the resistance of the conductor. Note that when \( q = 0 \) in (4.23) the zero sequence distance parameter can be simplified to,

\[
D_{X0} = \prod_{p=1}^{n-1} \prod_{c=p+1}^{n} d_{p,c}^{-2/n}, \quad (4.25)
\]

where \( d_{p,c} \) is the distance between conductors \( p \) and \( c \). Also note that in the three phase case, \( D_{X1} = \text{GMD} \).

Circularly configured sequence reactance distance parameter

Of special interest is the circularly configured \( n \)-phase transmission line (examples seen in Fig. 4.4). This is because circular HPO transmission lines have the best power density for use of ROW. Due to the symmetry of the circular configuration, this allows simplification of \( D_{Xq} \) in (4.23) to,
\[ D_{Xq\_circular} = \prod_{p=2}^{n} d_{1,p} \left( \frac{\cos \frac{2\pi (p-1)q}{n}}{n} \right), \quad (4.26) \]

where \( d_{1,p} \) is the distance between conductor 1 and conductor \( p \). All phase spacing distances can be related to \( d_{1,2} \) (the phase to nearest phase distance) termed \( d_1 \) in this thesis for symmetric circularly configured lines (e.g. in Fig. 4.4),

\[ d_{1,p} = d_1 \sqrt{\frac{1 - \cos \frac{360 (p-1)}{n}}{1 - \cos \frac{360}{n}}}. \]

This allows the simplification of \( D_{Xq\_circular} \) for circularly configured lines to be a function of phase to nearest phase spacing distance, \( d_1 \), and \( n \) only,

\[ D_{Xq\_circular} = \begin{cases} d_1 \prod_{p=1}^{n-1} \left( \frac{1 - \cos \frac{360}{n}}{1 - \cos \frac{360p}{n}} \right)^{1} & q \neq 0, \\ d_1^{1-n} \prod_{p=1}^{n-1} \left( \frac{1 - \cos \frac{360}{n}}{1 - \cos \frac{360p}{n}} \right)^{1} & q = 0 \end{cases} \quad (4.27) \]

Any sequence impedance of any circularly configured \( n \)-phase transmission line can be calculated using distance parameters in (4.27) applied to (4.24).

4.8 Designing the Sequence Impedances to Specifications Using Optimization

Typically a transmission line is designed to meet many specifications, e.g., cost, voltage, efficiency, and power transmission capacity. This section addresses how a transmission line could be designed to meet sequence impedance specifications: the design specifies the transmission line sequence impedances, and the corresponding line ge-
ometry is found. Certain constraints are implemented such as the BIL and conductor arrangement (e.g. circularly configured, vertically configured, and double vertically configured). An optimization program is developed to minimize the difference between desired sequence impedances and actual sequence impedances.

An expansion of (4.13) reveals,

\[
\begin{bmatrix}
Z_0 \\
Z_1 \\
Z_2 \\
\vdots \\
Z_{n-1}
\end{bmatrix}
= 
\begin{bmatrix}
1 & 2 \cos \left(\frac{2\pi(n-1)}{n}\right) & 2 \cos \left(\frac{2\pi(n-2)}{n}\right) & \cdots & 2 \cos \left(\frac{2\pi(n-h)}{n}\right) & g \cos \left(\frac{2\pi(n-h)}{n}\right) \\
1 & 2 \cos \left(\frac{2\pi(n-1)}{n}\right) & 2 \cos \left(\frac{2\pi(n-2)}{n}\right) & \cdots & 2 \cos \left(\frac{2\pi(n-h)}{n}\right) & g \cos \left(\frac{2\pi(n-h)}{n}\right) \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
1 & 2 \cos \left(\frac{2\pi(n-1)}{n}\right) & 2 \cos \left(\frac{2\pi(n-2)}{n}\right) & \cdots & 2 \cos \left(\frac{2\pi(n-h)}{n}\right) & g \cos \left(\frac{2\pi(n-h)}{n}\right)
\end{bmatrix}
\begin{bmatrix}
Z_s \\
Z_{m1} \\
Z_{m2} \\
\vdots \\
Z_{mh}
\end{bmatrix}
\]

(4.28)

where for,

- even \( n \) \( g = 1 \) \( h = \frac{n}{2} \)
- odd \( n \) \( g = 2 \) \( h = \frac{n-1}{2} \)

Equation (4.28) is compactly written as,

\( \lambda = C\zeta \).

(4.29)

The notation \( \lambda \) in (4.29) refers to the \( n \) eigenvalues (sequence impedances) of \( Z_{ph} \), \( C \) is the indicated \( n \) by \( h \) coefficient matrix (\( n > h \)) in (4.28), and \( \zeta \) is the vector \([Z_s, Z_{m1}, \ldots ]^t\). Note in (4.28) that \( \lambda_1 = \lambda_{n-1}, \lambda_2 = \lambda_{n-2}, \ldots \) that is, \( \lambda_k = \lambda_{n-k} \) for \( k = 1, 2, \ldots, h \). The design problem is: given \( \lambda \), find \( \zeta \) to minimize the norm, \( |\lambda - C\zeta|_2 \).
\[
min_{d_1, d_2 \ldots} [(\lambda - C\zeta)^H(\lambda - C\zeta)],
\]

constrained by,
\[
d_1 < d_2 < d_3 < \ldots
\]
\[
d_i > d_{i, BIL}.
\]

The problem statement usually includes finding the conductor geometry to give the resulting \(\zeta\). If certain elements of \(\lambda\) are emphasized (i.e. weighted), then (4.29) becomes,
\[
w\lambda = wC\zeta,
\]
where \(w\) is a weighting matrix, (usually diagonal), and (4.30) becomes,
\[
\min_{d_1, d_2 \ldots} [(w\lambda - wC\zeta)^H(w\lambda - wC\zeta)].
\]

This is the familiar weighted least squares problem documented in many places in the literature (e.g., [112]). The elements of \(\zeta\) are nonlinear functions of the \(d_i\) and \(d_{i, BIL}\) is the distance required by the specified voltage and BIL or switching surge factors. Examples of the distances \(d_i\) can be found in Fig. 4.4. Inequality (4.31) could also be viewed as a configuration constraint, e.g. circular, vertical, or double vertical.

This method to design the sequence impedances in (4.29) – (4.34) is conveniently coded using constrained nonlinear programming in MATLAB with the FMINCON function [113]. The code for this design of sequence impedances can be found in Appendix B. For example, a six phase 50 Hz transmission line circularly configured with Drake conductors is to be designed. The zero, positive, and negative sequence impedances are specified and no bias is used (i.e., objectives weighted with 1.0); and the remaining three sequence impedances are not specified (i.e. weighted with zero). The parameters and solu-
tions are given in Table 4.5. The design is successful, and the desired sequence impedances met the actual sequence impedances. However this will not always hold true, if more sequence impedances were specified, or further constraints were added, the desired sequence impedances would not match the actual sequence impedances; however this optimization method will minimize the square of the residual (4.34). Note that \( d_1, d_2, \) and \( d_3 \) specify the designed solution for this six phase example (Fig. 4.4). This example is Use Case I. In a more general design, there may be many \( d_i \) calculated.

<table>
<thead>
<tr>
<th>Table 4.5 Designing the Sequence Impedances in Use Case I</th>
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<tr>
<td><strong>Inputs</strong></td>
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<td>Design sequence reactances to ( \lambda )</td>
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<td><strong>Constraints</strong></td>
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Potential applications for the design of transmission line sequence reactances include the specification of fault currents, consideration of power transfer capability, and mitigation of circuit unbalance.

**Conclusions drawn relating to sequence impedances**

Alternate methods to calculate the sequence impedances of an \( n \)-phase transmission line have been presented. It has been shown that line impedance matrices of circularly configured lines or transposed lines are symmetrical circulant Toeplitz. Special proper-
ties of circulant matrices allow for the calculation of the transmission line sequence impedances using the DFT of the first row of the circulant transmission line impedance matrix. In addition, innovative distance parameters (e.g., $D_{Xq}$) to calculate the sequence impedances of any transposed or circular transmission line are proposed. Fortescue’s generalized symmetrical component transformation is simplified and reformulated as a single matrix in general form. A novel method to design sequence impedances to specifications is presented and illustrated.

4.9 Six Phase vs. Double Circuit Three Phase Security Rating

The 6φ phase to neutral voltages are given by the vector $[1 \ b^5 \ b^4 \ b^3 \ b^2 \ b]^T$ where $b$ is $1/60^\circ$. Note that $b$ is one of the six complex roots of unity. It is possible to decouple the 6φ system into six single phase circuits seen in Figure 4.6 from [109] much like is done for 3φ systems and symmetrical components [109]. Note much of the work presented in this section and Section 4.9 was presented in [59, 114, 115].

The modal matrix $T$ for a six phase system [109] is,

$$T_6 = \frac{1}{\sqrt{6}}\begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 \\
1 & b^5 & b^4 & b^3 & b^2 & b \\
1 & b^4 & b^2 & 1 & b^4 & b^2 \\
1 & b^3 & 1 & b^3 & 1 & b^3 \\
1 & b^2 & b^4 & 1 & b^2 & b^4 \\
1 & b & b^2 & b^3 & b^4 & b^5
\end{bmatrix},$$

which has already been presented in general form in (4.4). The sequence impedances can be calculated using (4.5), (4.13), (4.19)-(4.20), or (4.24) and (4.27). The sequence impedances for six phase are in (4.14). The magnitude of each sequence reactance is analyzed.
For circularly configured 6φ with phase to nearest phase spacing between 10 and 50 feet and Drake conductors, termed Use Case J, the sequence reactances can be seen in Figure 4.7. Zero sequence is $0s$, positive sequence is $ps$, negative sequence is $ns$, the sequences that do not exist in the three phase case are termed by reference [109], two zero three phase is $0t$, two positive three phase is $pt$, and two negative three phase is $nt$.

![Diagram of Six Phase Sequence Components](image)

Figure 4.6 The Six Phase Sequence Components [109].
If the $6\phi$ voltage phase to phase is $1/\sqrt{3}$ times the comparison $3\phi$ phase to phase voltage magnitude, the spacing is assumed to be linearly related (this is an approximation), $\sqrt{3}$ times closer in the $6\phi$ line. Consider three cases as seen in Fig. 4.8, double circuit three phase, six phase, and compact six phase. A comparison is made to determine the positive and zero sequence reactance for the three cases. In addition the security rating for the three cases are compared.

To determine the increase in security rating for compact $6\phi$ as compared to a $6\phi$ design, the conductor configuration is shown in Figure 4.8. For the configuration in Figure 4.8, each distance is related to the original $6\phi$ distance, $d_2$. Therefore, the positive sequence reactances for 60 Hz lines are,
The zero sequence reactances are similarly calculated with Earth resistivity of 100 Ohm-
meter,

\[ X_{\text{double,3ph}}^+ = X_s - X_{m2} = 0.12134 \left( \ln \frac{d_{2.3\phi}}{GMR} \right) \frac{\Omega}{\text{mile}} \]

\[ X_{6\phi}^+ = X_s + X_{m1} - X_{m2} - X_{m3} = 0.12134 \left( \ln \frac{2d_{2.3\phi}}{GMR} \right) \frac{\Omega}{\text{mile}} \]

\[ X_{\text{compact,6ph}}^+ = X_s + X_{m1} - X_{m2} - X_{m3} = 0.12134 \left( \ln \frac{2d_{2.3\phi}}{\sqrt{3}GMR} \right) \frac{\Omega}{\text{mile}}. \]

Using GMR = 0.0375 ft corresponding to Drake, the \( X^+ \) vs. phase spacing is found and depicted in Figure 4.9. The percent increase in positive sequence reactance for 6φ and compact 6φ over double circuit 3φ is depicted in Figure 4.10. The \( X^0 \) vs. phase spacing is found and depicted in Figure 4.11. The percent increase in \( X^0 \) vs. phase spacing is in Figure 4.12 for 6φ and compact 6φ over double circuit 3φ.
Figure 4.8 Configurations for Comparing Double Circuit 3φ Compact 6φ and 6φ

Figure 4.9 Comparison of X+ for Double Circuit 3φ, 6φ, and Compact 6φ vs. Phase Spacing of the Original Double Circuit 3φ (for GMR of 0.0375 ft Drake Conductor).
Figure 4.10 The Percent Increase in Positive Sequence Reactance for 6φ and Compact 6φ Over Double Circuit 3φ Versus the Original Double Circuit 3φ Phase Spacing

Figure 4.11 Comparison of $X^0$ for Double Circuit 3φ, 6φ, and Compact 6φ vs. Phase Spacing of the Original Double Circuit 3φ (for GMR of 0.0375 ft Drake Conductor).
Figure 4.12 The Percent Increase in Zero Sequence Reactance for 6φ and Compact 6φ over Double Circuit 3φ Versus the Original Double Circuit 3φ Phase Spacing

Note that the zero sequence reactance of double circuit three phase transmission lines has mutual coupling between circuits. Reference [116] displays the ideal transposition for double circuit three phase lines, and no matter the transposition there is always mutual coupling between zero sequence components. For the double circuit 3φ case in Figure 4.8, the zero sequence coupling would be,

\[ Z_{00} = 2Z_1 + Z_3. \]

Due to the mutual coupling between zero sequence components, it may not be a fair comparison of HPO vs. the three phase multicircuit counterpart.

The sequence capacitance can also be compared and the positive and zero sequence capacitance is smaller for HPO vs. their multicircuit three phase counterpart.
4.10 Twelve Phase vs. Quadruple Three Phase Security Rating

For further testing of compact HPO, a comparison is made between quadruple 3φ and 12φ. The phase to phase voltage for 12φ is a factor of 0.299 less than the 3φ case. For this reason, the phases in compact 12φ are assumed to be compacted by the same factor. The configurations for the resultant 12 conductors can be seen in Figure 4.13. Using the configuration in Figure 4.13, the line impedance matrix for a circular or transposed 12φ transmission line is symmetrical circulant Toeplitz (SCT),

\[
Z_{12ph} = \begin{bmatrix}
Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} \\
Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} \\
Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} \\
Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} \\
Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} \\
Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} \\
Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} \\
Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} \\
Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} & Z_{m3} \\
Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} & Z_{m2} \\
Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S & Z_{m1} \\
Z_{m1} & Z_{m2} & Z_{m3} & Z_{m4} & Z_{m5} & Z_{m6} & Z_{m5} & Z_{m4} & Z_{m3} & Z_{m2} & Z_{m1} & Z_S
\end{bmatrix}
\]

Where the distances will be a factor of 0.29886 less for 12 phase vs. the distances in quadruple circuit 3 phase.

Figure 4.13 Configurations for Quadruple Circuit 3φ and 12φ
Analogous to the $6\phi$ case, the sequence components for a $12\phi$ system, pictorially shown in Figure 4.14 [57], are expressed in terms of one of the twelve complex roots of unity, namely $c = 1/30^\circ$. The twelve eigenvectors form the modal matrix,

$$T_{12} = \frac{1}{\sqrt[12]{1}} \begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & c^{10} & c^9 & c^8 & c^7 & c^6 & c^5 & c^4 & c^3 & c^2 & c^1 & c^0 \\
1 & c^{11} & c^{10} & c^9 & c^8 & c^7 & c^6 & c^5 & c^4 & c^3 & c^2 & c^1 \\
1 & c^9 & c^8 & c^7 & c^6 & c^5 & c^4 & c^3 & c^2 & c & 1 \\
1 & c^8 & c^7 & c^6 & c^5 & c^4 & c^3 & c^2 & c & 1 \\
1 & c^7 & c^6 & c^5 & c^4 & c^3 & c^2 & c & 1 \\
1 & c^6 & c^5 & c^4 & c^3 & c^2 & c & 1 \\
1 & c^5 & c^4 & c^3 & c^2 & c & 1 \\
1 & c^4 & c^3 & c^2 & c & 1 \\
1 & c^3 & c^2 & c & 1 \\
1 & c^2 & c & 1 \\
1 & c & 1
\end{bmatrix}.$$  

Similar to the $6\phi$ case, for $12\phi$ the twelve sequence impedances are found and shown in (4.15). Note that $T_{12}$ is independent of the values of the $Z_{mi}$ and $Z_s$ due to the fact that $Z_{ph}$ is in SCT form, and this modal matrix is given by the eigenvectors (4.16) arranged in columns.

For the configuration in Figure 4.13, use the following notation to relate all the distances to distance $d_1$ of the quadruple circuit $3\phi$ case. As before,

**Quadruple circuit three phase and twelve phase spacing**

$$d_{1.3\phi} = d_{1.3\phi} \quad d_{2.3\phi} = 1.932d_{1.3\phi}$$

$$d_{3.3\phi} = 2.732d_{1.3\phi} \quad d_{4.3\phi} = 3.346d_{1.3\phi}$$

$$d_{5.3\phi} = 3.732d_{1.3\phi} \quad d_{6.3\phi} = 3.864d_{1.3\phi}$$

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Compact twelve phase

\[ d_{1,12\phi} = 0.299d_{1,3\phi} \quad d_{2,12\phi} = 0.577d_{1,3\phi} \]

\[ d_{3,12\phi} = 0.816d_{1,3\phi} \quad d_{4,12\phi} = d_{1,3\phi} \]

\[ d_{5,12\phi} = 1.115d_{1,3\phi} \quad d_{6,12\phi} = 1.155d_{1,3\phi} \]

Using the distances above, the positive sequence reactance can be calculated for quadruple three phase vs. twelve phase,

\[ X^+_{4x,3ph} = X_s - X_{m4} = 0.12134 \left[ \ln \left( \frac{3.346d_1}{GMR} \right) \right] \text{ Ohm/mile} \]

\[ X^+_{12ph} = X_s + \sqrt{3}X_{m1} + X_{m2} - X_{m4} - \sqrt{3}X_{m5} - X_{m6} \]

\[ = 0.12134 \left[ 2.28 + \ln \left( \frac{6.692d_1}{GMR} \right) \right] \text{ Ohm/mile} \]

\[ X^+_{compact,12ph} = X_s + \sqrt{3}X_{m1} + X_{m2} - X_{m4} - \sqrt{3}X_{m5} - X_{m6} \]

\[ = 0.12134 \left[ 2.28 + \ln \left( \frac{2d_1}{GMR} \right) \right] \text{ Ohm/mile} \]

As an illustration with GMR = 0.0375 ft, Figure 4.15 and Figure 4.16 depict \( X^+ \) and the increase in \( X^+ \) in the 12\( \phi \) case.
1. Positive sequence (ps)

2. 6ps

3. 4ps

4. 3ps

5. 12ps

6. 0t

11. Negative sequence (ns)

10. 6ns

9. 4ns

8. 3ns

7. 12ns

Figure 4.14 Twelve Phase Symmetrical Components.
Figure 4.15 Comparison of $X^+$ for Quadruple Circuit 3φ, and Compact 12φ vs. Original Quadruple Circuit 3φ Phase Spacing (for GMR of 0.0375 ft Drake Conductor)

Figure 4.16 The Percent Increase in Security Rating for Compact 12φ over Quadruple Circuit 3φ versus the Original Quadruple Circuit 3φ Phase Spacing
4.11 Number of Fault Types for High Phase Order Systems

The most important application for generalized sequence components and sequence impedances is the analysis of polyphase transmission systems, and fault analysis of these systems. High phase order fault analysis has been discussed in many papers, e.g. [38-43]. Results from this section were also presented in [107].

High phase order has an increased number of fault types. Because of the large number of fault types in HPO circuits, techniques that simplify multiple solutions are desirable. Fault analysis using sequence components is one such technique. Certain types of faults can be grouped together because they require the same fault analysis (e.g. a fault from phase A-B has the same analysis as a fault from phase B-C; or a line to ground fault calculation for phase A is essentially the same as that for phase B). When the types of faults that are analysed by a common calculation yielding essentially the same results are grouped, the resulting groups are termed the significant (distinct) fault types. The numbers of fault types and significant fault types have been presented for three phase and six phase [39, 41, 50]. However, equations for the number of fault types and significant fault types for any phase order system have not appeared in the literature. The number of fault types \( F \) for an \( n \)-phase system is,

\[
F = 2^{n+1} - 2 - n. \tag{4.35}
\]

The number significant fault types of an HPO system is much less than the number of fault types, and Table 4.6 shows the number of fault types and significant fault types for a certain number of phases. The number of significant fault types \( F' \) for an \( n \)-phase system is,
\[ \gamma = K - 3 + \frac{1}{n} \sum_{d \mid n} \phi(d) 2^{\frac{n}{d}} \]  

(4.36)

where \( K = \begin{cases} 
\frac{n-1}{2} & \text{for odd } n \\
\frac{n}{2^2 + 2^{\frac{n}{2} - 1}} & \text{for even } n 
\end{cases} \)

Note that the summation in (4.36) is over all possible divisors \( d \) of \( n \) (all positive integers that divide evenly into \( n \)). For example for three phase, \( d \mid 3 \) results in the sum evaluated over \( d = 1, 3 \); \( d \mid 12 \) results in the sum evaluated over \( d = 1, 2, 3, 4, 6, 12 \). Also, \( \phi(d) \) is the Euler’s totient function also known as the ‘phi function’, which counts the totatives of \( d \), i.e. the positive integers that are relatively prime to \( d \), e.g. \( \phi(9) \) counts numbers relatively prime to 9, i.e. \( \phi(9) \) counts 1, 2, 4, 5, 7, and 8; that is 6 numbers: \( \phi(9) = 6 \). Other examples are, \( \phi(1)=1, \phi(2)=1, \phi(3)=2, \phi(4)=2, \) and so forth. Full examples of these innovative equations can be found in Appendix E and tables for the summation \( d \mid n \) and the phi function are in Table E.1 and Table E.2. The authors developed equations (4.35) and (4.36) from hand calculations counting the number of fault types and number of significant fault types for \( n \)-phase systems. A pattern was recognized, and (4.35) and (4.36) were developed.

Eq. (4.36) should assist in protective relay designs. However, additional faults may need to be studied; when two separate simultaneous faults occur on the same line, e.g. fault on phase A to Earth and fault from phase B to phase C. Although rare, these faults are discussed in [40] and may need to be studied in addition to the significant fault types in (4.36). Complex HPO fault analysis studies can be conducted utilising software such as OpenDSS by the Electric Power Research Institute (EPRI).
Table 4.6 Number of Fault Types and Significant Fault Types for Certain Number of Phases

<table>
<thead>
<tr>
<th>Number of phases</th>
<th>Number of significant fault types</th>
<th>Number of fault types</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>120</td>
</tr>
<tr>
<td>9</td>
<td>89</td>
<td>1013</td>
</tr>
<tr>
<td>12</td>
<td>445</td>
<td>8178</td>
</tr>
<tr>
<td>15</td>
<td>2445</td>
<td>65,519</td>
</tr>
<tr>
<td>18</td>
<td>15,367</td>
<td>524,268</td>
</tr>
</tbody>
</table>

4.12 HPO Fault Analysis

*Introduction*

Analysis of HPO faults have been studied extensively in [38-43] and others. An example done in circuit simulation is shown here for a typical, single line, six phase fault. A lumped circuit model was constructed ignoring line and ground capacitance to show the approach; the model in Chapter 5 includes line and ground capacitance. The model was implemented in MATLAB. The example shows how to calculate fault currents and voltages. A single line to ground fault was studied in the example presented here. The symmetrical components method and sequence impedance calculation methods proposed in Section 4.5 - 4.7 were used in this section. In addition, the difference in the fault voltages and currents during the transposed and horizontally / vertically configured untransposed cases were analyzed.

*Fault analysis using phase components*

For example purposes, analysis was conducted on a 100 mile long 288.7 kV six phase line with phase spacing of 23.1 ft and Drake conductors. The example is denomi-
nated as Use Case K. The line is terminated in $R_{\text{load}} + jX_{\text{load}}$. The values of $R_{\text{load}}$ and $X_{\text{load}}$ were calculated assuming that the load operates at rated voltage (i.e., 288.7 kV) and the complex load power for this purpose is 1 GVA at 0.86 power factor lagging. The case of no fault and fault on phase F are considered in Use Case K. The fault occurs phase F to ground with a fault resistance of 40 Ω, where $R_{\text{fault}} \ll R_{\text{load}}$. The circuit seen in Figure 4.17 was modeled and the results can be seen in Table 4.7. Use Case K is solved using phase component analysis to determine the fault current for a single phase to ground fault.

