Increased Ratings of Overhead Transmission Circuits Using HTLS and Compact Designs

Brian J. Pierre, Student Member, IEEE G. T. Heydt, Life Fellow, IEEE

Abstract—High temperature low sag (HTLS) conductors offer the option of higher transmission capacity for a given right of way (ROW). The basis of an HTLS conductor is its ability to operate at long term high temperature, thereby allowing higher long term current ratings. The lower sag characteristics are obtained by managing conductor design and thermal properties of the conductor. Concomitantly, power ratings are increased in HTLS designs. HTLS lines can also improve the security limits through decreased phase spacing and resulting decrease in positive sequence line reactance. Utilization of HTLS as a transmission option, and compact designs as a configuration option can be used separately or together to achieve desired transmission objectives. This paper discusses the advantages and disadvantages of HTLS compact line designs. The focus is on increased ratings, reconductoring circuits, and the identification of application sites. The paper introduces a method to approximate the positive and negative sequence reactances using the mutual and self reactances.

Index Terms—High temperature low sag conductor, overhead transmission, compact transmission, transmission engineering, line capacity, thermal rating, dynamic security rating.

I. HTLS AND COMPACT OVERHEAD TRANSMISSION LINE DESIGNS

High temperature low sag (HTLS) conductors can have an immediate impact on power systems. The basis of an HTLS conductor is its ability to dissipate more heat, without incurring excessive sag. This increases the thermal power rating of the line. However, it can increase the thermal rating of the line to the point where the line is no longer thermally limited, but it is security limited. HTLS lines can also improve the security limits of the line through decreased phase spacing. The phase conductor spacing of a line is determined by multiple factors, such as sag limits and live maintenance requirements. If HTLS lines are operating below thermal rating because the line is security limited they will incur lower sag than similar lines that are not HLTS. This suggests an alternative design with more compact phase spacing. The reduction in phase spacing decreases the positive sequence reactance ($X^+$) of the line which in turn may increase the security power rating of the line. The increased ratings can enhance power marketing capabilities. The reduced phase spacing can decrease the ROW, decreasing land costs and/or tower construction costs.

Note that there are two distinct contemporary main reasons for transmission expansion. The first relates to load growth: in this case the ampacity and thermal ratings of relatively short circuits are of importance. As an example, load growth in a major metropolitan area may necessitate upgrading of the transmission grid. The second main motivation for transmission expansion is the accommodation of new renewable resources. As an example, it is conjectured that the addition of wind generation in the northern plains of the United States will necessitate the addition of numerous high voltage circuits in that region [1]. The transmission expansion necessitated by the integration of large scale wind and solar resources are often characterized by long, security limited lines.

This paper will discuss the advantages and disadvantages of HTLS and/or compact lines. This paper includes: the calculation of thermal and security limits; the improvement of ratings of HTLS and compact designs; inclusion of HTLS and compact circuits in PowerWorld [2]; and test cases in the Western Electricity Coordinating Council (WECC) system.

II. THERMAL AND SECURITY RATINGS

High temperature low sag conductors can help the thermal rating and security rating of a transmission line. The thermal limit of a line relates to the heat which the conductor can handle, and therefore the current the conductor can tolerate. The power flow security limit in MW in the line can be calculated using,

$$P_{12} = \frac{|V_1| |V_2| \sin(\delta_1 - \delta_2)}{X_{12}^+}$$

where $V_1$ and $V_2$ are the voltages at the terminals of busses 1 and 2 respectively and $\delta_1$ and $\delta_2$ are the voltage angles. $\delta_1 - \delta_2$ is the maximum voltage phase angle difference for angular security. The security limit is usually calculated using 30° between voltage angle phases. As a line length increases, $X^+$ increases. As the $X^+$ increases the security limit decreases. Generally, long lines are limited by security constraints, whereas short lines are limited by thermal constraints.

III. INCREASED THERMAL RATING USING HTLS CONDUCTORS

The main purpose of high temperature low sag conductors is to improve the thermal rating of a line. A typical HTLS conductor can handle 1.6 to 3 times the current of a similar conventional conductor [3]. This increase in current is proportional to the increase in thermal rating. However, this increase in current comes at a dollar cost of up to 6.5 times that of a conventional conductor (see Table I). 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 [4], and consequently the conductor resistance can be higher than that seen for conventional conduc-

---

The authors acknowledge the support of the Power Systems Engineering Research Center (PSerc) which is a Generation III National Science Foundation Industry University Cooperative Research Center, awards EEC-0001880, EEC-0968993. The authors also acknowledge the support of the U.S. Department of Energy for its PSerc future grid initiative.

The authors are with the School of Electrical, Computer, and Energy Engineering at Arizona State University, Tempe, AZ 85287, and can be reached at {brian.pierre, heydt}@asu.edu.
tors. As an example, [4] 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 ACC with 0.1116 Ω/mi at 75°C and 0.1613 at 210°C [6].

Table I Increase in current and cost for HTLS conductor compared to conventional conductors

<table>
<thead>
<tr>
<th>Conductor type</th>
<th>Relative ampacity*</th>
<th>Relative cost*</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCC</td>
<td>2.0</td>
<td>2.5-3.0</td>
<td>CTC Cable [5]</td>
</tr>
<tr>
<td>ACCR</td>
<td>2.0-3.0</td>
<td>5.0-6.5</td>
<td>3M [6]</td>
</tr>
<tr>
<td>ACSR</td>
<td>1.6-2.0</td>
<td>2.0</td>
<td>J-Power [7]</td>
</tr>
<tr>
<td>ACSS/TW</td>
<td>1.8-2.0</td>
<td>1.2-1.5</td>
<td>Southwire [8]</td>
</tr>
<tr>
<td>ACSS/AW</td>
<td>1.8-2.0</td>
<td>1.2-1.5</td>
<td>Southwire [8]</td>
</tr>
<tr>
<td>ACIR/AW</td>
<td>2.0</td>
<td>3.0-5.0</td>
<td>LS Cable [9]</td>
</tr>
</tbody>
</table>

*Compared to conventional conductors [3], for typical commercially available HTLS conductors.

IV. DECREASED PHASE SPACING (COMPACT DESIGN)