![Fault Analysis Circuit Modeled in Use Case K](image)

Figure 4.17 Fault Analysis Circuit Modeled in Use Case K
Table 4.7 Use Case K: Six Phase, Phase F to Ground Fault Analysis Results of Phase Currents, Fault Current, Fault Voltage *

<table>
<thead>
<tr>
<th></th>
<th>No fault transposed case</th>
<th>No fault untransposed case</th>
<th>Fault transposed case</th>
<th>Fault untransposed case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_a$</td>
<td>642 A</td>
<td>675 A</td>
<td>670 A</td>
<td>683 A</td>
</tr>
<tr>
<td>$I_b$</td>
<td>642 A</td>
<td>643 A</td>
<td>511 A</td>
<td>529 A</td>
</tr>
<tr>
<td>$I_c$</td>
<td>642 A</td>
<td>634 A</td>
<td>502 A</td>
<td>513 A</td>
</tr>
<tr>
<td>$I_d$</td>
<td>642 A</td>
<td>638 A</td>
<td>655 A</td>
<td>651 A</td>
</tr>
<tr>
<td>$I_e$</td>
<td>642 A</td>
<td>632 A</td>
<td>785 A</td>
<td>793 A</td>
</tr>
<tr>
<td>$I_f$</td>
<td>642 A</td>
<td>612 A</td>
<td>1873 A</td>
<td>1782 A</td>
</tr>
<tr>
<td>$I_{fault}$</td>
<td>0</td>
<td>0</td>
<td>1751 A</td>
<td>1666 A</td>
</tr>
<tr>
<td>$V_{fault}$</td>
<td>321 kV</td>
<td>306 kV</td>
<td>70 kV</td>
<td>67 kV</td>
</tr>
</tbody>
</table>

*Solved with phase variables

**Generalized fault analysis with sequence components**

A general six phase fault analysis method using generalized sequence components is presented. A three phase general fault analysis is discussed in [112]. For the generalized case, assumptions are made that there is zero fault impedance, and the load current is much less than the fault current. Therefore the prefault load current is assumed to be negligible.

For a generalized per unit six phase example a single phase to neutral fault occurs on phase F. The prefault voltage is,

$$V_{abc}^{pre} = \begin{bmatrix} 1 \\ b^5 \\ b^4 \\ b^3 \\ b^2 \\ b \end{bmatrix}$$

The subscripts and superscripts $abc$ represent the phase components, $seq$ represents sequence components, $pre$ represents prefault conditions, and $post$ represents postfault
conditions. Using the line impedance modal matrix $T$, where $b = \frac{1}{60}$, the prefault sequence voltage is,

$$V_{seq}^\text{pre} = T^{-1}V_{abc}^{\text{pre}} = \frac{1}{\sqrt{6}} \begin{bmatrix}
1 & b^5 & b^4 & b^3 & b^2 & b \\
1 & b^4 & b^2 & 1 & b^4 & b^2 \\
1 & b^3 & 1 & b^3 & 1 & b^3 \\
1 & b^2 & b^4 & 1 & b^2 & b^4 \\
1 & 1 & b^3 & b^2 & b^3 & b^2 \\
1 & b & b^2 & b^3 & b^4 & b^5 \\
\end{bmatrix}^{-1} \begin{bmatrix}
1 \\
b^5 \\
b^4 \\
b^3 \\
b^2 \\
b \\
\end{bmatrix} = \begin{bmatrix}
0 \\
\sqrt{6} \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}.$$  

The assumption of ‘balanced’ line impedances is made. Similar to the prefault case, the postfault phase and sequence voltages are,

$$V_{abc}^{\text{post}} = \begin{bmatrix}
V_a^{\text{post}} \\
V_b^{\text{post}} \\
V_c^{\text{post}} \\
V_d^{\text{post}} \\
V_e^{\text{post}} \\
\end{bmatrix},$$  

$$V_{seq}^{\text{post}} = T^{-1}V_{abc}^{\text{post}} = \frac{1}{\sqrt{6}} \begin{bmatrix}
1 & b^5 & b^4 & b^3 & b^2 & b \\
1 & b^4 & b^2 & 1 & b^4 & b^2 \\
1 & b^3 & 1 & b^3 & 1 & b^3 \\
1 & b^2 & b^4 & 1 & b^2 & b^4 \\
1 & 1 & b^3 & b^2 & b^3 & b^2 \\
1 & b & b^2 & b^3 & b^4 & b^5 \\
\end{bmatrix}^{-1} \begin{bmatrix}
V_a^{\text{post}} \\
V_b^{\text{post}} \\
V_c^{\text{post}} \\
V_d^{\text{post}} \\
V_e^{\text{post}} \\
\end{bmatrix} = \frac{1}{\sqrt{6}} \begin{bmatrix}
V_a^{\text{post}} + V_b^{\text{post}} + V_c^{\text{post}} + V_d^{\text{post}} + V_e^{\text{post}} \\
V_a^{\text{post}} + bV_b^{\text{post}} + b^2V_c^{\text{post}} + b^3V_d^{\text{post}} + b^4V_e^{\text{post}} \\
V_a^{\text{post}} + bV_b^{\text{post}} + b^2V_c^{\text{post}} + b^3V_d^{\text{post}} + b^4V_e^{\text{post}} \\
V_a^{\text{post}} + b^3V_b^{\text{post}} + V_c^{\text{post}} + b^3V_d^{\text{post}} + V_e^{\text{post}} \\
V_a^{\text{post}} + b^4V_b^{\text{post}} + b^2V_c^{\text{post}} + V_d^{\text{post}} + b^4V_e^{\text{post}} \\
V_a^{\text{post}} + b^5V_b^{\text{post}} + b^4V_c^{\text{post}} + b^3V_d^{\text{post}} + b^2V_e^{\text{post}} \\
\end{bmatrix}.$$  

The postfault current in phase components and sequence components respectively are,
For a bolted fault at phase F there is zero postfault voltage for phase F. It is assumed that there is only one nonzero postfault current and this is at phase F. Assuming a fully transposed system, where \( Z_S \) is the self impedance and \( Z_{mi} \) is the mutual impedance, the line impedance matrix is in (4.2) which is diagonalized by modal matrix \( T \), namely the generalized sequence components transformation matrix. This results in a sequence component impedance matrix, in (4.14).

Utilizing the previously determined matrices and setting self and mutual impedances, self impedance, \( j0.133 \ (R = 0) \) and all mutual impedances, \( j0.0333 \) (per unit), the six unknowns (postfault voltages and fault current) can be solved simultaneously from,

\[
V_{seq}^{post} = jZ_{6seq}I_{seq}^{post} + V_{seq}^{pre}
\]

\[
\left[ V_a^{post} + V_b^{post} + V_c^{post} + V_d^{post} + V_e^{post} \\
V_a^{post} + bV_b^{post} + b^2V_c^{post} + b^3V_d^{post} + b^4V_e^{post} \\
V_a^{post} + b^2V_b^{post} + b^4V_c^{post} + b^4V_d^{post} + b^2V_e^{post} \\
V_a^{post} + b^3V_b^{post} + bV_c^{post} + b^3V_d^{post} + bV_e^{post} \\
V_a^{post} + b^4V_b^{post} + b^2V_c^{post} + b^4V_d^{post} + b^4V_e^{post} \\
V_a^{post} + b^5V_b^{post} + b^4V_c^{post} + b^3V_d^{post} + b^2V_e^{post}
\right]
\]

\[
= \text{diag} \left[ \begin{array}{cccccc}
I_F & b^5I_F & b^4I_F & b^3I_F & b^2I_F & bI_F \\
Z_s + 2Z_{m1} + 2Z_{m2} + Z_{m3} & Z_s + Z_{m1} - Z_{m2} - Z_{m3} & Z_s - Z_{m1} - Z_{m2} + Z_{m3} & Z_s - 2Z_{m1} + 2Z_{m2} - Z_{m3} & Z_s - Z_{m1} - Z_{m2} + Z_{m3} & Z_s + Z_{m1} - Z_{m2} - Z_{m3}
\end{array} \right] \cdot \left[ \begin{array}{c}
l_F \\
b^5l_F \\
b^4l_F \\
b^3l_F \\
b^2l_F \\
bbl_F
\end{array} \right] + \left[ \begin{array}{c}
0 \\
6 \\
0 \\
0 \\
0 \\
0
\end{array} \right].
\]
This solution can be viewed in a phasor diagram of the postfault and prefault phase voltages in Figure 4.18. The sequence voltages can also be viewed in Figure 4.19, and they are,

\[
\begin{bmatrix}
V_{pa}^{post} \\
V_{pb}^{post} \\
V_{pc}^{post} \\
V_{pd}^{post} \\
V_e^{post} \\
I_F
\end{bmatrix} = \begin{bmatrix}
0.90\angle-14^\circ \\
1.15\angle-71^\circ \\
1.25\angle-120^\circ \\
1.15\angle-169^\circ \\
0.90\angle134^\circ \\
7.5\angle150^\circ 
\end{bmatrix}.
\]

Figure 4.18 Fault Analysis Phasor Diagram of Prefault Voltages and Postfault Voltages after a Phase to Neutral Fault on Phase F for Generalized Fault Analysis Example. Phase Variables are Depicted.

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It is possible to validate the results approximately in this example by examining
the system response in phase A. In phase A, the postfault condition might be described as
an expectation of $1/0.0^\circ$ per unit voltage (the source) plus the voltage induced in phase A
due to the fault current in phase F. That mutually induced voltage is $(jX_m)(I_f) =
(7.5/150^\circ)(0.0333/90^\circ)$ per unit. When the mutually induced voltage is added to $1/0.0^\circ$, a
load end voltage in phase A of $0.9015/13.88^\circ$ per unit is found. This compares with
$0.90/14.00^\circ$ per unit as found before. To validate the sequence voltage results, the phase
components are multiplied by the inverse of the transformation matrix for six phase. It
can be determined from the sequence voltages that a large unbalance occurs with loss of
phase F.
4.13 The Transposition of HPO Overhead Circuits

Introduction

This section focuses on HPO transposition and voltage unbalance and much of this section was presented in [117]. Transposition of overhead AC transmission circuits has been used for decades. Transposing three phase lines has been studied extensively, e.g., [118, 119]. However, transposing HPO lines is infrequently discussed. The reasons for transposing lines can be found in the literature, e.g. [120-122]. In brief, untransposed transmission lines cause voltage and current unbalance that lead to problematic operating conditions, counter rotating torque on machines, increased losses in some cases, and protection considerations. For analysis purposes this section focuses only on unbalance caused by the transmission line (i.e., self impedances and mutual coupling among the phases).

The term ‘fully transposed’ may take on a range of meanings. For present purposes, assume that a fully transposed transmission line has a line impedance matrix in the form (4.12). The shunt capacitance is readily modeled through the use of a capacitance matrix: the capacitance matrix is in the same form as (4.12) with the capacitance to ground on the diagonals and the phase-phase capacitance on the off-diagonals. For the fully transposed case, the off-diagonal entries of the capacitance matrix are all equal and the diagonal entries are all equal.

The term ‘roll transposed’ refers to a transmission line that is physically ‘rolled’ as pictorially illustrated for a six phase example in Fig. 4.20. Fig. 4.20 may be in any configuration and any number of phases, the same roll transposition method applies to render
the capacitance matrix and impedance matrix in the $n$ by $n$ SCT form, (4.10) for even $n$ and (4.11) for odd $n$.

Circulant matrices have special properties that are discussed in [107, 110]. For three phase systems, roll transposed conductors are fully transposed; however, for HPO systems this observation is not true.

![Figure 4.20 An Illustration of ‘Rolling’ the Phases of a Six Phase Transmission Line in a Transposition Process](image)

*Figure 4.20 An Illustration of ‘Rolling’ the Phases of a Six Phase Transmission Line in a Transposition Process*

A comparison of fully transposed vs. roll transposed transmission lines

The fault analysis for a fully transposed line is straightforward because all the sequence impedances are equal (other than the zero sequence impedance). This property results in relatively simple protection schemes for fewer fault types as compared to the rolled transposition case. However, there are many disadvantages to fully transposing an HPO transmission line.

HPO transmission lines have lower phase to phase voltage than comparable three phase counterparts. This lower voltage permits closer phase conductor spacing. The closer phase spacing results in potential benefits, as mentioned in Chapter 2. If HPO lines were fully transposed, the phase compaction benefits may be lost: this is due to the fact that greater phase spacing is needed between phases $A$ and $C$ than $A$ and $B$ (for example)
in HPO lines. For this reason high phase order transmission lines should be roll transposed, not fully transposed. In addition, roll transposed designs are relatively simple from a construction point of view, whereas fully transposed designs require exchanging conductors and different tower configurations. Perhaps the most salient reason that roll transposition is preferred over full transposition is that the number of transposition sections needed is dramatically reduced in the case of roll transposition. Table 4.8 shows the number of transposition sections required for differently configured transmission lines to be either roll transposed or fully transposed.

In Table 4.8 the configuration of most interest is the circularly configured case because this design makes the best use of higher power transfer with limited ROW. Double vertical or vertically configured HPO transmission lines are also of interest because they can transfer high power with shorter tower heights as compared to comparable multicircuit three phase designs.

Voltage unbalance factor

A commonly accepted unbalance factor for three phase voltages is,

\[ U_{3ph} = \frac{|V_-|}{|V_+|} \]  \hspace{1cm} (4.37)

with \( V_- \) and \( V_+ \) denoting the negative and positive sequence voltages. Equation (4.37) will be termed the ‘three phase voltage unbalance factor’ for purposes of this thesis. Other common voltage unbalance factors are defined by National Electrical Manufacturers Association (NEMA) and Institute of Electrical and Electronics Engineers (IEEE) [123] and further unbalance factors are discussed in [120, 122]. For \( n \)-phase circuits there are \( n \) se-
quence voltages. Certain other sequence voltages that are similar to negative sequence voltage in the three phase case may result in undesired torque in rotating machines. For this reason, it appears to be useful to define an \( n \)-phase voltage unbalance factor (VUF) that models the positive sequence voltage in the denominator and all other sequences in the numerator.

Table 4.8 Number of Transpositions Sections for Full or Roll Transposition \((n = \text{Number of Phases})\)

<table>
<thead>
<tr>
<th>HPO conductor configuration (examples shown)</th>
<th>Transposition sections needed to be ‘roll transposed’</th>
<th>Transposition sections needed to be ‘fully transposed’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetrical circular (equal spacing)</td>
<td></td>
<td>( \frac{n!}{2} )</td>
</tr>
<tr>
<td>Vertical (equal spacing)</td>
<td></td>
<td>( n )</td>
</tr>
<tr>
<td>Double vertical (equal spacing)</td>
<td></td>
<td>( \frac{n!}{2} )</td>
</tr>
<tr>
<td>Horizontal (equal spacing)</td>
<td></td>
<td>( \frac{n!}{2} )</td>
</tr>
<tr>
<td>Arbitrary</td>
<td></td>
<td>( n! )</td>
</tr>
</tbody>
</table>

Therefore, a ‘generalized voltage unbalance factor’ is introduced,
where $n$ is the number of phases, zero sequence voltage is $V_0$, positive sequence voltage is $V_1$, negative sequence voltage is $V_{n-1}$ and the other sequences $1 < q < n-1$ are sequences that do not exist in the three phase case. To measure unbalance for an HPO transmission line the generalized VUF will be compared with three other possible measures of VUF. In this comparison it will be shown that the generalized VUF is a good indication of unbalance for an HPO transmission line.

The generalized VUF is used in this thesis to illustrate the consequences of transposition and geometry of the conductors for HPO transmission lines. A possible use of HPO is to supply HPO motors directly. Therefore, a HPO complex voltage unbalance factor (CVUF) could be useful to determine the derating of HPO motors with voltage unbalance. CVUFs are discussed in the literature [124, 125]. However, it should be noted that even a CVUF may not be a sufficient indication of voltage unbalance [126, 127]. In addition, the possibility of using a ‘balance factor’ could be beneficial to give a measurement indication of how balanced the system is. Also, unbalance causes counter rotating torque on machines and motors, further studies in the area of electrical machines should discuss how HPO unbalance affects torque on machines.

**Voltage unbalance factor as a measure of transposition effectiveness**

Transposition is needed in long line designs. However, transposition is expensive and can cause stress on conductors (e.g., mile for mile, faults are more likely in transposi-

\[
U_{nph} = \frac{\sqrt{\sum_{q=2}^{n-1} |V_q|^2} + |V_0|^2}{|V_1|},
\]

(4.38)
tion sections than ordinary sections [128], and mechanical stress occurs in transposition sections). For these reasons, it is beneficial to determine the number of transpositions needed to minimize the VUF to an acceptable level. If the transmission line is completely roll transposed, the VUF due to the transmission line impedances is zero.

The four VUFs compared are calculated in a way described in the flow chart in Fig. 4.21. For phase order \( n = 3k \) where \( k = 1, 2, \ldots \), a way to measure voltage unbalance for an HPO transmission line is to utilize the voltage unbalance of each three phase circuit that may be derived from the \( k \) different three phase subcircuits. For example, for a six phase transmission line, measurements of unbalance would be taken from two three phase circuits, i.e., unbalance on phases A, C, E, and unbalance on phases B, D, F. Both the maximum unbalance and the average unbalance are analyzed and compared to the generalized VUF.

A VUF comparison is made for the following test bed example, however note that similar examples follow the same trends and results. A long line example is used to emphasize the impact of transposition on voltage unbalance. Consider a 200 mile long six phase 79.7 kV voltage line-line (\( V_{ll} \)) transmission line and a twelve phase 41.2 kV \( V_{ll} \) transmission line; this is equivalent to a three phase 138 kV \( V_{ll} \) transmission line.
Figure 4.21 Flow Chart to Calculate Four Unbalance Factors for Comparison Purposes

All example lines carry 100 MVA of power at 0.8 power factor. Drake conductors are utilized with 5 ft phase to phase spacing. The height of the lowest conductor is 35 feet. This example is termed Use Case L. Examples are shown for six phase and twelve phase designs in configurations shown in Table 4.9 [51]. Dashed lines are insulators. The VUFs are calculated for each number of transposition sections applied to the example transmission lines, and the VUFs are compared in Figures 4.22-4.24.
Table 4.9 Different HPO Configurations for the Cited Test Bed Example (Drake, 200 mile, 100 MVA Line)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Configuration</th>
<th>Configuration</th>
<th>Configuration</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A six phase circular</td>
<td>B six phase double vertical</td>
<td>C six phase vertical</td>
<td>D twelve phase circular</td>
<td>E twelve phase double vertical</td>
</tr>
</tbody>
</table>

Configuration D: Twelve phase circular

Notice how low the VUF is to begin with. For this reason it is possible that no transposition is needed for circular designs.

Notice the generalized VUF is similar to the avg. of the two individual three phase circuits VUF and the maximum of the two individual three phase circuits VUF.

Notice how the unbalance factor for 3 phase applied to 6 phase is not a good indication of unbalance (solid line).

Configuration A is very similar to this case, and therefore not shown.

Figure 4.22 VUF vs. Number of Transpositions Sections for Configuration D (from Table 4.9)
Configuration C: Six phase vertical

Notice the generalized unbalance factor is similar to the average of the two individual three phase circuits unbalance factor and the maximum of the two individual three phase circuits unbalance factor.

Configuration E: twelve phase double vertical

Notice that after n/2 transposition the unbalance is the second lowest.

Notice how the generalized VUF is similar to the other measurements of VUF. Again showing that the generalized VUF is a good indicator of voltage unbalance.

Configuration B is very similar to this case, and therefore not shown.

Note that results were also checked with NEMA and IEEE voltage unbalance factors, and similar results were verified. The generalized VUF followed the same trends.
and similar magnitudes as the NEMA and IEEE VUFs. A few key results can be drawn from Figs. 4.22-4.24:

A. From these results it can be shown that generally for the first \( n/2 \) transpositions, with increase in transposition sections there is a decrease in VUF. Therefore one can determine if all transpositions are needed, or if it is more economical to use just enough transposition sections to reach an acceptable unbalance.

B. Notice that if the transmission line is circularly configured the VUF is very small and may not need any transposition.

C. Notice if the transmission line is double vertically configured, after \( n/2 \) transpositions, the VUF is often the second lowest. For this reason, it may be beneficial to use \( n/2 \) roll transposition sections instead of fully rotating the conductors and using \( n \) roll transpositions.

D. Notice that the defined generalized VUF is similar and corresponds to the average of the multicircuit three phase VUF and the maximum of the multicircuit three phase VUF. The generalized VUF is also shown to be a better indicator than using the three phase VUF applied to the HPO case. Therefore, an appropriate indication of voltage unbalance can be obtained with (5) without additional steps of converting to multicircuit three phase.

E. If a \( 3k \) order circuit \((k = 1, 2, \ldots)\) energizes \( k \) three phase rotating loads, the maximum of the multicircuit three phase VUF gives a measure of the greatest impact on the three phase rotating loads \([129, 130]\) and rectifier loads \([131]\). The generalized VUF also affords an appropriate impact measure. Further studies may also research
a CVUF to give a better indication of the effects of voltage unbalance on rotating loads [124, 125].

Conclusions drawn relating to transposition and voltage unbalance

Although there are no HPO transmission lines in existence, it is beneficial to study the possibility of HPO in the design of high density power transmission. This section discusses two aspects of HPO transmission: transposition and voltage unbalance. Definitions of ‘roll transposed’ and ‘fully transposed’ have been presented with advantages and disadvantages of each. The conclusion is that roll transposition should be used with HPO transmission lines that have high unbalance. In addition, a generalized voltage unbalance factor was introduced and verified through comparison to other unbalance measures. The generalized unbalance factor is an appropriate indication of voltage unbalance for an HPO transmission line and a better indication than using the traditional three phase unbalance factor. Fully rotating the phases in roll transposition may not be needed, that is, it may be sufficient to use just enough transposition sections to minimize the unbalance factor to an acceptable level. This is especially true for double vertical constructions where \( n/2 \) transposition sections may sufficiently attain a low level of voltage unbalance.

4.14 Operation in Steady State with an Open Phase

The majority transmission line faults are single phase to ground faults [111]. Upon occurrence of a fault, instead of tripping the entire line out of service, single pole switching has been proposed [132, 133]. Single pole switching refers to opening a faulted phase leaving the sound phases in operation. For the three phase case, this has been pro-
posed for high level bulk power applications (e.g., 500 kV) [132]. The advantages of single pole switching and single phase out of service relate to both minimizing the power level interrupted and improvement of circuit reliability. References [132, 134] document some of these ideas for the three phase case.

Steady state operation with a loss of phase for HPO systems may be better justified than the outage of all three phases. Single pole switching results in the loss of $1/n$ of the total power capacity. For example, if a six phase transmission line loses one phase, instead of tripping the entire circuit, one could remove the outaged phase and still allow for 83.3% the total line load; for the three phase case, that the retained transmission capability is 66.7% (see Fig. 4.25). For the $n$-phase case, the retained transmission capacity with loss of a single phase is $100(n-1)/n$%.

Figure 4.25 The Retained Transmission Capability with One Phase Out of Service
Single pole switching causes significant transients, and a transient stability assessment (in full $n$ phase detail) must be completed to determine if single pole switching is possible. This is a network simulation. There are references that discuss this for three phase [135] and for HPO [136]. The literature also discusses a phenomenon that occurs during open phase operation called ‘secondary arc current’ [137, 138]. Secondary arc current refers to the current that is still flowing in the open phase (faulted phase) due to coupling between the energized phases. In addition, operating with an open phase will cause high levels of negative and zero sequence current. However, there are sequence filtering approaches using a shunt compensator arrangement to, in effect, eliminate the zero and negative sequence components [133]. A disadvantage of single pole switching is the requirement for identification of the phase to be outaged, and the single pole outaging of that phase. There are also implications of single pole switching on system protection.

The analysis in this section focuses on the steady state analysis of an $n$-phase transmission line operating with an open phase. One potential way to identify whether operation with loss of phase is ‘tolerable’ is through the use of the voltage unbalance factor. The subject of unbalance factor was discussed in Section 4.12. Voltage unbalance factors are described in (4.38) and (4.37) along with other unbalance factors described in [120, 122, 123].

A comparison is made to determine the unbalance during open phase condition on an $n$-phase transmission line. The test bed circuit is shown in Fig. 4.26, an $n$-phase circuit with phase A open. Fig. 4.27 displays the transmission line voltage unbalance during operation with loss of one phase vs. the number of phases. The transmission line example in
Fig. 4.26 is a 200 kV voltage line to neutral, 100 mile long fully roll transposed line with Drake conductors serving a 200 MVA load at 0.8 power factor lagging. The height of the lowest conductor is 35 ft and the conductors are arranged circularly. The three phase conductor spacing is 25 ft and the phase spacing changes as the phase order increases as seen in Table 4.2. That is, the phase to nearest phase spacing decreases as phase order increases due to lower voltage line to line. Phase A is open and the voltage unbalance calculated. This example is Use Case N (see Appendix A).

The results of this analysis show that the transmission line voltage unbalance decreases as phase order increases initially during single open phase conditions. For the aforementioned example in Use Case N, unbalance for three phase is 4-12% (dependent on which unbalance factor used) and decreases to 1-4% for the six phase case.

A second analysis of voltage unbalance during open phase conditions is to calculate the unbalance at the secondary side of a transformer. That is, a transmission line is connected to a wye-delta (star-polygon for the HPO case) transformer and one phase is disconnected on the wye side of the transformer. The voltage unbalance on the delta side of the transformer during open phase operation is evaluated. The $n$-phase delta-wye connected transformer circuit diagram is shown in Figure 4.28. For example purposes, each phase leakage reactance will be 0.1 ohms and the magnetizing reactance of 10 ohms and a core loss resistance of 30 ohms. The voltage unbalance during an open phase condition vs. the number of phases can be seen in Figure 4.29.
Figure 4.26 Open Phase Operation $n$-phase Circuit for Use Case N
Figure 4.27 Transmission Line Voltage Unbalance Factor vs. Number of Phases with an Open Phase A for Use Case N

Figure 4.28 Wye-Delta (Star-Polygon) $n$-phase Transformer Connections
The use of HPO cables can take full advantage of the lower phase to phase voltage, allowing for decreased cable dielectric. A six phase cable design can be seen in Fig. 4.30. In addition, layered cables with different levels of dielectrics could be utilized as seen in the HPO cables in Fig. 4.31 and optimal packing could be used to reduce cable size further as seen in Fig. 4.32. For example if twelve conductors were in one cable, optimal packing of the cable for space considerations can be seen in Figure 4.32. Optimal packing determines that the smallest circle, that twelve circles of equal size (diameter = 1
ft), can fit into has a diameter = 4.029 ft (this ration of 1 to 4.029 holds true no matter what units). The point of these designs are to compact the cable size.

Using a finite element analysis tool, the electric fields in the cable could be determined and forced to be evenly distributed using different dielectrics. This may have the advantage of a smaller overall cable (possibly less dielectric material) and lower electric fields at the outside of the cable. The disadvantages are the same as described in overhead HPO transmission. Also, the capacitance may increase which could be a disadvantage. In these designs, unbalance may occur due to the uneven geometry of the cable. Therefore, HPO layered cables are more likely to be applied to short cable designs. If these designs were used in long cable designs transposition may need to be used as described in Section 4.13. In addition, HPO cables may be designed to optimize to a specific impedance and capacitance level, similar to designing the sequence impedances as in Section 4.8. A comparison could be made between HPO cables and three phase or HVDC cables. Note that typically high voltage cables individually insulate each phase [139]; however, a HPO single cable could be beneficial in low voltage underground circumstances. There is a patent pending for these designs [140].

Figure 4.30 Conceptualized Design for a Six Phase Cable
Figure 4.31 Conceptualized Designs for a Twelve Phase Layered Cable

Figure 4.32 Conceptualized Design for an Optimally Packed Twelve Phase Two-Layer Cable
4.16 Networked System – Line Conversion from Double Circuit Three Phase to Six Phase

Throughout this chapter, a single $n$-phase line has been studied and in Chapter 5 a single $n$-phase transmission line analysis program is explained. Even though the basis of simulation is a single line, a networked full system should be studied with high phase order integrated in the system to determine system wide changes due to HPO integration. This has been briefly studied with small systems in [100]. For this reason, the IEEE 30 bus test system [141] will be used for an HPO integration study. The solution shall be found using OpenDSS [142]. Two cases are studied and compared: the existing two 132 kV three phase circuits between Glen Lyn and Claytor substations, and if a six phase line were utilized instead with increased voltage line to neutral. This section is not suggesting replacing the existing two three phase circuits with six phase, purely an analysis comparing the two cases.

The main advantages of upgrading to six phase vs. double circuit three phase is an increase in the thermal and security rating on the transmission line. For a six phase line, the thermal rating would be approximately 173%, the security rating be approximately 289%, and the SIL would be approximately 300% of the original double circuit three phase line. The increase in capacity is mainly due to an increase in voltage line to neutral (without an increase in voltage line to line). The increase in transmission line capacity comes without an increase in right of way. Therefore double circuit transmission lines in need of a significant increase in power capacity may be targeted for conversion to six phase.
The main disadvantages of upgrading to a six phase line with higher voltage is an additional two to four transformers. In addition, some construction modifications may be needed. The insulators from the tower to each phase would need to be changed to insulate to the higher voltage line to neutral. In addition, the clearance from phase to tower and phase to ground may need to be increased due to the higher voltage line to neutral. However, if the voltage on a double circuit three phase line were increased, the same advantages and disadvantages are realized, but with the added disadvantage of significantly more required right of way.

Figure 4.33 IEEE 30 Bus Test System [141]
Double circuit three phase compared to six phase

The goal of this study is to see how the six phase line would integrate in the networked system and compare to a double circuit three phase line. More specifically, a power flow study and fault studies throughout the system are analyzed, i.e. every phase to ground and every phase to phase fault possible in the entire system is studied to determine the system changes between the six phase and double circuit three phase line. The parameters changed are the positive and zero sequence impedance and capacitance, along with the voltage line to neutral as in Table 4.10. The line under study is between substations Glen Lyn and Claytor, originally a 132 kV double circuit three phase line. The six phase line has an extra two transformers; the additional transformer reactance is not modeled. The extra transformer reactance is insignificant on long transmission lines, and transformers can be manufactured down to near zero reactance.

Table 4.10 Six Phase and Double Circuit Three Phase Parameters for OpenDSS That are Changed for Study in Figure 4.33

<table>
<thead>
<tr>
<th></th>
<th>Double circuit 3φ</th>
<th>6φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{ll}$</td>
<td>132 kV</td>
<td>132 kV</td>
</tr>
<tr>
<td>$V_{ln}$</td>
<td>76.2 kV</td>
<td>132 kV</td>
</tr>
<tr>
<td>$V_{base}$</td>
<td>132 kV</td>
<td>228.6 kV*</td>
</tr>
<tr>
<td>$S_{base}$</td>
<td>100 MVA</td>
<td>100 MVA</td>
</tr>
<tr>
<td>$Z_{base}$</td>
<td>174.2 Ω</td>
<td>522.7 Ω</td>
</tr>
<tr>
<td>$R^+$</td>
<td>6.69 Ω</td>
<td>2.23 Ω</td>
</tr>
<tr>
<td>$R^o$</td>
<td>20.03 Ω</td>
<td>6.69 Ω</td>
</tr>
<tr>
<td>$X^+$</td>
<td>20.07 Ω</td>
<td>7.43 Ω</td>
</tr>
<tr>
<td>$X^o$</td>
<td>60.11 Ω</td>
<td>39.27 Ω</td>
</tr>
<tr>
<td>$C^+$</td>
<td>401.90 nF</td>
<td>542.56 nF</td>
</tr>
<tr>
<td>$C^o$</td>
<td>133.97 nF</td>
<td>200.95 nF</td>
</tr>
</tbody>
</table>

*Voltage base is $\sqrt{3}$ higher in the 6φ case for OpenDSS to model a 6φ line
This comparison between six phase and double circuit three phase (no changes to the line except shifting three phases by 60 degrees) reveals: a six phase line has smaller positive and zero sequence capacitance, greater positive and zero sequence reactance, and equal resistance. However, if the voltage line to neutral is increased by $\sqrt{3}$ in the six phase case and the voltage base is also increased by $\sqrt{3}$, then in per unit (the values in Table 4.10 had to be changed to incorporate a change in per unit for the 6φ case): a six phase line has greater positive and zero sequence capacitance, and smaller positive and zero sequence impedance as in Table 4.10 (due to the higher voltage base).

System power flow analysis

The complete power flow analysis of the system in Figure 4.33 is in Appendix C. In brief, upgrading to a six phase line with higher voltage line to neutral caused an increase in power flow on the Glen Lyn – Claytor transmission line to 122% of the original case, or an increase of 37.2 MVA. In addition, lines between buses 2-4, 2-6, 2-5, all increased in power flow, while transmission lines between buses 1-3 and 3-4 decreased in power flow. The entire system incurred changes in power flow, but the lines closest to the six phase line were affected the most. To illustrate the value of the upgrade, consider the case that the original construction had a complex power rating of 160 MVA. The upgraded circuit has a rating of 277.1 MVA ($\sqrt{3}$ higher than the double circuit 3φ case). The original loading of the double circuit line Glen Lyn – Claytor is 170.8 MVA (i.e. 10.8 MVA overloaded). The upgraded 6φ line is loaded at 208 MVA which is well below its 277.1 MVA rating.
System fault analysis

Relating to the fault performance of the original 3φ system versus the upgraded 6φ system, because the per unit impedance of the 6φ line is lower than that of the original construction, the expected fault currents are higher in the upgraded case. For example:

- At the Claytor terminal of the line bus 1 – 2, the original fault current for a phase to ground fault is 7083 A. A three phase fault current in one three phase circuit is 10,346 A (in each phase). The phase to phase fault current for the double circuit 3φ case is 8960 A.

- At Claytor, in the 6φ case, the phase to ground fault current is 8481 A. If three phases of the six phase circuit are faulted to ground, the fault current in each faulted phase is 37332 A. The phase to phase fault current for the 6φ case is 32331 A.

- The required circuit breaker interruption current rating of the 6φ upgrade is roughly triple that of the double circuit 3φ counterpart. This is consequence of the much higher power rating of the 6φ line.

- It is difficult to form conclusions on the fault response of a double circuit 3φ to a 6φ circuit: for example it is difficult to compare a 3φ A-B-C fault to a six phase A-C-E fault.

4.17 Applications

The application of HPO technologies has not really been accepted by the electric power industry. However, if one wishes to implement high energy and high power densi-
ty in given transmission rights of way, HPO is certainly one potential technology that deserves attention. Utilization of HPO designs seem best suited in certain applications:

- Long lines where ROW is expensive or impossible to obtain
- Upgrading existing double circuit three phase lines to increase power capacity
- Underground and undersea cables from a wind farm (especially if AC-DC-AC conversion is already used), and HPO could be generated at that wind farm
- Supplying HPO motors and rectifiers directly
- Supply $n$-single phase loads, this could allow for single pole switching and increased reliability. This could especially be beneficial in microgrids.
- For an application in which single pole switching is allowed. This is the case of steady state operation of an HPO line with one phase out of service.
- For the case of a new, long, transmission line where four transformers are needed; possibly use six phase instead of double circuit three phase.

4.18 Conclusions

High phase order systems can be advantageous to transfer bulk power with minimal ROW. Upgrading a multicircuit three phase transmission line to a high phase order circuit could allow for an increase in power capacity (e.g. six phase can increase the voltage line to neutral and power capacity by 73% compared to double circuit three phase). Due to the lower voltage phase to phase, compaction can be utilized thus receiving the benefits of a compact line. In addition, a compact HPO line when compared to its three phase counterpart, has decreased lightning exposure, can decrease the loading of adjacent transmission assets, can be designed to require few or no transpositions, and has shown to
be able to handle the increased fault complexity. However, there is increased cost at the terminal ends of the HPO transmission line, increased relay complexity, and possibly less aesthetic.

Using properties of circulant matrices, a generalized calculation method for the sequence impedances in terms of self and mutual impedances is presented. Additionally, a method of calculation of the sequence impedances is presented using geometric properties and phase spacing distances. A generalized form of the modal matrix $T$, namely the sequence components transformation is presented. A novel method to design sequence impedances using optimization techniques is presented. Also, transpositions of HPO systems are modeled with practical results utilizing a new possible HPO unbalance factor. A fault analysis using generalized sequence components has been illustrated and equations for the number of fault types and number of significant fault types are presented. In addition, analysis of HPO systems with the loss of one phase is presented. Lastly, a network example of six phase versus double circuit three phase is presented.
CHAPTER 5

A GRAPHICAL USER INTERFACE FOR THE STEADY STATE ANALYSIS OF A
HIGH PHASE ORDER TRANSMISSION LINE

5.1 Program Objectives: a Graphic User Interface for HPO Circuit Analysis

A high phase order analysis program was developed to run a steady state analysis of any $n$-phase transmission line. The main objective was to perform fault analysis of any fault type and any number of simultaneous faults for an $n$-phase transmission line. In addition, the program is to provide a transposition analysis, open phase condition analysis, electric and magnetic field analysis, line loss analysis, and sequence impedance calculations.

5.2 Verification and Validation of Program

To verify and validate this program, the basic functions were checked with existing power applications; PowerWorld for the three phase case and with OpenDSS for the HPO case. The program gave similar results to OpenDSS for HPO fault currents and voltages for single line to ground faults and single phase to phase faults. PowerWorld also gave similar results for the same analysis with three phase. The program is developed in MATLAB. The program uses an equivalent $\pi$ model to model a single $n$-phase transmission line as seen in Fig. 5.1. Throughout Section 5.5 the sending end and receiving end of the line are cited which refers to the ends of the line seen in Fig. 5.1. The code for this analysis program is shown in Appendix D. The graphical user interface can be seen in Fig. 5.2.
Figure 5.1 Transmission Line π Model

5.3 Program Description

This program allows for inputs of transmission line data, and runs an analysis to determine a multitude of results:

1. *Transmission line fault analysis*. This is the main expected use of the program. The program shows steady state voltage and current conditions for any type of fault or multiple simultaneous faults. The user can input the fault impedances. The program shows the voltages and currents for the prefault case, the fault case, and the open phase case (postfault case).

2. *An HPO transposition analysis, with voltage unbalance factor vs. the number of transposition sections used*. This analysis should allow the user to decide if transposition is needed; and if so, how many transposition sections are needed. It also shows the receiving end voltage for the transposed and untransposed case.

3. *Voltage unbalance factor calculations during open phase conditions*. This provides the unbalance after phases have been taken out of service. This allows anal-
ysis of the single phase switching, 3-phase switching, or all-phase switching cases. The unbalance factors are as per the methods shown in Section 4.13.

4. *An electric field and magnetic field analysis at one meter above ground level.* The electric and magnetic field strength for the given transmission line is shown for normal operation, during fault conditions, and during open phase conditions. The calculation method is the method of images [8] with zero Earth resistivity (i.e., a perfect equipotential surface at ground level).

5. *Transmission line loss analysis.* This is a simple analysis to determine the transmission line resistive losses during normal operation.

6. *Sequence impedance calculation.* The program shows all the sequence impedances of the transmission line under test. The method used is from Sections 4.5 – 4.7.

5.4 Limitations of the Developed Program

This GUI program was developed for illustrative purposes. There are limitations to the HPO analysis program described here. The program uses an equivalent π model which is often used for lines up to 150 miles [76] at 60 Hz. The program assumes a constant impedance load. The analysis is strictly in the sinusoidal steady state. Overhead shield wires are not modeled. The skin effect and change in resistance vs. temperature, and corona losses are not modeled.
Figure 5.2 The HPO Transmission Line Analysis Program; the Graphical User Interface
5.5 Illustrative Example of Use

An example of the program seen in Fig. 5.1 is shown here termed Use Case M. The input data for this example is in Table 5.1. Notice this example is a six phase 132 kV voltage line to neutral (i.e. equivalent to a 230 kV *V*<sub>ll</sub> double circuit three phase line) double vertically configured transmission line with Drake conductors. The fault example is a fault from phase A to ground with ten Ohm impedance and a simultaneous fault from phase C to phase D with fault impedance of 10 + j10 Ohms.

Initial simulation results are shown in Table 5.2, i.e. the receiving end voltage during normal conditions. Transposition analysis results are shown in Table 5.3. Conditions during the faults are shown in Table 5.4. Analysis after the faulted phases are opened is in Table 5.5. Electric field results during all conditions are in Table 5.6 along with similar magnetic field results in Table 5.7. Sequence impedances and transmission line losses are shown in Table 5.8.

### Table 5.1 HPO Analysis Program Example Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>6</td>
</tr>
<tr>
<td>Voltage <em>V</em>&lt;sub&gt;in&lt;/sub&gt; (kV)</td>
<td>132 kV</td>
</tr>
<tr>
<td>Total Load (MVA)</td>
<td>100 MVA</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.8</td>
</tr>
<tr>
<td>Line length (mi)</td>
<td>100 mi</td>
</tr>
<tr>
<td>Conductor GMR (ft)</td>
<td>0.0375 ft</td>
</tr>
<tr>
<td>Conductor diameter (in)</td>
<td>1.108 in.</td>
</tr>
<tr>
<td>Conductor resistance (Ohm/mi)</td>
<td>0.1422 Ohm/mi</td>
</tr>
<tr>
<td>Phase to nearest phase spacing (ft)</td>
<td>5 ft</td>
</tr>
<tr>
<td>Height to lowest conductor (ft)</td>
<td>50 ft</td>
</tr>
<tr>
<td>Conductor configuration (circular, vertical, or double vertical)</td>
<td>Double vertical</td>
</tr>
<tr>
<td>Fault to ground on phases…</td>
<td>1</td>
</tr>
<tr>
<td>Fault to ground impedance</td>
<td>10 Ohms</td>
</tr>
<tr>
<td>Phases faulted together…</td>
<td>3-4</td>
</tr>
<tr>
<td>Phase to phase fault impedance</td>
<td>10 + j10 Ohms</td>
</tr>
</tbody>
</table>
Table 5.2 Receiving End Voltage vs. Sending End Voltage

<table>
<thead>
<tr>
<th>Sending voltage (pu)</th>
<th>Receiving end voltage for a transposed line (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_a )</td>
<td>( 0.98\angle-3.2^\circ )</td>
</tr>
<tr>
<td>( V_b )</td>
<td>( 0.98\angle-63.2^\circ )</td>
</tr>
<tr>
<td>( V_c )</td>
<td>( 0.98\angle-123.2^\circ )</td>
</tr>
<tr>
<td>( V_d )</td>
<td>( 0.98\angle176.8^\circ )</td>
</tr>
<tr>
<td>( V_e )</td>
<td>( 0.98\angle116.8^\circ )</td>
</tr>
<tr>
<td>( V_f )</td>
<td>( 0.98\angle56.8^\circ )</td>
</tr>
</tbody>
</table>

Analysis: The sending end voltage is regulated to output 1.0 pu voltage. The receiving end voltage drops to 0.98 pu which is within the commonly cited operational range of 0.95 pu and 1.05 pu. The difference in voltage phase across the line is 3.2 degrees with the ‘receiving end’ lagging.
Analysis: notice that the phase voltages on the untransposed transmission line are unbalanced. However, the transposed line has equal voltages and each phase has equal angle difference between the sending end and receiving end of the transmission line. This is also shown in the unbalance factor, which is approximately 1.5% for the untransposed case, but notice if three \((n/2)\) roll transposition sections were used, all five indicators of voltage unbalance drop to approximately zero. The 1.5% unbalance is acceptable when compared to the NEMA recommended 3% and IEC recommended 2% maximum voltage unbalance in electrical supply systems [143].
Table 5.4 Conditions During Simultaneous Faults: Phase A to Ground and Phase C to D

<table>
<thead>
<tr>
<th>Receiving end voltage during fault (pu)</th>
</tr>
</thead>
</table>
| \[
\begin{bmatrix}
V_a \\
V_b \\
V_c \\
V_d \\
V_e \\
V_f \\
\end{bmatrix} = 
\begin{bmatrix}
0.08 \angle -71.0^\circ \\
0.84 \angle -93.2^\circ \\
1.24 \angle -160.3^\circ \\
1.21 \angle -164.8^\circ \\
1.19 \angle 134.1^\circ \\
0.82 \angle 84.1^\circ \\
\end{bmatrix} \\
\] |

<table>
<thead>
<tr>
<th>Currents during fault (pu)</th>
</tr>
</thead>
</table>
| \[
\begin{bmatrix}
I_a \\
I_b \\
I_c \\
I_d \\
I_e \\
I_f \\
\end{bmatrix} = 
\begin{bmatrix}
8.05 \angle -70.1^\circ \\
0.56 \angle -102.0^\circ \\
8.22 \angle -139.9^\circ \\
6.73 \angle 49.9^\circ \\
1.04 \angle 124.0^\circ \\
0.77 \angle 78.6^\circ \\
\end{bmatrix} \\
\] |

Analysis: after the simultaneous faults, the voltages vary widely and the fault currents are 6 to 8 times the phase current. References describe protection schemes for HPO transmission [49, 50].
Table 5.5 Conditions after Faulted Phases A, C, and D are Opened, and the System is Operated with these Phases Out of Service

<table>
<thead>
<tr>
<th>Receiving end voltage with faulted phases open (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[V_a] = [1.03\angle-2.1^\circ]$</td>
</tr>
<tr>
<td>$V_b = 1.02\angle-62.4^\circ$</td>
</tr>
<tr>
<td>$V_c = 1.02\angle-117.9^\circ$</td>
</tr>
<tr>
<td>$V_d = 0.97\angle178.1^\circ$</td>
</tr>
<tr>
<td>$V_e = 0.93\angle116.4^\circ$</td>
</tr>
<tr>
<td>$V_f = 0.97\angle54.5^\circ$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Currents with faulted phases open (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[I_a] = [0.02\angle-117.2^\circ]$</td>
</tr>
<tr>
<td>$I_b = 0.83\angle-70.8^\circ$</td>
</tr>
<tr>
<td>$I_c = 0.02\angle176.9^\circ$</td>
</tr>
<tr>
<td>$I_d = 0.01\angle154.3^\circ$</td>
</tr>
<tr>
<td>$I_e = 0.75\angle109.5^\circ$</td>
</tr>
<tr>
<td>$I_f = 0.78\angle46.8^\circ$</td>
</tr>
</tbody>
</table>

Unbalance factors from transmission line after faulted phases are opened

- Avg. 3ph circuits unbalance factor: 1.83%
- Max 3ph circuits unbalance factor: 1.85%
- 3ph unbalance factor applied to HPO: 1.68%
- HPO generalized unbalance factor: 5.99%
- IEEE unbalance factor: 3.91%

Analysis: phases A, C, and D are faulted, and outaged. These phases remain open and out of service. Single pole switching, three phase switching, and n-phase switching are studied in this example. The voltage unbalance is low using five different unbalance measures. This suggests that single pole switching could be utilized and it is possible to leave the remaining phases in service. NEMA and IEC recommend the maximum voltage unbalance of 3% and 2% respectively [143]. This is steady state analysis.
Table 5.6 Electric Field Analysis

Analysis: The magnitude of the electric field (rms) (the lateral profile of the electric field) at one meter above ground level for the six phase transmission line example is shown during different line conditions. The electric field is calculated using the method of images from [8]. There is symmetry in the electric field strength in some cases. The maximum electric field magnitude at one meter above ground level is approximately 0.12 kV/m (note that representative maximum electric field strengths for a 115 kV line of comparable design are in the range 0.1 – 2.0 kV/m and for 345 kV in the range of 2.3-5.6 kV/m [8]).
Table 5.7 Magnetic Field Analysis

Analysis – During normal operating conditions (i.e. no faults and all phases in service), for the example in Table 5.1, the magnetic field maximum is approximately 7.5 mG. During open phase conditions, the magnetic field maximum is approximately 13 mG (note that representative maximum magnetic field strengths for a 230-765 kV line of comparable design are in the range 3-300 mG [144]).
Table 5.8 Sequence Impedance Values, and Transmission Line Losses

<table>
<thead>
<tr>
<th>Transmission line sequence impedances</th>
<th>$\begin{bmatrix} Z_0 \ Z_1 \ Z_2 \ Z_3 \ Z_4 \ Z_5 \end{bmatrix} = \begin{bmatrix} 14.22 + j484.4 \ 14.22 + j77.1 \ 14.22 + j60.3 \ 14.22 + j57.6 \ 14.22 + j60.3 \ 14.22 + j77.1 \end{bmatrix}$ Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission line losses</td>
<td>0.851 MW</td>
</tr>
</tbody>
</table>

Analysis – The zero sequence transmission line reactance magnitude, $X_0$, is typically the highest of the sequence reactance magnitudes. The positive sequence impedance is $Z_1$, the negative sequence impedance is $Z_3$, and negative sequence and positive sequence impedance should be equal. The other sequence impedances are sequence impedances that do not exist in the three phase case. The transmission line loss (from $I^2R$) is 0.851 MW. This is 1.06% of the transmitted active power.
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Three main technologies were analyzed as innovative technologies for electric power transmission: compact phase spacing, high temperature low sag overhead conductors, and high phase order designs (greater than three phases). The main conclusions for these technologies are summarized below.

*High temperature low sag technologies*

High temperature low sag conductors are advantageous in increasing the thermal capacity of a transmission line to approximately twice that of traditional conductors. The main advantage of HTLS is increase of continuous thermal ratings (e.g., increase from ACSR 100 °C to HTLS 150-210 °C) and an increase in emergency thermal ratings (e.g. increase from ACSR 150 °C to HTLS 180-240 °C). The main disadvantage is cost (e.g., from 1.2 to 6.5 times the cost of conventional ACSR). HTLS conductors can be advantageous in reconductoring applications due to short reconductoring time and use of the existing towers, in addition to increased power marketing capabilities [91]. HTLS conductors have decreased sag characteristics of up to 33% compared to traditional ACSR conductors at 100 °C and up to 22% at 180 °C [22]. HTLS conductors can also be advantageous to indirectly increase the security (steady state stability) rating of a transmission asset by utilizing the decreased sag to compact the phases. Using HTLS conductors to compact phases depends on many factors, however for typical high voltage construction (existing lines with data given in [8])); the phase spacing can be reduced to approximately
47% using ACCC conductors compared to traditional designs with ACSR conductors. HTLS conductors may be used to increase the span length for new transmission construction up to approximately 115% of that of an ACSR conductor, and therefore decrease the number of towers necessary. Line lengths that favor HTLS, HTLS plus compaction, and compaction are presented for example cases. For typical lines (e.g., existing 230 – 500 kV lines with data given in [8]), lengths under 48 miles can benefit from upgrade to HTLS; lengths between 33 and 112 miles can benefit from HTLS with compact designs; and lengths longer than 77 miles can benefit from compact designs [82]. The line lengths cited are dependent on a number of application factors, and the conclusions are for illustration only. In addition, examples are analyzed using PowerWorld and TSAT for the use of HTLS and compaction where advantages and disadvantages for both the static and dynamic cases are studied. The dynamic damping improvement from compaction with HTLS was found to be minor. HTLS conductors are realistic and commercialized now.

HTLS conductors are used worldwide.

Phase compaction

Compact phase spacing increases overhead transmission line power flow, SIL, and security rating while simultaneously using limited ROW. Compact designs can decrease the necessary corridor width to 31% of traditional spaced designs and decrease the positive sequence reactance to as little as 73% compared to traditionally spaced lines [14]. In addition, calculations show an increase in line capacitance to 121% of traditionally spaced lines. Phase compaction can allow for an increase in security rating. Typical applications for Drake conductor were shown with 4.1% to 5.2% increase in power trans-
fer for a phase-phase spacing reduction of 25%; and 9.9% to 12.4% increase in power transfer for a spacing reduction of 50%. In addition, compaction can allow for an increase in the SIL of a transmission line to 133% of that compared to traditionally spaced lines [14, 16]. Compaction can also be used to redirect power flow in a more advantageous way to reduce loading of certain assets. The electric field at ground level can be decreased to 74% of a traditionally spaced line. In addition, the magnetic fields may be reduced [14]. Phase compaction affords reduced lightning exposure and smaller tower size. Compact phase designs are recommended for use where right of way is limited.

High phase order transmission

High phase order systems can be advantageous to transfer bulk power with minimal ROW. Upgrading a multicircuit three phase transmission line to a high phase order circuit could allow for an increase in power capacity, e.g. six phase can increase the voltage line to neutral and power capacity by 73% compared to double circuit three phase, and twelve phase can increase the transmission line power capacity by 234%. In addition, the security rating and SIL of a six phase line can increase to 289% and 300% respectively compared to double circuit three phase line (the increased ratings are mainly due to an increase in voltage line to neutral without an increase in the voltage line to line).

Due to the lower voltage phase to phase, compaction can be utilized thus receiving the benefits of a compact line. A six phase line may allow for compaction to 57% of a double circuit three phase line and twelve phase may allow for compaction to 30% compared to a quadruple circuit three phase line. In addition, a compact HPO line when compared to its three phase counterpart, has decreased lightning exposure, can decrease the
loading of adjacent transmission assets, can be designed to require few or no transpositions, and has shown to be able to handle the increased fault complexity. However, there may be increased cost at the terminal ends of the HPO transmission line and increased protection complexity.

New algorithms to calculate the sequence impedances of $n$-phase systems were presented. The subject of generalized sequence components was developed in connection with the special properties of certain impedance matrices. The special impedance matrix forms investigated are Toeplitz and symmetric circulant matrices. These matrices occur as the line impedance matrix which model an overhead transmission line. The Toeplitz forms have useful general properties related to their eigenstructure (e.g., every $n$ by $n$ circulant matrix has the same $n$ eigenvectors; and the eigenvalues of circulant matrices are readily calculated by direct inspection of the matrix entries using the discrete Fourier transform) [59]. These properties lead to the discussion of the significance of generalized sequence components. A generalized form for of the modal matrix $T$, namely the sequence components transformation, is presented for any number of phases. Additionally, a method of calculation of the sequence impedances is presented using geometric properties and phase spacing distances. In addition, a sequence impedance design method was presented using optimization of the difference between actual line impedance and desired line impedance [107, 108]. This was done using the method of minimization of mean squares. An example is shown in Section 4.8 to design the sequence impedances exactly to specifications. However, this design method may not always meet exact specifications if more limiting constraints are added to the phase spacing distances and line configuration.
Transpositions of HPO systems are modeled with practical results utilizing a new possible HPO unbalance factor. Transposition analysis indicates HPO lines that are circularly configured rarely need transposition. HPO lines that are double vertically configured can use \( n/2 \) roll transpositions to minimize unbalance. Typically the more transposition sections used, the lower the unbalance; therefore, the number of transposition sections utilized may depend on how low of an unbalance factor is desired [117].

A fault analysis using generalized sequence components has been illustrated and equations for the number of fault types and number of significant fault types are presented. For example three phase, six phase, twelve phase, and 18 phase lines have 5, 23, 445, and 15,367 significant fault types and 11, 120, 8178, and 524,268 fault types respectively [107, 115].

The analysis of HPO systems with the loss of one phase is presented. Single pole switching would result in 91.7\% of capacity to remain in service for twelve phase, 83.3\% for six phase, and 66.7\% for three phase. As phase order increases, the retained power capacity increases with loss of phase. Illustrative examples for single pole operation with loss of phase are in Section 4.13. The unbalance in the three phase case examples is 4-12\% whereas in the six phase case is 1-4\%.

The majority of the results in this thesis relate to overhead transmission. However, attention is given for a compact high phase order cable design with multiple layers. The lower voltage phase to phase in the high phase order case allows for less dielectric material and a more compact cable [140].
Potential advantages of high phase order AC transmission should be viewed in terms of the network with which the HPO circuits are integrated. A network example of the IEEE 30 bus test system with an integrated six phase transmission line versus a double circuit three phase line is presented. The network simulation in OpenDSS focuses on a system wide power flow and fault study. The power flow on the system changes significantly, and the six phase line power flow increases to 121% compared to the original double circuit three phase case. The network fault study results conclude that the six phase line has higher fault current, which is a consequence of increasing the line capacity and power flow.

Lastly, a graphically user interface and HPO analysis program was developed to apply the algorithms and models in this thesis to example n-phase designs.

6.2 Recommendations

High temperature low sag conductors, compact designs, and high phase order designs are all recommended for high power density transmission, where right of way is difficult or expensive to obtain. The research in this dissertation becomes increasingly important as: worldwide population increases, electric energy consumption increases, and new transmission corridors become rare and harder to obtain. It is recommended to also research other technologies that may be beneficial in increasing the power transfer capabilities of existing rights of way.

High temperature low sag conductors were proven to be beneficial in increasing the thermal capacity of a line, and can be cost effective due to the short outage construction time and use of existing towers. HTLS conductors are realistic and commercialized
now, and HTLS can be cost effective in specific circumstances. High temperature low sag conductors are recommended for reconductoring applications when a transmission line is in need of greater power capacity during contingencies. HTLS conductors are also recommended as an investment on specific transmission corridors to improve power marketing capabilities. HTLS conductors will be used mostly on short (approximately 47 miles or less) thermally limited lines. HTLS can also be used for specific spans where sag and clearance are the main issues.

Compact transmission designs are recommended for areas where right of way is difficult or expensive to obtain. Compact designs have been used worldwide in limited circumstances [14, 16]. Compact designs should be considered for long transmission lines that are security limited. Compact phase spacing can also be used to decrease electric and magnetic fields at ground level and the edge of the right of way. Compaction is recommended for use to increase the surge impedance loading of a transmission line. Also, compaction can be used to adjust power flow in a system. Compact designs may also be beneficial to add an extra circuit to an existing right of way.

Recommendations are to continue HPO research and explore commercial applications and specific circumstances where HPO may be beneficial. High phase order transmission is not used today, but pilot test lines have been built and tested. Some possible commercial applications for HPO designs are conversion from multicircuit three phase to HPO to increase power transmission capacity without increasing right of way. Other possible applications are: long transmission lines, overhead or underground transmission from wind farms where AC – DC – AC conversion is already used, and supplying HPO
motors or rectifiers directly. In addition, HPO may have applications where single pole
switching is allowed and could be beneficial in microgrids to improve reliability. For the
case of a new, long, transmission line where four transformers are needed; it is recom-
mended to consider six phase instead of double circuit three phase.
REFERENCES


[100] X. Deng, “Exploring six-phase transmission lines for increasing power transfer with limited right of way,” Arizona State University, Tempe AZ, 2012.


Table A.1 shows the several use cases which appear in this research. A brief indication of conclusions is given, and reference is made to the main body of this document for additional detail.

Table A.1 Use Cases A, B, and C

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Objective</th>
<th>Test Bed</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Compare thermal limit and security limit</td>
<td>Voltage line to line = 500 kV Frequency = 60 Hz Conductor = Drake Number of conductors in bundle = 3 Bundle spacing = 18 in Phase to nearest phase spacing = 35 ft Number of phases = 3 Configuration of conductors = horizontal transposed</td>
<td>Short lines are thermally limited, long lines are security limited. See Section 2.2.</td>
</tr>
<tr>
<td>B</td>
<td>Percent decrease in positive sequence reactance due to decrease in phase spacing</td>
<td>Frequency = 60 Hz Number of phases = 3 Conductor = Drake Original phase spacing = 30 ft Configuration of conductors = horizontal transposed</td>
<td>Decrease in phase spacing decreases the positive sequence reactance See Section 2.2.</td>
</tr>
<tr>
<td>C</td>
<td>Compaction to alleviate congestion</td>
<td>PowerWorld WECC Summer 2009 peak load Line location = Los Angeles area Sending power busses = Rinaldi and Northridge Receiving power bus = Tarzana Voltage line to line = 230 kV Frequency = 60 Hz</td>
<td>If used correctly, compaction can help alleviate congestion by shifting power flow to nearby transmission assets. See Section 2.3. HTLS beneficial to increase thermal limits and decrease sag to allow for compaction. Compaction can increase security limits. See Section 3.4.</td>
</tr>
</tbody>
</table>
### Table A.2 Use Cases D and E

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Objective</th>
<th>Test Bed</th>
<th>Conclusions</th>
</tr>
</thead>
</table>
| **D**    | Compaction increases line capacitance | Voltage line to line = 500 kV  
Frequency = 60 Hz  
Conductor = Bluebird  
Number of conductors in bundle = 3  
Bundle spacing = 18 in  
Number of phases = 3  
Original phase to nearest phase spacing = 40 ft  
Original configuration of conductors = horizontal transposed  
Compact phase to nearest phase spacing = 23.1 ft  
Compact configuration of conductors = Delta transposed | Conduction increases line capacitance. For this example it adds 22.2\% additional VAr to the line charging  
See Section 2.4 |
| **E**    | Lengths favorable for HTLS, compact, or HTLS and compact designs | Three cases analyzed  
Voltages 230, 345, 500 kV  
Frequency 60 Hz  
Conductor = Drake  
Number of conductors in bundle = 2, 2, 3  
Bundle spacing = 18 in  
Phase to nearest phase spacing = 20, 25, 35 ft  
Configuration of conductors = horizontal transposed  
Maximum allowed bus voltage phase angle difference = 30 degrees | Conclusions seen in Table 3.1. In brief short lines are beneficial to use HTLS conductors only, medium length lines are beneficial to use HTLS with compact designs, and long lines are beneficial for compact designs only.  
See Section 3.2 |
## Table A.3 Use Cases F, G, and H

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Objective</th>
<th>Test Bed</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F</strong></td>
<td>Utilize HTLS conductors to increase span length. Compare span needed with ACSR conductor vs. HTLS conductor</td>
<td></td>
<td>HTLS conductor allows for an increase in span length by 12%. See Section 3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ACSR Drake conductor</td>
<td>HTLS ACCR Linnet conductor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ampacity 900 A</td>
<td>942 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Diameter 1.108 in.</td>
<td>0.724</td>
</tr>
<tr>
<td></td>
<td>Tensile strength (RTS)</td>
<td>31,500 lbs.</td>
<td>13,900 lbs</td>
</tr>
<tr>
<td></td>
<td>% of tensile strength horizontal</td>
<td>18%</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>Conductor weight</td>
<td>1.093 lb/ft</td>
<td>0.385 lb/ft</td>
</tr>
<tr>
<td></td>
<td>Allowable sag</td>
<td>10 ft</td>
<td>10 ft</td>
</tr>
<tr>
<td></td>
<td>Span length from (3.1)</td>
<td>644 ft</td>
<td>720 ft</td>
</tr>
<tr>
<td></td>
<td>% of towers needed</td>
<td>100%</td>
<td>88%</td>
</tr>
<tr>
<td><strong>G</strong></td>
<td>Long line case - upgrading with HTLS, compaction, and both to improve power transfer capabilities</td>
<td>PowerWorld WECC Summer 2009 peak load</td>
<td>Line lines are mostly beneficial from compaction, and in some cases can benefit from HTLS. See Section 3.4</td>
</tr>
<tr>
<td></td>
<td>Line location = Wyoming and Idaho</td>
<td>Sending power bus = Bridger</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Receiving power bus = Populus and 3 Mile Knoll</td>
<td>Voltage line to line = 345 kV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency = 60 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>Error in HPO positive sequence reactance when using GMD in the calculation</td>
<td>Frequency = 50 Hz</td>
<td>Using GMD in the calculation of HPO positive sequence impedance is inaccurate. See Section 4.7</td>
</tr>
<tr>
<td></td>
<td>Conductor = Drake</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Phase to nearest phase spacing = 1, 4, 10 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Configuration of conductors = circular</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use Case</td>
<td>Objective</td>
<td>Test Bed</td>
<td>Conclusions</td>
</tr>
<tr>
<td>----------</td>
<td>-----------</td>
<td>----------</td>
<td>-------------</td>
</tr>
</tbody>
</table>
| I        | Design the sequence impedances | Number of phases = 6  
Frequency = 50 Hz  
Conductor = Drake  
Configuration of conductors = circular  
Specified positive sequence reactance = 0.4 Ohm/mi  
Specified negative sequence reactance = 0.4 Ohm/mi  
Specified zero sequence reactance = 3.0 Ohm/mi  
BIL constraints: \( d_1 > 1.5 \text{ m} \), \( d_2 > 2.6 \text{ m} \), \( d_3 > 3.0 \text{ m} \) | The sequence impedances can be designed to specifications using transmission line design and optimization  
See Section 4.8 |
| J        | Sequence impedance magnitudes | Number of phases = 6  
Frequency = 60 Hz  
Conductor = Drake  
Configuration of conductors = circular | Shows the magnitudes six sequence impedances with phase to nearest phase spacing from 10-50 ft  
See Section 4.9 |
| K        | HPO fault analysis | Voltage line to neutral = 288.7 kV  
Frequency = 60 Hz  
Number of phases = 6  
Conductor = Drake  
Configuration of conductors = circular  
Line length = 100 miles  
Phase to nearest phase spacing = 23.1 ft  
Total load = 1 GVA  
Power factor = 0.8  
Fault resistance = 40 Ohms  
Faulted phase = phase F  
Self impedance = j0.133 pu  
Mutual impedances = j0.333 pu | A general HPO fault analysis is shown  
See Section 4.12 |
### Table A.5 Use Cases L and M

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Objective</th>
<th>Test Bed</th>
<th>Conclusions</th>
</tr>
</thead>
</table>
| L        | Transposition analysis | Voltage line to neutral = 79.9 kV  
Number of phases = 6, 12  
Configurations = 6φ circular, 6φ double vertical, 6φ vertical, 12φ circular, 12φ double vertical  
Total load = 100 MVA  
Power factor = 0.8  
Conductor type = Drake  
Phase to nearest phase spacing = 5 ft  
Height to lowest conductor = 35 ft | Circular lines have low unbalance, double vertical lines require half the transpositions, a generalized voltage unbalance factor can help define HPO unbalance  
See Section 4.13 |
| M        | HPO analysis program example | See Table 5.1 in Section 5.5 | Large example to show the functionality of the developed HPO analysis program  
See Section 5.5 |
| N        | Steady state operation with one phase out of service | Voltage line to neutral = 200 kV  
Configurations = circular fully transposed  
Length = 100 miles  
Total load = 200 MVA  
Power factor = 0.8  
Conductor type = Drake  
3φ phase to nearest phase spacing = 25 ft  
Height to lowest conductor = 35 ft  
Phase A open | The result shows unbalance for circuit seen in Fig. 4.27 during open phase A condition vs. the number of phases.  
See Section 4.14 |
B.1 Main Executable Code

fmincon_main.m

% FMINCON main
% Brian Pierre
% 6/26/2014
% MATLAB 7.9.0 (R2009b)

%% Optimize the distances between conductors to get specified sequence
...% reactances
clear all; clc;

%This script requires other scripts:
% minimization_function.m
% constraints.m
% Cond_geometry.m

%algorithm options, some find better or faster solutions than others
OPTIONS = optimset('Algorithm','interior-point');
OPTIONS = optimset('Algorithm','active-set');

%% %%%%%%%%%%%% USER DEFINED parameters
n=6; %number of phases
f=50; %Hz %system frequency
GMR=0.0375/3.28; %m %GMR of conductors
d12_BIL=1.5; %m %BIL constraints

%%% Determine all BIL constraints
config=1;
h=100;
% get BIL constraints based on phase to nearest phase constraint
[pos_x, pos_y]=Cond_geometry(n, d12_BIL, h, config);
% Get dph
ddph=zeros(n,n);
for p=1:1:n
    for q=1:1:n
        if q==p
            %distance to self just set as 1
            ddph(p,q)=0.001;
        else
            %phase spacing distance
            ddph(p,q)=sqrt((pos_x(p)-pos_x(q))^2+(pos_y(p)-pos_y(q))^2);
        end
    end
end

%%% initial starting point for algorithm
% will used the BIL distances as the initial starting point
% initialization for the zero sequence reactance
\[
d_0(1) = d_{12BIL}^{(1-n)}; \\
\text{for } p = 1:1:n-1 \\
\quad d_0(1) = d_0(1) \ast ((1 - \cos(2\pi/n))/(1 - \cos(2\pi*p/n)))^\left(\frac{1}{2}\right); \\
\text{end} \\
x_0(1) = 0.062844 \ast \frac{f}{50} \ast (\log(d_0(1)/GMR) + 7.93402 \ast n);
\]

% initialization for the other sequence reactances
\[
\text{for } q = 1:1:n-1 \\
\quad d_0(q+1) = d_{12BIL}; \\
\quad \text{for } p = 1:1:n-1 \\
\quad \quad d_0(q+1) = d_0(q+1) \ast ((1 - \cos(2\pi/n))/(1 - \cos(2\pi*p/n)))^\left(\frac{1}{2}\cos(2\pi*p*q/n)\right); \\
\quad \text{end} \\
x_0(q+1) = 0.062844 \ast \frac{f}{50} \ast \log(d_0(q+1)/GMR);
\]

\[
d_{vec} = \text{nonzeros(\text{triu}(ddph,1)')} \quad \% \text{initial distance guess} \\
x_0 \times ' \quad \% \text{which gives an initial impedance guess} \\
x_0 = [x_0; d_{vec}] \quad \% \text{initial overall guess} \\
\text{Initial guess} = x_0
\]

\[
\%\% \text{ solve} \\
[x, fval, xit, OUTPUT] = \text{FMINCON(}'minimization\_function'\', x_0, [], [], [], [], [], [], [], [], [], [], [', 'constraints')] \\
\]
\[
Xseq\_calculated = x(1:n,1); \\
dd = x(n+1:end)'; \\
\text{ddph\_new} = \text{triu}(\text{ones}(n),1); \\
\text{ddph\_new}\_2 = \text{tril}(\text{ddph\_new}) + \text{tril}(\text{ddph\_new},0)'; \\
\text{ddph\_new}\_2(1:n+1:end) = 1; \\
\]
\[
\%\% \text{ solution} \\
\text{Run\_data} = OUTPUT \\
\text{Was\_a\_solution\_found} = xit \\
\text{Sequence\_impedances} = x(1:n,1) \\
D = x(n+1:end,1)'; \\
b = \text{triu}(\text{ones}(n),1); \\
b(b==1) = D; \\
\text{Distance\_matrix} = b \\
\text{Objective\_function\_error\_in\_solution} = fval
B.2 Constraints Code

constraints.m

```matlab
%constraints
function [c,ceq]=constraints(x)
%% %%%%%%%%%%%%%%%%% USER DEFINED
n=6; %number of phases
f=50; %Hz %system frequency
GMR=0.0375/3.28; %m %GMR of conductors
d12_BIL=1.5; %m %BIL constraints

xnew=x';
config=1;
h=100;

%% distance matrix of BIL constraints
[pos_x, pos_y]=Cond_geometry(n, d12_BIL, h, config);
%Get dph
ddph=zeros(n,n);
for p=1:n
  for q=1:n
    if q==p
      %distance to self just set as 1
      ddph(p,q)=0;
    else
      %phase spacing distance
      ddph(p,q)=sqrt((pos_x(p) - pos_x(q))^2 + (pos_y(p) - pos_y(q))^2);
    end
  end
end
d_vec=nonzeros(triu(ddph,1)');
%% constraints
%inequality constraints
for p=1:length(d_vec)
  c(p,1)=d_vec(p)-x(p+n); %BIL constraints
end

%put new distance guess into correct form
dd=xnew(n+1:end)';
ddph_new = triu(ones(n),1);
ddph_new(~ddph_new')=dd;
ddph_new2=tril(ddph_new)+tril(ddph_new,0)';
ddph_new2(1:n+1:end)=1;

%equality constraints
%non-linear sequence impedance constraints
for seq=0:n-1
  Deqn_gen=1;
  for gg=1:n-1
    Dtot=1;
    for ff=1:n
```

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hh=ff+gg;
while hh>n
    hh=hh-n;
end
Dtot=Dtot*ddph_new2(ff,hh);%(1/n);
end
Deqn_gen=Deqn_gen*Dtot^(-cosd(360*gg*seq/n)/n);%(-
cosd(360*gg*seq/n));
end
if seq==0
    ceq(seq+1,1)=x(1)-0.062844*f/50*(log(Deqn_gen/GMR)+n*7.93402);
else
    ceq(seq+1,1)=x(seq+1)-0.062844*f/50*log(Deqn_gen/GMR);
end
B.3 The Minimization Function

minimization_function.m

%minimization function
function [min_function] = minimization_function(x)
% X is the given sequence reactances
%x is the calculated optimized sequence reactances
% w is the weight matrix
%% %%%%%%%%%%%%USER DEFINED
n=6;
%user given sequence reactances in Ohm/km
X(1)=3.0; %zero sequence
X(2)=0.4; %positive seq.
% X(3)= ... (ADD MORE TO DEFINE MORE SEQUENCE IMPEDANCES)

%weights
w(1)=1;
w(2)=1;
%w(3)= ... (ADD MORE TO DEFINE MORE SEQUENCE IMPEDANCES)

%% for sequences user doesn't define

nq=length(X); %number of sequence reactances to design

%all other seq. reactances weighted to zero (ones you don't design)
for p=nq+1:1:n
    X(p)=1;
end
for p=nq+1:1:n
    w(p)=0;
end
X=X';
w=w';

%% main function
% min_function=((w.*(X-x(1:n)))*(w.*(X-x(1:n))))
min_function=((w.*(X-x(1:n)))'*(w.*(X-x(1:n))));

B.4 Code to Determine Conductor Geometry

Cond_geometry.m

%%% Geometry
%inputs: number of phases, phase spacing, height of cond., configuration
%configuration 1=circular, 2=double vertical, 3=vertical
%outputs: x and y position of each conductor.
function [pos_x, pos_y]=Cond_geometry(n, d, h, config)

%find phase spacing distances
degree=360/n;
dn=d/sqrt(2-2*cosd(degree)); %distance phase to neutral

%get positions of each conductor
if config==1 %circular
    pos_x=[dn];
    for p=1:1:n-1;
        degree=p*360/n;
        if degree>0 && degree<=90
            d1=dn*cosd(degree);
            d2=d1; end
        if degree>90 && degree<=180
            degree=180-degree;
            d1=dn*cosd(degree);
            d2=-d1; end
        if degree>180 && degree<=270
            degree=degree-180;
            d1=dn*cosd(degree);
            d2=-d1; end
        if degree>270
            degree=360-degree;
            d1=dn*cosd(degree);
            d2=d1; end
        pos_x(1,p+1)=d2;
    end
    h=h+dn;
    pos_y=[h];
    for p=1:1:n-1;
        degree=p*360/n;
        if degree>0 && degree<=90
            h1=dn*sin(d);egree);
            h2=h+h1; end
        if degree>90 && degree<=180
            degree=180-degree;
            h1=dn*sin(degree);
            h2=h+h1; end
        if degree>180 && degree<=270
            degree=degree-180;
            h1=dn*sin(degree);
            h2=h-h1; end
        if degree>270
            h2=h-h1; end
        end
    end
end
degree=360-degrees;
h1=dn*sind(degree);
h2=h-h1; end
pos_y(1,p+1)=h2;
end
elseif config==2 %double vertical
if rem(n,2)==0
for p=1:1:n/2
    pos_x(p)=-dn;
    h2=h+d*p-d;
    pos_y(1,p)=h2;
    pos_y(1,n-p+1)=h2;
end
for p=n/2+1:1:n
    pos_x(p)=dn;
end
else
    for p=1:1:(n+1)/2
        pos_x(p)=-dn;
        h2=h+d*p-d;
        pos_y(1,p)=h2;
        pos_y(1,n-p+1)=h2;
    end
    pos_x((n+3)/2)=dn;
    pos_y(1,(n+3)/2)=pos_y(1,(n+1)/2)-d/2;
    for p=(n+5)/2:1:n
        pos_x(p)=dn;
        h2=pos_y(1,p-1)-d;
        pos_y(1,p)=h2;
    end
end
else %vertical
    for p=1:1:n
        pos_x(p)=0;
        h2=h+d*p-d;
        pos_y(1,p)=h2;
    end
end
APPENDIX C

IEEE 30 BUS TEST SYSTEM DATA AND RESULTS
### C.1 Power Flow Results Double Circuit 3 Phase

CIRCUIT ELEMENT POWER FLOW

(Power Flow into element from indicated Bus)

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| ELEMENT = "Line.1-2" |
| B1 1 | 28.9 +j | -3.5 | 29.1 | -0.9926 |
| B1 2 | 28.9 +j | -3.5 | 29.1 | -0.9926 |
| B1 3 | 28.9 +j | -3.5 | 29.1 | -0.9926 |
| TERMINAL TOTAL | 86.6 +j | -10.6 | 87.3 | -0.9926 |
| B2 1 | -28.0 +j | 5.2 | 28.5 | -0.9835 |
| B2 2 | -28.0 +j | 5.2 | 28.5 | -0.9835 |
| B2 3 | -28.0 +j | 5.2 | 28.5 | -0.9835 |
| TERMINAL TOTAL | -84.0 +j | 15.5 | 85.4 | -0.9835 |

| ELEMENT = "Line.1C-2C" |
| B1 1 | 28.9 +j | -3.5 | 29.1 | -0.9926 |
| B1 2 | 28.9 +j | -3.5 | 29.1 | -0.9926 |
| B1 3 | 28.9 +j | -3.5 | 29.1 | -0.9926 |
| TERMINAL TOTAL | 86.6 +j | -10.6 | 87.3 | -0.9926 |
| B2 1 | -28.0 +j | 5.2 | 28.5 | -0.9835 |
| B2 2 | -28.0 +j | 5.2 | 28.5 | -0.9835 |
| B2 3 | -28.0 +j | 5.2 | 28.5 | -0.9835 |
| TERMINAL TOTAL | -84.0 +j | 15.5 | 85.4 | -0.9835 |

| ELEMENT = "Line.1-3" |
| B1 1 | 29.2 +j | 1.5 | 29.3 | 0.9986 |
| B1 2 | 29.2 +j | 1.5 | 29.3 | 0.9986 |
| B1 3 | 29.2 +j | 1.5 | 29.3 | 0.9986 |
| TERMINAL TOTAL | 87.7 +j | 4.6 | 87.8 | 0.9986 |
| B3 1 | -28.2 +j | 0.8 | 28.2 | -0.9996 |
| B3 2 | -28.2 +j | 0.8 | 28.2 | -0.9996 |
| B3 3 | -28.2 +j | 0.8 | 28.2 | -0.9996 |
| TERMINAL TOTAL | -84.6 +j | 2.4 | 84.6 | -0.9996 |

| ELEMENT = "Line.2-4" |
| B2 1 | 14.5 +j | 1.3 | 14.6 | 0.9959 |
| B2 2 | 14.5 +j | 1.3 | 14.6 | 0.9959 |
| B2 3 | 14.5 +j | 1.3 | 14.6 | 0.9959 |
TERMINAL TOTAL  43.6 +j  4.0  43.8  0.9959
B4  1  -14.2 +j  -1.6  14.3  0.9938
B4  2  -14.2 +j  -1.6  14.3  0.9938
B4  3  -14.2 +j  -1.6  14.3  0.9938
TERMINAL TOTAL  -42.6 +j  -4.8  42.9  0.9938

ELEMENT = "Line.3-4"
B3  1  27.4 +j  -1.2  27.4  -0.9991
B3  2  27.4 +j  -1.2  27.4  -0.9991
B3  3  27.4 +j  -1.2  27.4  -0.9991
TERMINAL TOTAL  82.2 +j  -3.6  82.3  -0.9991
B4  1  -27.1 +j  1.7  27.2  -0.9980
B4  2  -27.1 +j  1.7  27.2  -0.9980
B4  3  -27.1 +j  1.7  27.2  -0.9980
TERMINAL TOTAL  -81.3 +j  5.2  81.5  -0.9980

ELEMENT = "Line.2-5"
B2  1  27.5 +j  0.6  27.5  0.9998
B2  2  27.5 +j  0.6  27.5  0.9998
B2  3  27.5 +j  0.6  27.5  0.9998
TERMINAL TOTAL  82.4 +j  1.8  82.4  0.9998
B5  1  -26.5 +j  2.1  26.6  -0.9970
B5  2  -26.5 +j  2.1  26.6  -0.9970
B5  3  -26.5 +j  2.1  26.6  -0.9970
TERMINAL TOTAL  -79.4 +j  6.2  79.7  -0.9970

ELEMENT = "Line.2-6"
B2  1  20.1 +j  0.2  20.1  0.9999
B2  2  20.1 +j  0.2  20.1  0.9999
B2  3  20.1 +j  0.2  20.1  0.9999
TERMINAL TOTAL  60.3 +j  0.6  60.3  0.9999
B6  1  -19.5 +j  0.4  19.5  -0.9997
B6  2  -19.5 +j  0.4  19.5  -0.9997
B6  3  -19.5 +j  0.4  19.5  -0.9997
TERMINAL TOTAL  -58.4 +j  1.3  58.4  -0.9997

ELEMENT = "Line.4-6"
B4  1  24.0 +j  -5.3  24.6  -0.9765
B4  2  24.0 +j  -5.3  24.6  -0.9765
B4  3  24.0 +j  -5.3  24.6  -0.9765
TERMINAL TOTAL  72.1 +j  -15.9  73.8  -0.9765
B6  1  -23.8 +j  5.7  24.5  -0.9722
B6  2  -23.8 +j  5.7  24.5  -0.9722
B6  3  -23.8 +j  5.7  24.5  -0.9722
TERMINAL TOTAL  -71.5 +j  17.2  73.5  -0.9722

ELEMENT = "Line.5-7"
B5  1  -4.9 +j  3.9  6.3  -0.7806
B5  2  -4.9 +j  3.9  6.3  -0.7806
B5  3  -4.9 +j  3.9  6.3  -0.7806
TERMINAL TOTAL  -14.8 +j  11.8  18.9  -0.7806
B7  1  5.0 +j  -4.5  6.7  -0.7431
B7  2  5.0 +j  -4.5  6.7  -0.7431
B7  3  5.0 +j  -4.5  6.7  -0.7431
TERMINAL TOTAL  14.9 +j  -13.4  20.1  -0.7431
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182
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**Note:** The table above represents various table entries with complex numbers and their terminal totals for different elements and their respective branches. The elements are identified by their unique labels (e.g., ELEMENT = "Line.23-24").
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B6  3  5.3 +j  0.0  5.3  1.0000
B6  0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  15.8 +j  0.0  15.8  1.0000
B10 1  5.3 +j  0.4  5.3  -0.9971
B10 2  5.3 +j  0.4  5.3  -0.9971
B10 3  5.3 +j  0.4  5.3  -0.9971
B10 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  -15.8 +j  1.2  15.9  -0.9971

ELEMENT = "Transformer.9-11"
B9  1  0.0 +j  -5.3  5.3  0.0000
B9  2  0.0 +j  -5.3  5.3  0.0000
B9  3  0.0 +j  -5.3  5.3  0.0000
B9  0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  0.0 +j  -15.8  15.8  0.0000

ELEMENT = "Transformer.9-10"
B9  1  9.2 +j  1.9  9.4  0.9787
B9  2  9.2 +j  1.9  9.4  0.9787
B9  3  9.2 +j  1.9  9.4  0.9787
B9  0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  27.7 +j  5.8  28.3  0.9787

ELEMENT = "Transformer.4-12"
B4  1  14.7 +j  4.6  15.5  0.9537
B4  2  14.7 +j  4.6  15.5  0.9537
B4  3  14.7 +j  4.6  15.5  0.9537
B4  0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  44.2 +j  13.9  46.4  0.9537

ELEMENT = "Transformer.12-13"
B12 1  -14.7 +j  -3.1  15.1  0.9787
B12 2  -14.7 +j  -3.1  15.1  0.9787
B12 3  -14.7 +j  -3.1  15.1  0.9787
B12 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  -44.2 +j  -9.3  45.2  0.9787

ELEMENT = "Transformer.12-13"
B13 1  0.0 +j  3.7  3.7  0.0000
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B13 3  0.0 +j  3.7  3.7  0.0000
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**ELEMENT = "Transformer.28-27"**

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<td>+j</td>
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**TERMINAL TOTAL**: 18.0 +j 5.0 18.7 0.9639

**ELEMENT = "Capacitor.B10"**

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**TERMINAL TOTAL**: 0.0 +j -20.8 20.8 -0.0000

**ELEMENT = "Capacitor.B24"**

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**TERMINAL TOTAL**: 0.0 +j -4.5 4.5 1.0000

**ELEMENT = "Load.B2"**

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**TERMINAL TOTAL**: 21.7 +j 12.7 25.1 0.8631

**ELEMENT = "Load.B3"**

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**TERMINAL TOTAL**: 2.4 +j 1.2 2.7 0.8944

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Power Conversion Elements

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ELEMENT = "Load.B16"
B16 1  1.2 +j  0.6  1.3  0.8893
B16 2  1.2 +j  0.6  1.3  0.8893
B16 3  1.2 +j  0.6  1.3  0.8893
B16 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  3.5 +j  1.8  3.9  0.8893

ELEMENT = "Load.B17"
B17 1  3.0 +j  1.9  3.6  0.8406
B17 2  3.0 +j  1.9  3.6  0.8406
B17 3  3.0 +j  1.9  3.6  0.8406
B17 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  9.0 +j  5.8 10.7  0.8406

ELEMENT = "Load.B18"
B18 1  1.1 +j  0.3  1.1  0.9627
B18 2  1.1 +j  0.3  1.1  0.9627
B18 3  1.1 +j  0.3  1.1  0.9627
B18 0  0.0 +j  0.0  0.0  1.0000
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ELEMENT = "Load.B19"
B19 1  3.2 +j  1.1  3.4  0.9415
B19 2  3.2 +j  1.1  3.4  0.9415
B19 3  3.2 +j  1.1  3.4  0.9415
B19 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  9.5 +j  3.4 10.1  0.9415

ELEMENT = "Load.B20"
B20 1  0.7 +j  0.2  0.8  0.9529
B20 2  0.7 +j  0.2  0.8  0.9529
B20 3  0.7 +j  0.2  0.8  0.9529
B20 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  2.2 +j  0.7  2.3  0.9529

ELEMENT = "Load.B21"
B21 1  5.8 +j  3.7  6.9  0.8423
B21 2  5.8 +j  3.7  6.9  0.8423
B21 3  5.8 +j  3.7  6.9  0.8423
B21 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL 17.5 +j 11.2 20.8  0.8423

ELEMENT = "Load.B23"
B23 1  1.1 +j  0.5  1.2  0.8944
B23 2  1.1 +j  0.5  1.2  0.8944
B23 3  1.1 +j  0.5  1.2  0.8944
B23 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  3.2 +j  1.6  3.6  0.8944

ELEMENT = "Load.B24"
B24 1  2.9 +j  2.2  3.7  0.7923
B24 2  2.9 +j  2.2  3.7  0.7923
B24 3  2.9 +j  2.2  3.7  0.7923
B24 0  0.0 +j  0.0  0.0  1.0000

188
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<p>| ELEMENT = &quot;Generator.B13&quot; | |
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| B13 1                     | -0.0 +j -3.7   | 3.7     | 0.0000 |
| B13 2                     | -0.0 +j -3.7   | 3.7     | 0.0000 |
| B13 3                     | -0.0 +j -3.7   | 3.7     | 0.0000 |</p>
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Total Circuit Losses = 17.6 +j 33.1
## C.2 Power Flow Results Six Phase

**CIRCUIT ELEMENT POWER FLOW**

(Power Flow into element from indicated Bus)

### Power Delivery Elements

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<th>Bus Phase</th>
<th>MW</th>
<th>+j Mvar</th>
<th>MVA</th>
<th>PF</th>
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**ELEMENT = "Vsource.SOURCE"**

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<th>MVA</th>
<th>PF</th>
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**TERMINAL TOTAL**

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**ELEMENT = "Line.1X-2X"**

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B4  2  -18.7 +j  -0.9  18.7  0.9989
B4  3  -18.7 +j  -0.9  18.7  0.9989
TERMINAL TOTAL  -56.0 +j  -2.6  56.1  0.9989

ELEMENT = "Line.3-4"
B3  1  17.9 +j  1.8  18.0  0.9948
B3  2  17.9 +j  1.8  18.0  0.9948
B3  3  17.9 +j  1.8  18.0  0.9948
TERMINAL TOTAL  53.7 +j  5.5  54.0  0.9948
B4  1  -17.8 +j  -1.8  17.9  0.9951
B4  2  -17.8 +j  -1.8  17.9  0.9951
B4  3  -17.8 +j  -1.8  17.9  0.9951
TERMINAL TOTAL  -53.3 +j  -5.3  53.6  0.9951

ELEMENT = "Line.2-5"
B2  1  29.0 +j  2.2  29.1  0.9971
B2  2  29.0 +j  2.2  29.1  0.9971
B2  3  29.0 +j  2.2  29.1  0.9971
TERMINAL TOTAL  86.9 +j  6.6  87.2  0.9971
B5  1  -27.9 +j  0.9  27.9  -0.9995
B5  2  -27.9 +j  0.9  27.9  -0.9995
B5  3  -27.9 +j  0.9  27.9  -0.9995
TERMINAL TOTAL  -83.7 +j  2.6  83.7  -0.9995

ELEMENT = "Line.2-6"
B2  1  23.7 +j  0.8  23.7  0.9994
B2  2  23.7 +j  0.8  23.7  0.9994
B2  3  23.7 +j  0.8  23.7  0.9994
TERMINAL TOTAL  71.0 +j  2.5  71.1  0.9994
B6  1  -22.8 +j  0.5  22.8  -0.9997
B6  2  -22.8 +j  0.5  22.8  -0.9997
B6  3  -22.8 +j  0.5  22.8  -0.9997
TERMINAL TOTAL  -68.4 +j  1.6  68.4  -0.9997

ELEMENT = "Line.4-6"
B4  1  19.5 +j  -2.9  19.7  -0.9892
B4  2  19.5 +j  -2.9  19.7  -0.9892
B4  3  19.5 +j  -2.9  19.7  -0.9892
TERMINAL TOTAL  58.5 +j  -8.7  59.2  -0.9892
B6  1  -19.4 +j  3.1  19.6  -0.9878
B6  2  -19.4 +j  3.1  19.6  -0.9878
B6  3  -19.4 +j  3.1  19.6  -0.9878
TERMINAL TOTAL  -58.1 +j  9.2  58.9  -0.9878

ELEMENT = "Line.5-7"
B5  1  -3.5 +j  2.9  4.5  -0.7750
B5  2  -3.5 +j  2.9  4.5  -0.7750
B5  3  -3.5 +j  2.9  4.5  -0.7750
TERMINAL TOTAL  -10.6 +j  8.6  13.6  -0.7750
B7  1  3.6 +j  -3.5  5.0  -0.7141
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B7  3  3.6 +j  -3.5  5.0  -0.7141

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| B24 2 | -0.5+j | -0.5 | 0.7 | 0.7401 |
| B24 3 | -0.5+j | -0.5 | 0.7 | 0.7401 |
| TERMINAL TOTAL | -1.5+j | -1.4 | 2.1 | 0.7401 |

ELEMENT = "Line.25-26"
| B25 1 | 0.5+j | 0.7 | 0.8 | -0.5457 |
| B25 2 | 0.5+j | 0.7 | 0.8 | -0.5457 |
| B25 3 | 0.5+j | 0.7 | 0.8 | -0.5457 |
| TERMINAL TOTAL | 1.5+j | 1.4 | 2.1 | 0.7386 |

ELEMENT = "Line.25-27"
| B25 1 | 1.2+j | 0.8 | 1.4 | 0.8317 |
| B25 2 | 1.2+j | 0.8 | 1.4 | 0.8317 |
| B25 3 | 1.2+j | 0.8 | 1.4 | 0.8317 |
| TERMINAL TOTAL | 3.5+j | 2.4 | 4.3 | 0.8317 |

ELEMENT = "Line.27-29"
| B27 1 | 2.1+j | 0.6 | 2.1 | 0.9656 |
| B27 2 | 2.1+j | 0.6 | 2.1 | 0.9656 |
| B27 3 | 2.1+j | 0.6 | 2.1 | 0.9656 |
| TERMINAL TOTAL | 6.2+j | 1.7 | 6.4 | 0.9656 |

| ELEMENT | B29 1 | -2.0+j | -0.5 | 2.1 | 0.9709 |
| B29 2 | -2.0+j | -0.5 | 2.1 | 0.9709 |
| B29 3 | -2.0+j | -0.5 | 2.1 | 0.9709 |

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**TPS 198**
B1D 3  -33.0 +j  -7.4  33.9  0.9756
B1D 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL -99.1 +j  -22.3  101.6  0.9756

ELEMENT = "Transformer.1-1Z"
B1 1  33.0 +j  7.4  33.9  0.9756
B1 2  33.0 +j  7.4  33.9  0.9756
B1 3  33.0 +j  7.4  33.9  0.9756
B1 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  99.1 +j  -22.3  101.6  0.9756

B1Z 1  -33.0 +j  -7.4  33.9  0.9756
B1Z 2  -33.0 +j  -7.4  33.9  0.9756
B1Z 3  -33.0 +j  -7.4  33.9  0.9756
B1Z 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  99.1 +j  -22.3  101.6  0.9756

B1Y 1  -33.0 +j  -7.4  33.9  0.9756
B1Y 2  -33.0 +j  -7.4  33.9  0.9756
B1Y 3  -33.0 +j  -7.4  33.9  0.9756
B1Y 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  99.1 +j  -22.3  101.6  0.9756

B1X 1  -33.0 +j  -7.4  33.9  0.9756
B1X 2  -33.0 +j  -7.4  33.9  0.9756
B1X 3  -33.0 +j  -7.4  33.9  0.9756
B1X 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  99.1 +j  -22.3  101.6  0.9756

ELEMENT = "Transformer.2-2Z"
B2 1  -32.9 +j  -11.0  34.7  0.9487
B2 2  -32.9 +j  -11.0  34.7  0.9487
B2 3  -32.9 +j  -11.0  34.7  0.9487
B2 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL -98.7 +j  -32.9  104.0  0.9487
B2Z 1  32.9 +j  11.0  34.7  0.9487
B2Z 2  32.9 +j  11.0  34.7  0.9487
B2Z 3  32.9 +j  11.0  34.7  0.9487
B2Z 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  98.7 +j  32.9  104.0  0.9487

ELEMENT = "Transformer.2Z-2Y"
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B2Z 2  -32.9 +j  -11.0  34.7  0.9487
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ELEMENT = "Transformer.9-10"
B9  1  9.4 +j  1.8  9.6  0.9822
B9  2  9.4 +j  1.8  9.6  0.9822
B9  3  9.4 +j  1.8  9.6  0.9822
B9  0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  28.2 +j  5.4  28.7  0.9822
B10 1 -9.4 +j -1.5  9.5  0.9871
B10 2 -9.4 +j -1.5  9.5  0.9871
B10 3 -9.4 +j -1.5  9.5  0.9871
B10 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL -28.2 +j -4.6  28.6  0.9871

ELEMENT = "Transformer.4-12"
B4  1  14.4 +j  5.0  15.2  0.9448
B4  2  14.4 +j  5.0  15.2  0.9448
B4  3  14.4 +j  5.0  15.2  0.9448
B4  0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  43.2 +j  15.0  45.7  0.9448
B12 1 -14.4 +j -3.5  14.8  0.9718
B12 2 -14.4 +j -3.5  14.8  0.9718
B12 3 -14.4 +j -3.5  14.8  0.9718
B12 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL -43.2 +j -10.5  44.5  0.9718

ELEMENT = "Transformer.12-13"
B12 1 0.0 +j -3.4  3.4  0.0000
B12 2 0.0 +j -3.4  3.4  0.0000
B12 3 0.0 +j -3.4  3.4  0.0000
B12 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  0.0 +j  10.2  10.2  0.0000

ELEMENT = "Transformer.28-27"
B28 1  6.1 +j  1.7  6.3  0.9650
B28 2  6.1 +j  1.7  6.3  0.9650
B28 3  6.1 +j  1.7  6.3  0.9650
B28 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL  18.2 +j  5.0  18.9  0.9650
B27 1 -6.1 +j -1.2  6.2  0.9806
B27 2 -6.1 +j -1.2  6.2  0.9806
B27 3 -6.1 +j -1.2  6.2  0.9806
B27 0  0.0 +j  0.0  0.0  1.0000
TERMINAL TOTAL -18.2 +j -3.7  18.6  0.9806

ELEMENT = "Capacitor.B10"
B10 1 -0.0 +j -6.9  6.9  0.0000
B10 2  0.0 +j -6.9  6.9  1.0000
B10 3  0.0 +j -6.9  6.9  1.0000
TERMINAL TOTAL -0.0 +j -20.8  20.8  0.0000
B10 0 0.0 +j 0.0 0.0 1.0000
B10 0 0.0 +j 0.0 0.0 1.0000
B10 0 0.0 +j 0.0 0.0 1.0000
    TERMINAL TOTAL 0.0 +j 0.0 0.0 1.0000

ELEMENT = "Capacitor.B24"
B24 1 0.0 +j -1.5 1.5 1.0000
B24 2 0.0 +j -1.5 1.5 1.0000
B24 3 0.0 +j -1.5 1.5 -0.0000
    TERMINAL TOTAL 0.0 +j -4.5 4.5 -0.0000
B24 0 0.0 +j 0.0 0.0 1.0000
B24 0 0.0 +j 0.0 0.0 1.0000
B24 0 0.0 +j 0.0 0.0 1.0000
    TERMINAL TOTAL 0.0 +j 0.0 0.0 1.0000

===============

Power Conversion Elements

Bus Phase  MW  +j Mvar  MVA  PF

ELEMENT = "Load.B2"
B2  1 7.2 +j 4.2 8.4 0.8631
B2  2 7.2 +j 4.2 8.4 0.8631
B2  3 7.2 +j 4.2 8.4 0.8631
B2  0 0.0 +j 0.0 0.0 1.0000
    TERMINAL TOTAL 21.7 +j 12.7 25.1 0.8631

ELEMENT = "Load.B3"
B3  1 0.8 +j 0.4 0.9 0.8944
B3  2 0.8 +j 0.4 0.9 0.8944
B3  3 0.8 +j 0.4 0.9 0.8944
B3  0 0.0 +j 0.0 0.0 1.0000
    TERMINAL TOTAL 2.4 +j 1.2 2.7 0.8944

ELEMENT = "Load.B4"
B4  1 2.5 +j 0.5 2.6 0.9785
B4  2 2.5 +j 0.5 2.6 0.9785
B4  3 2.5 +j 0.5 2.6 0.9785
B4  0 0.0 +j 0.0 0.0 1.0000
    TERMINAL TOTAL 7.6 +j 1.6 7.8 0.9785

ELEMENT = "Load.B5"
B5  1 31.4 +j 6.3 32.0 0.9803
B5  2 31.4 +j 6.3 32.0 0.9803
B5  3 31.4 +j 6.3 32.0 0.9803
B5  0 0.0 +j 0.0 0.0 1.0000
    TERMINAL TOTAL 94.2 +j 19.0 96.1 0.9803

ELEMENT = "Load.B7"
B7  1 7.6 +j 3.6 8.4 0.9022
B7  2 7.6 +j 3.6 8.4 0.9022
B7  3 7.6 +j 3.6 8.4 0.9022
B7  0 0.0 +j 0.0 0.0 1.0000
    TERMINAL TOTAL 22.8 +j 10.9 25.3 0.9022
ELEMENT = "Load.B8"
B8  1  10.0 +j 10.0  14.1  0.7071
B8  2  10.0 +j 10.0  14.1  0.7071
B8  3  10.0 +j 10.0  14.1  0.7071
B8  0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  30.0 +j 30.0  42.4  0.7071

ELEMENT = "Load.B10"
B10 1  1.9 +j  0.7  2.0  0.9454
B10 2  1.9 +j  0.7  2.0  0.9454
B10 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  5.8 +j  2.0  6.1  0.9454

ELEMENT = "Load.B12"
B12 1  3.7 +j  2.5  4.5  0.8309
B12 2  3.7 +j  2.5  4.5  0.8309
B12 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  11.2 +j  7.5  13.5  0.8309

ELEMENT = "Load.B14"
B14 1  2.1 +j  0.5  2.1  0.9683
B14 2  2.1 +j  0.5  2.1  0.9683
B14 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  6.2 +j  1.6  6.4  0.9683

ELEMENT = "Load.B15"
B15 1  2.7 +j  0.8  2.9  0.9565
B15 2  2.7 +j  0.8  2.9  0.9565
B15 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  8.2 +j  2.5  8.6  0.9565

ELEMENT = "Load.B16"
B16 1  1.2 +j  0.6  1.3  0.8893
B16 2  1.2 +j  0.6  1.3  0.8893
B16 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  3.5 +j  1.8  3.9  0.8893

ELEMENT = "Load.B17"
B17 1  3.0 +j  1.9  3.6  0.8406
B17 2  3.0 +j  1.9  3.6  0.8406
B17 0  0.0 +j  0.0  0.0  1.0000
   TERMINAL TOTAL  9.0 +j  5.8 10.7  0.8406

ELEMENT = "Load.B18"
B18 1  1.1 +j  0.3  1.1  0.9626
B18 2  1.1 +j  0.3  1.1  0.9626
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B18 0  0.0 +j  0.0  0.0  1.0000
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204
B30      0       0.0 +j    0.0        0.0       1.0000
    TERMINAL TOTAL 10.6 +j    1.9       10.8       0.9843

ELEMENT = "Generator.B2"
B2       1  13.3 +j   13.3       18.9       0.7071
B2       2  13.3 +j   13.3       18.9       0.7071
B2       3  13.3 +j   13.3       18.9       0.7071
B2       0  0.0 +j    0.0        0.0       1.0000
    TERMINAL TOTAL -40.0 +j   40.0       56.6       -0.7071

ELEMENT = "Generator.B5"
B5       1  -0.0 +j    -10.1      10.1       0.0000
B5       2  -0.0 +j    -10.1      10.1       0.0000
B5       3  -0.0 +j    -10.1      10.1       0.0000
B5       0   0.0 +j    0.0        0.0       1.0000
    TERMINAL TOTAL -0.0 +j    -30.3      30.3       0.0000

ELEMENT = "Generator.B8"
B8       1  -0.0 +j    -10.6      10.6       0.0000
B8       2  -0.0 +j    -10.6      10.6       0.0000
B8       3  -0.0 +j    -10.6      10.6       0.0000
B8       0   0.0 +j    0.0        0.0       1.0000
    TERMINAL TOTAL -0.0 +j    -31.7      31.7       0.0000

ELEMENT = "Generator.B11"
B11      1  -0.0 +j    -5.1        5.1       0.0000
B11      2  -0.0 +j    -5.1        5.1       0.0000
B11      3  -0.0 +j    -5.1        5.1       0.0000
B11      0   0.0 +j    0.0        0.0       1.0000
    TERMINAL TOTAL -0.0 +j    -15.3      15.3       0.0000

ELEMENT = "Generator.B13"
B13      1  -0.0 +j    -3.4        3.4       0.0000
B13      2  -0.0 +j    -3.4        3.4       0.0000
B13      3  -0.0 +j    -3.4        3.4       0.0000
B13      0   0.0 +j    0.0        0.0       1.0000
    TERMINAL TOTAL -0.0 +j    -10.2      10.2       0.0000

Total Circuit Losses = 12.3 +j  -1.6
### C.3 Fault Study Results Double Circuit Three Phase

#### FAULT STUDY REPORT

**ALL-Node Fault Currents**

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<th>Bus</th>
<th>Node 1 X/R</th>
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**ONE-Node to ground Faults**

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### C.4 Fault Study Results Six Phase

**FAULT STUDY REPORT**

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<td>1.081</td>
</tr>
<tr>
<td>&quot;B11&quot;</td>
<td>2</td>
<td>3</td>
<td>12555</td>
<td>1.081</td>
<td>0.541</td>
<td>0.541</td>
</tr>
<tr>
<td>&quot;B13&quot;</td>
<td>1</td>
<td>2</td>
<td>14174</td>
<td>0.536</td>
<td>0.536</td>
<td>1.072</td>
</tr>
<tr>
<td>&quot;B13&quot;</td>
<td>2</td>
<td>3</td>
<td>14174</td>
<td>1.072</td>
<td>0.536</td>
<td>0.536</td>
</tr>
</tbody>
</table>
APPENDIX D

CODE FOR HPO ANALYSIS PROGRAM
D.1 Program Files

The code in this appendix builds a graphical user interface with the ability to run simulations on a steady state \(n\)-phase transmission line. The simulations include fault studies, transposition analysis, electric and magnetic field analysis, sequence impedance and losses calculations. The program is well described in Chapter 5.

Files needed to run program:

- test.m - Main executable file, builds and manages the GUI
- test.fig - The GUI (may need editing depending on computer screen used), cannot be included here, must contact me for actual file.
- N_phase_sim3.m - Performs the main analysis, fault, and transposition studies
- Form_Zph_for_n_phase.m - Builds the impedance matrix for an \(n\)-phase line
- Form_C_for_n_phase.m - Builds the capacitance matrix for \(n\)-phase line
- Form_T_any_phase_order.m – Builds the model matrix that transforms between sequence and phase components for an \(n\)-phase system
- Cond_geometry.m – Determines the location of each conductor in space
- mag_field.m - Magnetic field analysis
- ele_field.m - Electric field analysis
D.2 Main Executable Code

test.m

```matlab
function varargout = test(varargin)
% TEST M-file for test.fig
% TEST, by itself, creates a new TEST or raises the existing
% singleton*.
% H = TEST returns the handle to a new TEST or the handle to
% the existing singleton*.
% TEST('CALLBACK', hObject, eventData, handles, ...) calls the local
% function named CALLBACK in TEST.M with the given input argu-
% ments.
% TEST('Property', 'Value', ...) creates a new TEST or raises the
% existing singleton*. Starting from the left, property value
% pairs are
% applied to the GUI before test_OpeningFcn gets called. An
% unrecognized property name or invalid value makes property ap-
% plication
% stop. All inputs are passed to test_OpeningFcn via varargin.
% *See GUI Options on GUIDE's Tools menu. Choose "GUI allows only
% one
% instance to run (singleton)".
% See also: GUIDE, GUIDATA, GUIDATA
% Edit the above
text to modify the response to help test
% Last Modified by GUIDE v2.5 26-Feb-2014 14:39:12

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
    'gui_Singleton', gui_Singleton, ...
    'gui_OpeningFcn', @test_OpeningFcn, ...
    'gui_OutputFcn', @test_OutputFcn, ...
    'gui_LayoutFcn', [], ...
    'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT
```
% --- Executes just before test is made visible.
function test_OpeningFcn(hObject, eventdata, handles, varargin)

% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to test (see VARARGIN)

% Choose default command line output for test
%handles.MyData.Sload=[];

%add static images to gui
axes(handles.axes1)
imshow('ASU.jpg')
axes(handles.axes2)
imshow('Title.jpg')
axes(handles.axes4)
imshow('Vs.jpg')
axes(handles.axes5)
imshow('Vr_untrans.jpg')
axes(handles.axes6)
imshow('Vr_fully_trans.jpg')
axes(handles.axes7)
imshow('Vr_ft_post_fault.jpg')
axes(handles.axes8)
imshow('Vr_ft_faults_opened.jpg')

handles.output = hObject;
handles.MyData.config=1;
guidata(hObject, handles); % Update handles structure
% UIWAIT makes test wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = test_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
%inputs

%Clear everything once simulation is ran.
clc;
set(handles.text2, 'string', 'Running simulation...');
set(handles.radio_Vs, 'Value', 0);
set(handles.radio_Vr_untrans, 'Value', 0);
set(handles.radio_Vr_ft, 'Value', 0);
set(handles.radio_Vr_ft_f, 'Value', 0);
set(handles.radio_Vr_ft_fo, 'Value', 0);
set(handles.radio_trans_U, 'Value', 0);
set(handles.radio_E_field, 'Value', 0);
legend(handles.axes3, 'hide');
cla(handles.axes3);
guidata(hObject, handles);

%get inputs from Gui
n=str2double(get(handles.edit_n, 'string')); %number of phases %must be even
d=str2double(get(handles.edit_d, 'string')); %5; %ft phase spacing between phase A and B
h=str2double(get(handles.edit_h, 'string')); %35; %ft height of lowest conductor to ground
Length=str2double(get(handles.edit_L, 'string')); %200; %miles
Voltage=str2double(get(handles.edit_V, 'string')); %79.7; %voltage line to neutral
GMR=str2double(get(handles.edit_GMR, 'string')); %0.0375; %ft. Drake conductor radius
r_cond=str2double(get(handles.edit_r, 'string')); %1.108; %diameter of Drake conductor in feet
Rcond=str2double(get(handles.edit_Res, 'string')); %0.1422; %Ohm/mile %drake at 75 deg C
Sload=str2double(get(handles.edit_S, 'string')); %100; %power factor
pf=str2double(get(handles.edit_pf, 'string')); %0.8; %power factor
faults=str2num(get(handles.edit_faults, 'string')); %1; %phases faulted
Rf=str2double(get(handles.edit_Zf, 'string')); %40; %fault resistance
Xf=str2double(get(handles.edit_Zf_X, 'string')); %0; %fault reactance
Zf=Rf+1i*Xf; %fault impedance to ground
faults_ph_ph=str2double(get(handles.edit_ph_ph_faults, 'string'));
Rf_ph_ph=str2double(get(handles.edit_Zf_ph_ph, 'string'));
Xf_ph_ph=str2double(get(handles.edit_Zf_ph_ph_X, 'string'));
Zf_ph_ph=Rf_ph_ph+1i*Xf_ph_ph; %fault impedance phase to phase
config=handles.MyData.config;

%call main function:
[Vspu, Vr_untransposed, Vr_fully_trans, Vr_w_faults, ...
 Vr_ft_faults_opened, Ir_untransposed, Ir_fully_trans, ...
 Ir_w_faults, Ir_ft_faults_opened, U, Uopen, Losses, Zseq, X_est, drop2, E, B]=N_phase_sim3(n, d, h, Length, ...
 Voltage, GMR, r_cond, Rcond, Sload, pf, faults, Zf, faults_ph_ph, Zf_ph_ph, config);

%store results in data structure
handles.MyData.Vs=Vspu;
handles.MyData.Vr_untransposed=Vr_untransposed;
handles.MyData.Vr_fully_trans=Vr_fully_trans;
handles.MyData.Vr_w_faults=Vr_w_faults;
handles.MyData.Vr_ft_faults_opened=Vr_ft_faults_opened;
handles.MyData.U=U;
handles.MyData.Uopen=Uopen;
handles.MyData.Ir_untransposed=Ir_untransposed;
handles.MyData.Ir_fully_trans=Ir_fully_trans;
handles.MyData.Ir_w_faults=Ir_w_faults;
handles.MyData.Ir_ft_faults_opened=Ir_ft_faults_opened;
handles.MyData.Losses=Losses;
handles.MyData.Zseq=Zseq;
handles.MyData.X_est=X_est;
handles.MyData.drop2=drop2;
handles.MyData.E=E;
handles.MyData.B=B;

%update data structure and say simulation is complete
set(handles.text2, 'string', 'Simulation run complete. Click buttons
above to view results.');
guidata(hObject, handles);

function edit_n_Callback(hObject, eventdata, handles)
% hObject    handle to edit_n (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') return
%        str2double(get(hObject,'String')) returns contents of edit_n
%        as a double

% --- Executes during object creation, after setting all properties.
function edit_n_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_n (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit_V_Callback(hObject, eventdata, handles)
% hObject    handle to edit_V (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_V as text
%        str2double(get(hObject,'String')) returns contents of edit_V
%        as a double

% --- Executes during object creation, after setting all properties.
function edit_V_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_V (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
% handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
                get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit_d_Callback(hObject, eventdata, handles)
% hObject    handle to edit_d (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_d as text
%        str2double(get(hObject,'String')) returns contents of edit_d as a double

% --- Executes during object creation, after setting all properties.
function edit_d_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_d (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
                get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit_h_Callback(hObject, eventdata, handles)
% hObject    handle to edit_h (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_h as text
%        str2double(get(hObject,'String')) returns contents of edit_h as a double

% --- Executes during object creation, after setting all properties.
function edit_h_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_h (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
                get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit_L_Callback(hObject, eventdata, handles)
% hObject    handle to edit_L (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_L as text
%        str2double(get(hObject,'String')) returns contents of edit_L
% as a double

% --- Executes during object creation, after setting all properties.
function edit_L_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to edit_L (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    empty - handles not created until after all CreateFcns
               % called
    % Hint: edit controls usually have a white background on Windows.
    % See ISPC and COMPUTER.
    if ispc && isequal(get(hObject,'BackgroundColor'),
                        get(0,'defaultUicontrolBackgroundColor'))
        set(hObject,'BackgroundColor','white');
    end

function edit_r_Callback(hObject, eventdata, handles)
    % hObject    handle to edit_r (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    % Hints: get(hObject,'String') returns contents of edit_r as text
    %        str2double(get(hObject,'String')) returns contents of edit_r
    % as a double

    % --- Executes during object creation, after setting all properties.
    function edit_r_CreateFcn(hObject, eventdata, handles)
        % hObject    handle to edit_r (see GCBO)
        % eventdata  reserved - to be defined in a future version of MATLAB
        % handles    empty - handles not created until after all CreateFcns
               % called
        % Hint: edit controls usually have a white background on Windows.
        % See ISPC and COMPUTER.
        if ispc && isequal(get(hObject,'BackgroundColor'),
                            get(0,'defaultUicontrolBackgroundColor'))
            set(hObject,'BackgroundColor','white');
        end

function edit_Res_Callback(hObject, eventdata, handles)
    % hObject    handle to edit_Res (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    % Hints: get(hObject,'String') returns contents of edit_Res as text
    %        str2double(get(hObject,'String')) returns contents of edit_Res
    % as a double

    % --- Executes during object creation, after setting all properties.
    function edit_Res_CreateFcn(hObject, eventdata, handles)
        % hObject    handle to edit_Res (see GCBO)
        % eventdata  reserved - to be defined in a future version of MATLAB
        % handles    empty - handles not created until after all CreateFcns
               % called
        % Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit_S_Callback(hObject, eventdata, handles)
    % hObject    handle to edit_S (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    % Hints: get(hObject,'String') returns contents of edit_S as text
    %        str2double(get(hObject,'String')) returns contents of edit_S
    % as a double

    % --- Executes during object creation, after setting all properties.
    function edit_S_CreateFcn(hObject, eventdata, handles)
        % hObject    handle to edit_S (see GCBO)
        % eventdata  reserved - to be defined in a future version of MATLAB
        % handles    empty - handles not created until after all CreateFcns
        % called
        % Hint: edit controls usually have a white background on Windows.
        % See ISPC and COMPUTER.
        if ispc && isequal(get(hObject,'BackgroundColor'),
            get(0,'defaultUicontrolBackgroundColor'))
            set(hObject,'BackgroundColor','white');
        end

    % --- Executes during object creation, after setting all properties.
    function edit_GMR_Callback(hObject, eventdata, handles)
        % hObject    handle to edit_GMR (see GCBO)
        % eventdata  reserved - to be defined in a future version of MATLAB
        % handles    structure with handles and user data (see GUIDATA)
        % Hints: get(hObject,'String') returns contents of edit_GMR as text
        %        str2double(get(hObject,'String')) returns contents of edit_GMR
        % as a double

        % --- Executes during object creation, after setting all properties.
        function edit_GMR_CreateFcn(hObject, eventdata, handles)
            % hObject    handle to edit_GMR (see GCBO)
            % eventdata  reserved - to be defined in a future version of MATLAB
            % handles    empty - handles not created until after all CreateFcns
            % called
            % Hint: edit controls usually have a white background on Windows.
            % See ISPC and COMPUTER.
            if ispc && isequal(get(hObject,'BackgroundColor'),
                get(0,'defaultUicontrolBackgroundColor'))
                set(hObject,'BackgroundColor','white');
            end

        % --- Executes during object creation, after setting all properties.
        function edit_pf_Callback(hObject, eventdata, handles)
            % hObject    handle to edit_pf (see GCBO)
            % eventdata  reserved - to be defined in a future version of MATLAB
            % handles    structure with handles and user data (see GUIDATA)
            % Hints: get(hObject,'String') returns contents of edit_pf as text
function edit_pf_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to edit_pf (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    empty - handles not created until after all CreateFcns called
    % Hint: edit controls usually have a white background on Windows.
    if ispc && isequal(get(hObject,'BackgroundColor'),
        get(0,'defaultUicontrolBackgroundColor'))
        set(hObject,'BackgroundColor','white');
    end
end

function edit_faults_Callback(hObject, eventdata, handles)
    % hObject    handle to edit_faults (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    % Hints: get(hObject,'String') returns contents of edit_faults as text
    %        str2double(get(hObject,'String')) returns contents of edit_faults as a double
end

function edit_Zf_Callback(hObject, eventdata, handles)
    % hObject    handle to edit_Zf (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    % Hints: get(hObject,'String') returns contents of edit_Zf as text
    %        str2double(get(hObject,'String')) returns contents of edit_Zf as a double
end

function edit_Zf_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to edit_Zf (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    empty - handles not created until after all CreateFcns called
    % Hint: edit controls usually have a white background on Windows.
    %       See ISPC and COMPUTER.

if ispc && isequal(get(hObject,'BackgroundColor'),
         get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit_Zf_X_Callback(hObject, eventdata, handles)
% hObject    handle to edit_Zf_X (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_Zf_X as text
%        str2double(get(hObject,'String')) returns contents of edit_Zf_X as a double

% --- Executes during object creation, after setting all properties.
function edit_Zf_X_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_Zf_X (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
         get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

%%%%%% VOLTAGE BUTTONS

% --- Executes on button press in push_Vs.
function push_Vs_Callback(hObject, eventdata, handles)
% hObject    handle to push_Vs (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Voltage on the sending end of the transmission line:
Phase A, phase B,...
V=mat2str(round(abs(handles.MyData.Vs)*100)/100);
Vang=mat2str(round(angle(handles.MyData.Vs)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', V, char(10),
char(10), 'Angle: ', Vang];
set(handles.text2,'string',ss);

% --- Executes on button press in push_Vr_untrans.
function push_Vr_untrans_Callback(hObject, eventdata, handles)
% hObject    handle to push_Vr_untrans (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Voltage on the recieving end of the transmission line if the line were untransposed:
Phase A, phase B,...
V=mat2str(round(abs(handles.MyData.Vr_untransposed)*100)/100);
Vang=mat2str(round(angle(handles.MyData.Vr_untransposed)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', V, char(10), str2, char(10), 'Angle: ', Vang];
set(handles.text2, 'string', ss);

% --- Executes on button press in push_Vr_ft.
function push_Vr_ft_Callback(hObject, eventdata, handles)
% hObject    handle to push_Vr_ft (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Voltage on the receiving end of the transmission line if the line were fully roll transposed: ';
str2='Phase A, phase B,... ';
str3='Simple check voltage angle difference, P=V1*V2/X*sin(delta): ';
str4='Angle drop should be around: ';

drop2=handles.MyData.drop2;
Vr_ft_pu=abs(handles.MyData.Vr_fully_trans);
if isreal(drop2) == 1
    drop=num2str(round(drop2*100)/100);
else
    drop='greater than 90 degree drop, unstable!';
end
V=mat2str(round(abs(Vr_ft_pu)*100)/100);
Vang=mat2str(round(angle(handles.MyData.Vr_fully_trans)*360/(2*pi)*100)/100);
Vang1=mat2str(abs(round(angle(handles.MyData.Vr_fully_trans(1,1))*360/(2*pi)*100)/100));
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', V, char(10), str2, char(10), 'Angle: ', Vang, char(10), str3, str4, drop, ' is: ', Vang1];
set(handles.text2, 'string', ss);

% --- Executes on button press in push_Vr_ft_f.
function push_Vr_ft_f_Callback(hObject, eventdata, handles)
% hObject    handle to push_Vr_ft_f (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% --- Executes on button press in push_Vr_untrans.
str='Voltage on the receiving end of the fully roll transposed transmission line with designated faults applied: ';
str2='Phase A, phase B,... ';
V=mat2str(round(abs(handles.MyData.Vr_w_faults)*100)/100);
Vang=mat2str(round(angle(handles.MyData.Vr_w_faults)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', V, char(10), str2, char(10), 'Angle: ', Vang];
set(handles.text2, 'string', ss);

% --- Executes on button press in push_Vr_open.
function push_Vr_open_Callback(hObject, eventdata, handles)
% hObject    handle to push_Vr_open (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Voltage on the recieving end of the fully roll transposed transmission line after faulted phases have been opened:';
str2='Phase A, Phase B,.... '
V=mat2str(round(abs(handles.MyData.Vr_ft_faults_opened)*100)/100);
Vang=mat2str(round(angle(handles.MyData.Vr_ft_faults_opened)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', V, char(10), char(10), 'Angle: ', Vang];
set(handles.text2, 'string', ss);

%%%%%%%% VOLTAGE GRAPHING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% --- Executes on button press in radio_Vs.
function radio_Vs_Callback(hObject, eventdata, handles)
  % hObject    handle to radio_Vs (see GCBO)
  % eventdata  reserved - to be defined in a future version of MATLAB
  % handles    structure with handles and user data (see GUIDATA)
  % Hint: get(hObject,'Value') returns toggle state of radio_Vs
  n=str2double(get(handles.edit_n, 'string'));
  if (get(hObject, 'Value') == 1)
    axes(handles.axes3);
    hold on;
    V=handles.MyData.Vs;
    s_r=real(V);
    s_i=imag(V);
    h=[];
    for m=1:1:n
      h(m)=plot([0,s_r(m)], [0,s_i(m)], 'LineWidth', 2, 'Color', 'r');
    end
    handles.MyData.h1=h;
    title('Voltage phasor diagrams');
    xlabel('real (pu)');
    ylabel('imaginary (pu)');
    guidata(hObject, handles);
  else
    h=handles.MyData.h1;
    for m=1:1:n
      delete(h(m));
    end
    guidata(hObject, handles);
  end

% --- Executes on button press in radio_Vr_untrans.
function radio_Vr_untrans_Callback(hObject, eventdata, handles)
  % hObject    handle to radio_Vr_untrans (see GCBO)
  % eventdata  reserved - to be defined in a future version of MATLAB
  % handles    structure with handles and user data (see GUIDATA)
  % Hint: get(hObject,'Value') returns toggle state of radio_Vr_untrans
  n=str2double(get(handles.edit_n, 'string'));
  if (get(hObject, 'Value') == 1)
    axes(handles.axes3);
    hold on;
    V=handles.MyData.Vr_untransposed;
    s_r=real(V);
s_i = imag(V);
h = [];
for m = 1:1:n
    h(m) = plot([0, s_r(m)], [0, s_i(m)], '--', 'LineWidth', 2, 'Color', 'b');
end
handles.MyData.h2 = h;
guida(hObject, handles);
title('Voltage phasor diagrams');
xlabel('real (pu)');
ylabel('imaginary (pu)');
else
    h = handles.MyData.h2;
    for m = 1:1:n
        delete(h(m));
    end
    guida(hObject, handles);
end

% --- Executes on button press in radio_Vr_ft.
function radio_Vr_ft_Callback(hObject, eventdata, handles)
% hObject    handle to radio_Vr_ft (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
if (get(hObject, 'Value') == 1) || (get(hObject, 'Max'))
    axes(handles.axes3);
    hold on;
    V = handles.MyData.Vr_fully_trans;
    s_r = real(V);
    s_i = imag(V);
    h = [];
    for m = 1:1:n
        h(m) = plot([0, s_r(m)], [0, s_i(m)], '--', 'LineWidth', 2, 'Color', 'g');
    end
    handles.MyData.h3 = h;
guida(hObject, handles);
title('Voltage phasor diagrams');
xlabel('real (pu)');
ylabel('imaginary (pu)');
else
    h = handles.MyData.h3;
    for m = 1:1:n
        delete(h(m));
    end
    guida(hObject, handles);
end

% --- Executes on button press in radio_Vr_ft_f.
function radio_Vr_ft_f_Callback(hObject, eventdata, handles)
% hObject    handle to radio_Vr_ft_f (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: get(hObject,'Value') returns toggle state of radio_Vr_ft_fo
n=str2double(get(handles.edit_n,'string'));
if (get(hObject, 'Value')==1) %get(hObject, 'Max'))
    axes(handles.axes3);
    hold on;
    V=handles.MyData.Vr_w_faults;
    s_r=real(V);
    s_i=imag(V);
    h=[];
    for m=1:1:n
        h(m)=plot([0,s_r(m)],[0,s_i(m)], '-.', 'LineWidth', 2, 'Color', 'm');
    end
    handles.MyData.h4=h;
    guidata(hObject, handles);
    title('Voltage phasor diagrams');
    xlabel('real (pu)');
    ylabel('imaginary (pu)');
else
    h=handles.MyData.h4;
    for m=1:1:n
        delete(h(m));
    end
    guidata(hObject, handles);
end

% --- Executes on button press in radio_Vr_ft_fo.
function radio_Vr_ft_fo_Callback(hObject, eventdata, handles)
% hObject    handle to radio_Vr_ft_fo (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: get(hObject,'Value') returns toggle state of radio_Vr_ft_fo
n=str2double(get(handles.edit_n,'string'));
if (get(hObject, 'Value')==1) %get(hObject, 'Max'))
    axes(handles.axes3);
    hold on;
    V=handles.MyData.Vr_ft_faults_opened;
    s_r=real(V);
    s_i=imag(V);
    h=[];
    for m=1:1:n
        h(m)=plot([0,s_r(m)],[0,s_i(m)], ':', 'LineWidth', 2.2, 'Color', 'k');
    end
    handles.MyData.h5=h;
    guidata(hObject, handles);
    title('Voltage phasor diagrams');
    xlabel('real (pu)');
    ylabel('imaginary (pu)');
else
    h=handles.MyData.h5;
    for m=1:1:n
        delete(h(m));
    end
    guidata(hObject, handles);
% --- Executes on button press in radio_trans_U.
function radio_trans_U_Callback(hObject, eventdata, handles)
% hObject    handle to radio_trans_U (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: get(hObject,'Value') returns toggle state of radio_trans_U
if n is a multiple of 3 more unbalance analysis
n=str2double(get(handles.edit_n,'string'));
U=handles.MyData.U;
if (get(hObject,'Value')==1)
%get(hObject, 'Max'))
if rem(n,3)==0
%maximum unbalance in 3 phase circuits
axes(handles.axes3);
Um=U(:,1:n/3);
U(1:n,n/3+2)=max(Um');
%plot of unbalance factors
p=1:n;
hold on;
h(1)=plot(p, U(:,n/3+4), '-.','LineWidth', 2, 'Color', 'red');
h(2)=plot(p, U(:,n/3+3), 'LineWidth', 2, 'Color', 'green');
h(3)=plot(p, U(:,n/3+1), '--','LineWidth', 2, 'Color', 'black');
h(4)=plot(p, U(:,n/3+2), ':','LineWidth', 2, 'Color', 'c');
h(5)=plot(p, U(:,n/3+5), '--','LineWidth', 2, 'Color', 'm');
title('Unbalance vs. # of transposition sections');
xlabel('Number of transposition sections');
ylabel('Unbalance factor in %');
legend('U nph (Generalized)', 'U 3ph-n (V-/V+)', 'U avg. for 3ph circuits' ,...'
U max for 3ph circuits', 'IEEE U');
hold off;
mm=5;
handles.MyData.mm=mm;
 handles.MyData.h6=h;
guida(hObject, handles);
else
%plot of unbalance factors
p=1:n;
hold on;
h(1)=plot(p, U(:,1), '-.','LineWidth', 2, 'Color', 'red');
h(2)=plot(p, U(:,2), 'LineWidth', 2, 'Color', 'green');
h(3)=plot(p, U(:,3), '--','LineWidth', 2, 'Color', 'm');
xlabel('Number of transposition sections');
ylabel('Unbalance factor in %');
legend('U 3ph-n (V-/V+)', 'U nph (Generalized)', 'IEEE U');
hold off;
mm=3;
 handles.MyData.mm=mm;
 handles.MyData.h6=h;
guida(hObject, handles);
end
else
    mm=handles.MyData.mm;
    h=handles.MyData.h6;
    for m=1:mm
        delete(h(m));
    end
    legend(handles.axes3, 'hide');
guidata(hObject, handles);
end

%---------------- CURRENT BUTTONS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% --- Executes on button press in push_Ir_untrans.
function push_Ir_untrans_Callback(hObject, eventdata, handles)
% hObject    handle to push_Ir_untrans (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Current on the transmission line if the line were untransposed:
    Phase A, phase B, ..... '
I=mat2str(round(abs(handles.MyData.Ir_untransposed)*100)/100);
Iang=mat2str(round(angle(handles.MyData.Ir_untransposed)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', I, char(10), char(10), 'Angle: ', Iang];
set(handles.text2, 'string', ss);

% --- Executes on button press in push_Ir_ft.
function push_Ir_ft_Callback(hObject, eventdata, handles)
% hObject    handle to push_Ir_ft (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Current on the transmission line if the line were fully roll transposed:
    Phase A, phase B, ..... '
I=mat2str(round(abs(handles.MyData.Ir_fully_trans)*100)/100);
Iang=mat2str(round(angle(handles.MyData.Ir_fully_trans)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', I, char(10), char(10), 'Angle: ', Iang];
set(handles.text2, 'string', ss);

% --- Executes on button press in push_Ir_ft_f.
function push_Ir_ft_f_Callback(hObject, eventdata, handles)
% hObject    handle to push_Ir_ft_f (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Current on the fully roll transposed transmission line with designated faults applied:
    Phase A, phase B, ..... '
I=mat2str(round(abs(handles.MyData.Ir_w_faults)*100)/100);
Iang=mat2str(round(angle(handles.MyData.Ir_w_faults)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', I, char(10), char(10), 'Angle: ', Iang];
set(handles.text2, 'string', ss);

% --- Executes on button press in push_Ir_ft_fo.
function push_Ir_ft_fo_Callback(hObject, eventdata, handles)
% hObject    handle to push_Ir_ft_fo (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Current on the fully roll transposed transmission line after faulted phases have been opened: '
str2='Phase A, phase B,.... '
I=mat2str(round(abs(handles.MyData.Ir_ft_faults_opened)*100)/100);
Iang=mat2str(round(angle(handles.MyData.Ir_ft_faults_opened)*360/(2*pi)*100)/100);
ss=[str, char(10), str2, char(10), 'Magnitude (pu): ', I, char(10), char(10), 'Angle: ', Iang];
set(handles.text2, 'string', ss);

% --- Executes on button press in push_Losses.
function push_Losses_Callback(hObject, eventdata, handles)
% hObject    handle to push_Losses (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Transmission line losses in MW: '
Losses_untran=num2str(round(handles.MyData.Losses(1,1)*100000)/100000);
Losses_fully_tran=num2str(round(handles.MyData.Losses(1,2)*100000)/100000);
ss=[str, char(10), 'Untransposed: ', Losses_untran, char(10), 'Fully transposed: ', Losses_fully_tran];
set(handles.text2, 'string', ss);

% --- Executes on button press in radio_Cir.
function radio_Cir_Callback(hObject, eventdata, handles)
% hObject    handle to radio_Cir (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: get(hObject,'Value') returns toggle state of radio_Cir
handles.MyData.config=1;
set(handles.radio_Cir, 'Value', 1);
set(handles.radio_Doub_Ver, 'Value', 0);
set(handles.radio_Vertical, 'Value', 0);
guidata(hObject, handles);

% --- Executes on button press in radio_Doub_Ver.
function radio_Doub_Ver_Callback(hObject, eventdata, handles)
% hObject    handle to radio_Doub_Ver (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: get(hObject,'Value') returns toggle state of radio_Doub_Ver
handles.MyData.config=2;
set(handles.radio_Cir, 'Value', 0);
set(handles.radio_Doub_Ver, 'Value', 1);
set(handles.radio_Vertical, 'Value', 0);
guidata(hObject, handles);
% --- Executes on button press in radio_Vertical.
function radio_Vertical_Callback(hObject, eventdata, handles)
% hObject    handle to radio_Vertical (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hint: get(hObject,'Value') returns toggle state of radio_Vertical
handles.MyData.config=3;
set(handles.radio_Cir, 'Value', 0);
set(handles.radio_Doub_Ver, 'Value', 0);
set(handles.radio_Vertical, 'Value', 1);
guidata(hObject, handles);

% --- Executes on button press in push_Seq_Imp.
function push_Seq_Imp_Callback(hObject, eventdata, handles)
% hObject    handle to push_Seq_Imp (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
str='Sequence impedances in Ohms:
Xseq=abs(imag(handles.MyData.Zseq));
Xpos=num2str(round(Xseq(2,1)*100)/100);
X_est=num2str(round(handles.MyData.X_est*100)/100);
Zseq=mat2str(round(handles.MyData.Zseq*100)/100);
ss=[str, char(10), Zseq, char(10), 'exact X+: ', Xpos, char(10), ...
    'approx. X+: ', X_est, char(10), 'approximation using GMD, exact uses distances during each transposition to get Zph accurately'];
set(handles.text2, 'string', ss);

function edit_ph_ph_faults_Callback(hObject, eventdata, handles)
% hObject    handle to edit_ph_ph_faults (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_ph_ph_faults as text
%        str2double(get(hObject,'String')) returns contents of edit_ph_ph_faults as a double
% --- Executes during object creation, after setting all properties.
function edit_ph_ph_faults_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit_ph_ph_faults (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
% called
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject, 'BackgroundColor', 'white');
end

function edit_Zf_ph_ph_Callback(hObject, eventdata, handles)
% hObject    handle to edit_Zf_ph_ph (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_Zf_ph_ph as text
% str2double(get(hObject,'String')) returns contents of edit_Zf_ph_ph as a double

% --- Executes during object creation, after setting all properties.
function edit_Zf_ph_ph_CreateFcn(hObject, eventdata, handles)
    hObject handle to edit_Zf_ph_ph (see GCBO)
    eventdata reserved - to be defined in a future version of MATLAB
    handles empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit_Zf_ph_ph_X_Callback(hObject, eventdata, handles)
    hObject handle to edit_Zf_ph_ph_X (see GCBO)
    eventdata reserved - to be defined in a future version of MATLAB
    handles structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit_Zf_ph_ph_X as text
% str2double(get(hObject,'String')) returns contents of edit_Zf_ph_ph_X as a double

% --- Executes during object creation, after setting all properties.
function edit_Zf_ph_ph_X_CreateFcn(hObject, eventdata, handles)
    hObject handle to edit_Zf_ph_ph_X (see GCBO)
    eventdata reserved - to be defined in a future version of MATLAB
    handles empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in push_U_loss_of_ph.
function push_U_loss_of_ph_Callback(hObject, eventdata, handles)
    hObject handle to push_U_loss_of_ph (see GCBO)
    eventdata reserved - to be defined in a future version of MATLAB
    handles structure with handles and user data (see GUIDATA)
str='Unbalance from transmission line after faulted phases are opened in %';
U=round(abs(handles.MyData.Uopen)*100)/100
ss=[str, char(10), ...
    'Avg. 3ph circuits unbalance factor: ',
    mat2str(U(1)), char(10), ...
    'Max. 3ph circuits unbalance factor: ',
    mat2str(U(2)), char(10), ...}
'3ph unbalance factor applied to the HPO case: ', mat2str(U(3)), char(10), ...
'HPO generalized unbalance factor: ', mat2str(U(4)), char(10), ...
'IEEE unbalance factor: ', mat2str(U(5))];
set(handles.text2, 'string', ss);

% --- Executes on button press in radio_E_field.
function radio_E_field_Callback(hObject, eventdata, handles)
    % hObject    handle to radio_E_field (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    if (get(hObject, 'Value')==1)
        axes(handles.axes3);
        E=handles.MyData.E;
        [~,k]=size(E);
        x=-(k-1)/2:1:(k-1)/2;
        h=[];
        hold on;
        h(1)=plot(x, E(2,:), '-.', 'LineWidth', 2, 'Color', 'red');
        h(2)=plot(x, E(1,:), 'LineWidth', 2, 'Color', 'green');
        h(3)=plot(x, E(3,:), '--', 'LineWidth', 2, 'Color', 'black');
        h(4)=plot(x, E(4,:), ':', 'LineWidth', 2, 'Color', 'c');
        h(5)=plot(x, E(5,:), '--', 'LineWidth', 2, 'Color', 'm');
        xlabel('Number of transposition sections');
        ylabel('Unbalance factor in %');
        title(sprintf('Electric field vs. horizontal distance 
from tower at 1m height'));
        xlabel('Distance (m)');
        ylabel('Electric Field (kV/m)');
        legend('E-field start of line', 'E-field end of line untransposed', ... 'E-field end of line transposed', ... 'E-field during fault', 'E-field with faulted phases open');
        hold off;
        handles.MyData.h7=h;
        guidata(hObject, handles);
    else
        h=handles.MyData.h7;
        for p=1:1:5
            delete(h(p));
        end
        legend(handles.axes3, 'hide');
        guidata(hObject, handles);
    end
    % Hint: get(hObject,'Value') returns toggle state of radio_E_field

% --- Executes on button press in radio_M_field.
function radio_M_field_Callback(hObject, eventdata, handles)
    % hObject    handle to radio_M_field (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)
    if (get(hObject, 'Value')==1)
axes(handles.axes3);
B=handles.MyData.B;
[~,k]=size(B);
x=-(k-1)/2:1:(k-1)/2;
h=[];
hold on;
h(1)=plot(x, B(2,:), '-.', 'LineWidth', 2, 'Color', 'red');
h(2)=plot(x, B(1,:), 'LineWidth', 2, 'Color', 'green');
h(3)=plot(x, B(3,:), '--', 'LineWidth', 2, 'Color', 'black');
h(4)=plot(x, B(4,:), ':', 'LineWidth', 2, 'Color', 'c');
h(5)=plot(x, B(5,:), '--', 'LineWidth', 2, 'Color', 'm');
xlabel('Number of transposition sections');
ylabel('Unbalance factor in %');
title(sprintf('Magnetic field vs. horizontal distance from tower at 1m height'));

%title('M-field vs. horizontal distance from tower at 1m height');
xlabel('Distance (m)');
ylabel('Magnetic Field (mG)');
legend('B-field start of line', 'B-field end of line untransposed',...
'B-field end of line transposed',...
'B-field during fault', 'B-field with faulted phases open');
hold off;
handles.MyData.h8=h;
guidata(hObject, handles);
else
    h=handles.MyData.h8;
    for p=1:1:5
        delete(h(p));
    end
    legend(handles.axes3, 'hide');
guidata(hObject, handles);
end
% Hint: get(hObject,'Value') returns toggle state of radio_M_field
% Brian Pierre
% simulation of a HPO transmission line with pi line modeled
% solve for voltage at the receiving end and current in each phase
% code for an n-phase system with circularly, vertically, or double vertical
% configured conductors
% solve for unbalance caused by transmission line left untransposed and
% after each transposition
% solve for fault conditions after any number of faults occur with different
% fault impedances

function [Vspu, Vr_untransposed, Vr_fully_trans, Vr_w_faults, ...
    Vr_ft_faults_opened, Ir_untransposed, Ir_fully_trans, ...
    Ir_w_faults, Ir_ft_faults_opened, U, Uopen, Losses, Zseq, X_GMD,
    drop2, E, B]=N_phase_sim3(n, d, h, Length, ...
    Voltage, GMR, r_cond, Rcond, Sload, pf, faults, Zf, faults_ph_ph,
    Zf_ph_ph, config)

%% Adjust Inputs
re=r_cond/2/12; % radius of cond. in ft. % change for different bundle
configurations
GMRe=GMR;
Vin=Voltage*10^3;
Vll=Voltage*sqrt(2-2*cosd(360/n));
Sload=Sload*10^6/n; % VA
phi=acosd(pf);
Zl=Vin^2/Sload*(cosd(phi)+1i*sind(phi));
% P=Sload*pf; % another way to check load is correct
% Q=sqrt(Sload^2-P^2);
% Zlll=Vin^2/(P-1i*Q)
Ibase=Sload/Vln;

% Self Reactance
S=1i*0.12134*(log(1/GMRe)+7.93402); % Ohm/mile
S=(S+Rcond);

% Geometry
% find phase spacing distances
[config 1=circular, 2=double vertical, 3=vertical
[pos_x, pos_y]=Cond_geometry(n, d, h, config);
% Get dph
ddph=zeros(n,n);
for p=1:1:n
    for q=1:1:n
        if q==p
            % distance to self just set as 1
            ddph(p,q)=1;
        else
            % phase spacing distance
        end
    end
end

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ddph(p,q)=sqrt((pos_x(p)-pos_x(q))^2+(pos_y(p)-pos_y(q))^2);
end
end

%% Sending Voltage
%Ax=b this part forms the b. Contains n rows of Vs and n rows of 0.
a=exp(1i*2*pi/n);
Vspu=[ ];
for p=0:1:n-1
  Vspu=[Vspu; a'^(n-(n-p))];
end
Vs=Vln*Vspu;
zero=zeros(n,1);
b=[Vs; zero];

%% Builds identity matrix
All=eye(n);
Ann=-All;

%need T for sequence components
T=Form_T_any_phase_order(n);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% %% Transpositions
%%What's the unbalance after each transposition.
%Also what's the ending voltage phasor diagram
ep=8.854*10^-12;
Zseq2=0; Zph2=0;
%loop through number of transposition sections to be fully transposed (n)
for p=1:1:n
  pos_xn=pos_x;
  pos_yn=pos_y;
  Zph=zeros(n);
  P=zeros(n);
  X_D=0;
  for m=1:1:p
    %find impedance matrix
    Z=Form_Zph_for_n_phase(n, S, pos_xn, pos_yn)*Length/p; %Ohms
    %find capacitance matrix. No transpose
    P1=Form_C_for_n_phase(n, re, pos_xn, pos_yn)/p;
    Zph=Zph+Z; %add each transposition impedance matrix together
    P=P+P1; %add each transposition capacitance matrix together
    pos_xn=circshift(pos_xn,[0,1]); %transpose
    pos_yn=circshift(pos_yn,[0,1]); %transpose
  end
  C=2*pi*ep*inv(P)*1609*Length;
  C=abs(C);
  Zseq1=round(diag(T^Zph*T)*10000000)/10000000;
  if round(Zph*1)/1==round(Zph2*1)/1

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% 'This never happens Zph = Zph after an additional transposition'
% end
% if Zseq22==Zseq11
% 'WTF, diag(Zseq) = diag(Zseq) after an additional transposition'
% end
% Zph22=Zph;
% Zseq22=Zseq11;

%convert capacitance matrix into useable for An1
Zc=1./(1i*2*pi*60*C2);

%Build An1 matrix where diagonal entries include all ph-ph capacitances
% load, with ph-g cap. Non-diagonal entries include only neg. ph-ph
%cap.
An1=1./(2*Zc);
Zl_mat=ones(n,1)*1/Zl;
An1_diag=sum(An1,2)+Zl_mat;
for m=1:1:n
    An1(m,m)=An1_diag(m,1);
end
An1=-An1;
for m=1:1:n
    An1(m,m)=-An1(m,m);
end
A=[A11, Zph; An1, Ann];

%'Van_r, Vbn_r, ... Vnn_r, Ia, Ib, ... In'
x=A\b;
Vp=abs(x(1:n));
Vph=x(1:n)/Vln;
Iph=x(n+1:2*n)/Ibase;
if p==1
    %voltage of receiving end of untransposed line. used for graphing
    %later
    Vr_untransposed=Vph;
    Ir_untransposed=Iph;
    I=(Ibase*abs(Ir_untransposed)).^2;
    Loss_untran=sum(Rcond*Length*I)/(10^6);
    E_unTrans=ele_field(pos_x, pos_y, n, C, Vr_untransposed*Vln);
    B_untrans=mag_field(pos_x, pos_y, n, Ir_untransposed*Ibase);
    Zseq_untran=T\Zph*T; %Ohm/mi
    Xseq_untran=imag(diag(Zseq_untran))
    Zph1=Zph(1,:)
    for mm=0:1:n-1
        eigenval(mm+1,1)=1;
        for kk=1:1:n
            %store ph-g for other purposes
            %end for kk
            %end for mm
        end
        %end for mm
    end
    %end for p
eigenval(mm+1,1)=eigenval(mm+1,1)+2*pi*mm*(kk-1)/n);
    end
end
eigenval=imag(eigenval)
end

%% Unbalance calculations
T3=Form_T_any_phase_order(3);
if rem(n,3)==0
    %check 3 phase unbalance factors
    U3sum=0;
    Umax=0;
    for m=1:1:n/3
        V3=[Vph(m); Vph(m+n/3); Vph(m+2*n/3)];
        V3seq=abs(T3\V3);
        U(p,m)=V3seq(3)/V3seq(2)*100; %unbalance of one 3 phase circuit
        U3sum=U3sum+U(p,m);
    end
    %avg. unbalance of 3 phase circuits
    U(p,n/3+1)=U3sum/(n/3);
end

%Sequence components and unbalance calculations
Vtot=0; Vmaxi=0;
for m=1:1:n
    Vtot=Vtot+Vp(m);
    if Vp(m) > Vmaxi
        Vmaxi=Vp(m);
    end
end
Vavg=Vtot/n;
Vseq=abs(T\Vph);
Vseqt=Vseq(1)^2;
for m=3:1:n
    Vseqt=Vseqt+(Vseq(m))^2;
end
if rem(n,3)==0
    U(p,n/3+3)=Vseq(n)/Vseq(2)*100; %6ph unbalance in percent V-/V+
    U(p,n/3+4)=sqrt(Vseqt)/Vseq(2)*100; %6ph generalized unbalance
    U(p,n/3+5)=(Vmaxi-Vavg)/Vavg*100; %IEEE unbalance factor
else
    U(p,1)=Vseq(n)/Vseq(2)*100; %6ph unbalance in percent V-/V+
    U(p,2)=sqrt(Vseqt)/Vseq(2)*100; %6ph generalized unbalance
    U(p,3)=(Vmaxi-Vavg)/Vavg*100; %IEEE unbalance factor
end

end

Vr_fully_trans=Vph;
Ir_fully_trans=Iph;
I=(Ibase*abs(Ir_untransposed)).^2;
Loss_fully_tran=sum(Rcond*Length*I)/(10^6);
Losses=[Loss_untran, Loss_fully_tran];
Zph
Zseq=diag(T\Zph*T)

%% Simple Checkers of sequence impedances (all ways to calculate them)

%GMD
Dph=zeros(n,n);
for p=1:1:n
  for q=1:1:n
    if q==p
      % given a self reactance
      Dph(p,q)=1;
    elseif p>q
      Dph(p,q)=1;
    else
      % phase spacing distance
      Gph=sqrt((pos_x(p)-pos_x(q))^2+(pos_y(p)-pos_y(q))^2);
      Dph(p,q)=Gph^(1/((n-1)*n/2));
    end
  end
end
GMD=prod(Dph(:)); % ft
X_GMD=0.12134*log(GMD/GMRe)*Length % Ohm

%Dx+_circular
Deqn=1;
for p=2:1:n
  dp=norm(pos-(pos(p))^2+(pos_y(p))^2);
  Deqn=Deqn*dp^(-cosd(360*(p-1)/n));
end
X_Dxplus_cir=0.12134*log(Deqn/GMRe)*Length

%generalized Dx+
Deqn_gen=1;
for gg=1:1:n-1
  Dtot=1;
  for ff=1:1:n
    hh=ff+gg;
    if hh>n
      hh=hh-n;
    end
    Dtot=Dtot*ddph(ff,hh)^(1/n);
  end
  Deqn_gen=Deqn_gen*Dtot^(-cosd(360*gg/n));
end
X_Dxplus_gen=0.12134*log(Deqn_gen/GMRe)*Length

%generalized Dxseq
ddph
Xseq=[];
for seq=0:1:n-1
  Deqn_gen=1;
  for gg=1:1:n-1
    Dtot=1;
    for ff=1:1:n
      ddph
hh=ff+gg;
while hh>n
    hh=hh-n;
end
Dtot=Dtot*ddph(ff,hh);%^(1/n);
end
Deqn_gen=Deqn_gen*Dtot^(-cosd(360*gg*seq/n)/n);%(-
cosd(360*gg*seq/n));
end
if seq==0
    Xseq(seq+1,1)=0.12134*(log(Deqn_gen/GMRe)+n*7.93402)*Length;
else
    Xseq(seq+1,1)=0.12134*log(Deqn_gen/GMRe)*Length;
end
end
Xseq

%Dxseq_circular
for seq=0:1:n-1
    Deqn=1;
    for p=2:1:n
        dph=sqrt((pos_x(1)-pos_x(p))^2+(pos_y(1)-pos_y(p))^2);
        Deqn=Deqn*dph^(-cosd(360*(p-1)*seq/n));
    end
    if seq==0
        X_Dseq_cir(seq+1,1)=0.12134*(log(Deqn/GMRe)+n*7.93402)*Length;
    else
        X_Dseq_cir(seq+1,1)=0.12134*log(Deqn/GMRe)*Length;
    end
end
X_Dseq_cir

%Dxseq_circular again with d12 only
for seq=0:1:n-1
    Deqn=1;
    for p=1:1:n-1
        Deqn=Deqn*(sqrt((1-cos(2*pi*p/n))/(1-cos(2*pi/n))))^(-
cosd(360*p*seq/n));
    end
    Deqn=Deqn*d;
    if seq==0
        X_Dseq_cir(seq+1,1)=0.12134*(log(Deqn/GMRe)+n*7.93402)*Length;
    else
        X_Dseq_cir(seq+1,1)=0.12134*log(Deqn/GMRe)*Length;
    end
end
X_Dseq_cir

%generalized Dx0
Dx0_gen=1;
for gg=1:1:n
    for ff=1:1:n
        Dx0_gen=Dx0_gen*ddph(gg,ff)^(-1/(n));
    end
end
end
X_Dxzero_gen=0.12134*(log(Dx0_gen/GMRe)+n*7.93402)*Length

%generalized Dx0 simplified
Dx0_gen=1;
for gg=1:1:n-1
  for ff=gg+1:1:n
    Dx0_gen=Dx0_gen*ddph(gg,ff)^(-2/(n));
  end
end
X_Dxzero_gen=0.12134*(log(Dx0_gen/GMRe)+n*7.93402)*Length

% line parameters estimates with GMD, GMDn, and exact with positive seq. calculation
Res_pm=Rcond; %Ohm/mi
Res=Res_pm*Length; %Ohm

Zph_pm=Zph/Length; %Ohm/mi
Zseq_pm=T\Zph_pm*T; %Ohm/mi

Xpos_pm=imag(Zseq_pm(2,2)); %Ohm/mi
Xpos=Xpos_pm*Length %Ohm %exact positive sequence reactance for circular lines
GMDvsXpos=abs(Xpos-X_GMD)/Xpos*100; %error from GMD approximation

Xzero_pm=imag(Zseq_pm(1,1)); %Ohm/mi
Xzero=Xzero_pm*Length

C_pm=C2/Length; %F/mi
C_seq_pm=T\C_pm*T; %F/mi
Cpos_pm=real(C_seq_pm(2,2)); %F/mi
Cpos=Cpos_pm*Length; %F
Czero_pm=real(C_seq_pm(1,1)); %F/mi
C_GMD=2*pi*ep/log(GMD/re)*1609*Length; %F
B_est_pm=2*pi*60*C_GMD;
B_for_PW=real(2*pi*60*Cpos_pm); %Mhos/mile

Sloadt=Sload*n;
P=Sloadt*pf;
Q=sqrt(Sloadt^2-P^2);
Zlt=Vln^2/(P-1i*Q);
Zline=Res+li*X_GMD;
Vrr=Zlt/(Zlt+Zline);
Vrr_mag=abs(Vrr);

drop1=asind(P*X_GMD/(n*Vln*Vrr_mag*Vln));

V_ft=abs(Vr_fully_trans);
Pflow=real((Vln*V_ft(1,1))^2/Zlt)+Loss_fully_tran*10^6;
drop2=asind(Pflow*imag(Zseq(2,1))/(n*Vln^2*V_ft(1,1)));

%% FAULTS
An2=An1;
% phase to ground fault
for p=1:1:length(faults)
    pp=faults(p);
    An1(pp,pp)=An1(pp,pp)-1/Zl+1/(Zl*Zf/(Zl+Zf));
    An1(pp,pp)=An1(pp,pp)+1/Zf;
end

% phase to phase faults
faults_ph_ph=strread(faults_ph_ph, '%s', 'delimiter', ',');
for p=1:1:length(faults_ph_ph)
    ph_ph=str2double(strread(faults_ph_ph{p,1}, '%s', 'delimiter', '- '));
    for m=1:1:length(ph_ph)-1
        ph=[ph_ph(m), ph_ph(m+1)];
        An1(ph(1),ph(1))=An1(ph(1),ph(1))+1/Zf_ph_ph;
        An1(ph(2),ph(2))=An1(ph(2),ph(2))+1/Zf_ph_ph;
        An1(ph(1),ph(2))=An1(ph(1),ph(2))-1/Zf_ph_ph;
        An1(ph(2),ph(1))=An1(ph(2),ph(1))-1/Zf_ph_ph;
    end
end
% recalculate
A=[A11, Zph; An1, Ann];
%'Van_r, Vbn_r, ... Vnn_r, Ia, Ib, ... In'
x=A\b;
Vph=x(1:n)/Vln;
Iph=x(n+1:2*n)/Ibase;

Vr_w_faults=Vph;
Ir_w_faults=Iph;

% After fault, circuit opened
Zl2=10^100; \W

% open phases that were faulted
% build array of all phases that were faulted
phph=faults;
for p=1:1:length(faults_ph_ph)
    ph_ph1=str2double(strread(faults_ph_ph{p,1}, '%s', 'delimiter', '- '));
    phph=[phph, ph_ph1'];
end

% make the load on those phases huge (aka opening the phase)
for p=1:1:length(phph)
    pp=phph(p);
    An2(pp,pp)=1/Zl2;%An1(p,p)+1/Zl2;
end
A=[A11, Zph; An2, Ann];
%'Van_r, Vbn_r, ... Vnn_r, Ia, Ib, ... In'
x=A\b;
Vph=x(1:n)/Vln;
Iph=x(n+1:2*n)/Ibase;
Vr_ft_faults_opened=Vph;
Ir_ft_faults_opened=Iph;

%% Unbalance with faulted circuits open
%each circuit
%if n is a multiple of 3 more unbalance analysis
if rem(n,3)==0
  %check 3 phase unbalance factors
  U3sum=0; Umax=0;
  for m=1:1:n/3
    V3=[Vph(m); Vph(m+n/3); Vph(m+2*n/3)];
    V3seq=abs(T3\V3);
    U1=V3seq(3)/V3seq(2)*100; %unbalance of one 3 phase circuit
    U3sum=U3sum+U1;
    if U1>Umax %maximum 3 ph unbalanced circuit
      Umax=U1;
    end
  end
  %avg. unbalance of 3 phase circuits
  Uopen(1)=U3sum/(n/3);
  Uopen(2)=Umax;
else
  Uopen(1)=0;
  Uopen(2)=0;
end

%Sequence components and unbalance calculations
Vp=abs(Vr_ft_faults_opened);
Vtot=0; Vmaxi=0;
for m=1:1:n
  Vtot=Vtot+Vp(m);
  if Vp(m) > Vmaxi
    Vmaxi=Vp(m);
  end
end
Vavg=Vtot/n; %sum(Vp)/n;
Vseq=abs(T\Vph);
Vseqt=Vseq(1)^2;
for m=3:1:n
  Vseqt=Vseqt+(Vseq(m))^2;
end
Uopen(3)=Vseq(n)/Vseq(2)*100; %6ph unbalance in percent V-/V+
Uopen(4)=sqrt(Vseqt)/Vseq(2)*100; %6ph generalized unbalance
Uopen(5)=(Vmaxi-Vavg)/Vavg*100; %IEEE unbalance factor

%% electric and mag. fields
% sending current
Is=Vs/(Zl+S*Length);

%mag. field
Bxy=mag_field(pos_x, pos_y, n, Is);
B=[B_untrans; Bxy];
Bxy=mag_field(pos_x, pos_y, n, Ir_fully_trans*Ibase);
B=[B; Bxy];
Bxy=mag_field(pos_x, pos_y, n, Ir_w_faults*Ibase);
B=[B; Bxy];
Bxy=mag_field(pos_x, pos_y, n, Ir_ft_faults_opened*Ibase);
B=[B; Bxy];

%ele. field
Exy=ele_field(pos_x, pos_y, n, C, Vs);
E=[E_untrans; Exy];
Exy=ele_field(pos_x, pos_y, n, C, Vr_fully_trans*Vln);
E=[E; Exy];
Exy=ele_field(pos_x, pos_y, n, C, Vr_w_faults*Vln);
E=[E; Exy];
Exy=ele_field(pos_x, pos_y, n, C, Vr_ft_faults_opened*Vln);
E=[E; Exy];

%%
'Simulation complete'
end
D.4  Line Impedance Matrix Code

Form_Zph_for_n_phase.m

%Brian Pierre
%Builds Zph matrix. Done for any phase order, n.

function [Zph]=Form_Zph_for_n_phase(n, S, pos_x, pos_y)
Zph=zeros(n,n);
for p=1:1:n
    for q=1:1:n
        if q==p
            %given a self reactance
            Zph(p,q)=S;
        else
            %mutual calculation based on a phase spacing distance
            dph=sqrt((pos_x(p)-pos_x(q))^2+(pos_y(p)-pos_y(q))^2);
            Zph(p,q)=1i*0.12134*(log(1/dph)+7.93402);
        end
    end
end
end
D.5 Capacitance Matrix Code

Form_C_for_n_phase.m

%Brian Pierre
%Builds a Capacitance matrix. Done for any phase order, n.

function Pa=Form_C_for_n_phase(n, re, pos_x, pos_y)

%Format is done in Glover Power Systems Analysis 4th ed. Book Page 207–
%210.
%Build Pa
Pa=zeros(n,n);
for p=1:1:n
    for q=1:1:n
        if p==q
            h11=2*pos_y(p);
            Pa(p,q)=log(h11/re);
        end
        if p~=q
            h11=2*pos_y(p); %height from phase n to same phase n image
            h22=2*pos_y(q);
            d12=sqrt((pos_x(p)-pos_x(q))^2+(pos_y(p)-pos_y(q))^2);
            %distance between phase p and q
            TS=abs(h11-h22)/2;
            if h11>=h22
                RT=h11-TS;
            else
                RT=h22-TS;
            end
            %height between phase p and image of phase q
            h12=sqrt(RT^2+TS^2);
            Pa(p,q)=log(h12/d12);
        end
    end
end
%C matrix is equal to inv(Pa)
%C=inv(Pa)*1609;
end
D.6 Form $n$-phase Sequence Components Transformation Matrix

Form_T_any_phase_order.m

%Brian Pierre
%Builds the modal matrix, the sequence component transformation matrix, $T$
%for any phase order, $n$.

function [T]=Form_T_any_phase_order(n)
T=zeros(n,n);
a=exp(1i*2*pi/n);
for p=1:1:n
    for q=1:1:n
        T(p,q)=a^(-((p-1)*(q-1)));
    end
end
T=1/sqrt(n)*T;
end
D.7 Code to Determine Conductor Geometry

Cond Geometry.m

%%% Geometry
% inputs: number of phases, phase spacing, height of cond., configuration
% configuration 1=circular, 2=double vertical, 3=vertical
% outputs: x and y position of each conductor.
function [pos_x, pos_y]=Cond_Geometry(n, d, h, config)

%find phase spacing distances
degree=360/n;
dn=d/sqrt(2-2*cosd(degree));
%distance phase to neutral

%get positions of each conductor
if config==1 %circular
    pos_x=[dn];
    for p=1:1:n-1;
        degree=p*360/n;
        if degree>0 && degree<=90
            d1=dn*cosd(degree);
            d2=d1; end
        if degree>90 && degree<=180
            degree=180-degree;
            d1=dn*cosd(degree);
            d2=-d1; end
        if degree>180 && degree<=270
            degree=degree-180;
            d1=dn*cosd(degree);
            d2=d1; end
        pos_x(1,p+1)=d2;
    end
    h=h+dn;
    pos_y=[h];
    for p=1:1:n-1;
        degree=p*360/n;
        if degree>0 && degree<=90
            h1=dn*sind(degree);
            h2=h+h1; end
        if degree>90 && degree<=180
            degree=180-degree;
            h1=dn*sind(degree);
            h2=h+h1; end
        if degree>180 && degree<=270
            degree=degree-180;
            h1=dn*sind(degree);
            h2=h-h1; end
if degree>270
    degree=360-degree;
    h1=dn*sind(degree);
    h2=h-h1; end
    pos_y(1,p+1)=h2;
end
elseif config==2 %double vertical
    if rem(n,2)==0
        for p=1:1:n/2
            pos_x(p)=-dn;
            h2=h+d*p-d;
            pos_y(1,p)=h2;
            pos_y(1,n-p+1)=h2;
        end
    for p=n/2+1:1:n
        pos_x(p)=dn;
    end
    else
        for p=1:1:(n+1)/2
            pos_x(p)=-dn;
            h2=h+d*p-d;
            pos_y(1,p)=h2;
            pos_y(1,n-p+1)=h2;
        end
        pos_x((n+3)/2)=dn;
        pos_y(1,(n+3)/2)=pos_y(1,(n+1)/2)-d/2;
        for p=(n+5)/2:1:n
            pos_x(p)=dn;
            h2=pos_y(1,p-1)-d;
            pos_y(1,p)=h2;
        end
    end
else %vertical
    for p=1:1:n
        pos_x(p)=0;
        h2=h+d*p-d;
        pos_y(1,p)=h2;
    end
end
D.8  

Magnetic Field Calculation Code

mag_field.m

function Bxy=mag_field(pos_x, pos_y, n, I)
y=1; %mag. field at 1 meter above ground
x=-60:1:60; %range of mag. field calculation
pos_x=pos_x/3.28;
pos_y=pos_y/3.28;
for m=1:1:121
    Hxtot=0; Hytot=0;
    for p=1:1:n
        Hx=I(p)*((y-pos_y(p))/(2*pi*((x(m)-pos_x(p))^2+(y-pos_y(p))^2))); %A/m
        Hxtot=Hxtot+Hx;
        Hy=I(p)*((x(m)-pos_x(p))/(2*pi*((x(m)-pos_x(p))^2+(y-pos_y(p))^2)));
        Hytot=Hytot+Hy;
    end
    Hxtot=abs(Hxtot); Hytot=abs(Hxtot);
    Hxy=sqrt(Hxtot^2+Hytot^2); %A/m
    %magnetic field in %mG
    Bxy(m)=4*pi*10^-7*Hxy*10^7; %10^4 to convert T to G, 10^3 to convert to mG.
end
Bxy_max=max(Bxy);
end
D.9  Electric Field Calculation Code

ele_field.m

function Exy=ele_field(pos_x, pos_y, n, C, Vln)
y=1; % e. field at 1 meter above ground
x=-60:1:60; % meters % range of e. field calculation
pos_x=pos_x/3.28084; % meters
pos_y=pos_y/3.28084; % meters
ep=8.854*10^-12; % F/m
Q=((C/1609)*(Vln/10^3))'; % kV*F/m
for m=1:1:121
    Extot=0;
    Eytot=0;
    for p=1:1:n
        Ex=Q(p)*(x(m)-pos_x(p))/(2*pi*ep*((x(m)-pos_x(p))^2+(y-pos_y(p))^2))-
        Q(p)*(x(m)-pos_x(p))/(2*pi*ep*((x(m)-pos_x(p))^2+(y+pos_y(p))^2));
        Ey=Q(p)*(y-pos_y(p))/(2*pi*ep*((x(m)-pos_x(p))^2+(y-pos_y(p))^2))-
        Q(p)*(y-pos_y(p))/(2*pi*ep*((x(m)-pos_x(p))^2+(y+pos_y(p))^2));
        Extot=Extot+Ex;
        Eytot=Eytot+Ey;
    end
    Exy(m)=sqrt(Extot^2+Eytot^2); % kV/m
end
Exy_max=max(Exy); end
APPENDIX E

EXAMPLES FOR CALCULATION OF NUMBER OF FAULT TYPES
E.1 Significant Fault Type Examples

The number of fault types and significant fault types for \( n \)-phase systems is explained in Section 4.11. This appendix shows the method and examples of how to calculate the number of fault types and significant fault types. The number of fault types \( F \) for an \( n \)-phase system is,

\[
F = 2^{n+1} - 2 - n.
\]  

(A.1)

The number of significant fault types \( \Gamma \) for an \( n \)-phase system is,

\[
\Gamma = K - 3 + \frac{1}{n} \sum_{d \mid n} \phi(d) 2^{\frac{n}{d}}
\]

where \( K = \begin{cases} 
2^{\frac{n-1}{2}+1} & \text{for odd } n \\
2^{\frac{n}{2}} + 2^{\frac{n}{2}-1} & \text{for even } n
\end{cases} \)

Note that the summation in (A.2) is over all possible divisors \( d \) of \( n \) (all positive integers that divide evenly into \( n \)). Examples for the summation \( d \mid n \) are in Table E.1. Also, \( \phi(d) \) is the Euler’s totient function also known as the ‘phi function’, which counts the totatives of \( d \), i.e. the positive integers that are relatively prime to \( d \). Examples of the phi function are in Table E.2 for \( n = 1 \) to \( n = 24 \).

Three phase example (\( n = 3 \)): The number of fault types is,

\[
F = 2^{3+1} - 2 - 3 = 11.
\]

To calculate the number of significant fault types, the summation is over all positive integers that divide evenly into 3, i.e. \( d = 1 \) and \( d = 3 \),

\[
\Gamma = 2^{\frac{n-1}{2}+1} - 3 + \frac{1}{n} \sum_{d \mid n} \phi(d) 2^{\frac{n}{d}}
\]
\[
\Gamma = 2^{\frac{n-1}{2}+1} - 3 + \frac{1}{n} \left( \phi(1)2^1 + \phi(3)2^3 \right)
\]
\[
\Gamma = 2^{\frac{3-1}{2}+1} - 3 + \frac{1}{3} \left( \phi(1)2^1 + \phi(3)2^3 \right)
\]

Examples of the phi function are in Table E.2 for \( n = 1 \) to \( n = 24 \).

\[
\phi(1) = 1 \text{ and } \phi(3) = 2
\]
\[
\Gamma = 2^{\frac{3-1}{2}+1} - 3 + \frac{1}{3} \left( \frac{3}{2^1 + 2 \left( \frac{3}{2^3} \right)} \right)
\]
\[
\Gamma = 5
\]

Six phase example \((n = 6)\)

The number of fault types is,
\[
F = 2^{6+1} - 2 - 6 = 120.
\]

The number of significant fault types is,
\[
\Gamma = 2^n + 2^{n-1} - 3 + \frac{1}{n} \sum_{d|n} \phi(d)2^\frac{n}{d}
\]
\[
\Gamma = 2^{\frac{n}{2}} + 2^{\frac{n}{2}-1} - 3 + \frac{1}{n} \left( \phi(1)2^1 + \phi(2)2^\frac{n}{2} + \phi(3)2^{\frac{n}{3}} + \phi(6)2^{\frac{n}{6}} \right)
\]
\[
\Gamma = 23
\]
Table E.1 The Summation \(d|n\)

<table>
<thead>
<tr>
<th>(n)</th>
<th>Positive integers that divide into (n) evenly</th>
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</thead>
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</tr>
<tr>
<td>24</td>
<td>1, 2, 3, 4, 6, 8, 12, 24</td>
</tr>
</tbody>
</table>

Twenty four phase example \((n = 24)\)

The number of fault types is,

\[
F = 2^{24+1} - 2 - 24 = 33,554,406.
\]

The number of significant fault types is,

\[
\Gamma = 2^n + 2^{n-1} - 3 + \frac{1}{n} \sum_{d|n} \phi(d) 2^{\frac{n}{d}}
\]
\[ \Gamma = 2^{n} + 2^{n-1} - 3 \]
\[ + \frac{1}{n}(\phi(1)2^{n} + \phi(2)2^{n} + \phi(3)2^{n} + \phi(4)2^{n} + \phi(6)2^{n} \]
\[ + \phi(8)2^{n} + \phi(12)2^{n} + \phi(24)2^{n}) \]
\[ \Gamma = 6141 + \frac{1}{24}(1)2^{24} + (1)2^{12} + (2)2^{8} + (2)2^{6} + (2)2^{4} + (4)2^{3} + (4)2^{2} + (8)2^{1} \]
\[ \Gamma = 705,393 \]

Table E.2 The Phi Function Examples

<table>
<thead>
<tr>
<th>(d)</th>
<th>Numbers relatively prime to (d)</th>
<th>(\phi(d))</th>
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</thead>
<tbody>
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</table>
E.2 Symmetrically Significant Fault Types

The significant fault types may be further grouped. For example, the five significant faults for a three phase system are:

- Phase – ground
- Phase – phase
- Phase – phase – ground
- Phase – phase – phase
- Phase – phase – phase – ground.

However, a phase – phase – phase fault has the same analysis and fault currents as a phase – phase – phase – ground fault; therefore these two faults can be grouped and count as one ‘symmetrically significant fault type.’ Another example of two significant faults that can be grouped into one symmetrically significant fault is in a four phase system, the phase to opposite phase fault and the phase to opposite phase to ground fault would be grouped (i.e. this one group includes a phase A-C fault, B-D fault, A-C-N fault, and B-D-N fault). In Table E.3 are values for the number of fault types, significant fault types, and symmetrically significant fault types for certain $n$-phase systems.
Table E.3  The Number of Fault Types for $n$-phase Systems

<table>
<thead>
<tr>
<th>Number of phases</th>
<th>Fault types</th>
<th>Significant fault types</th>
<th>Symmetrically significant fault types</th>
<th>Significant less symmetrically significant</th>
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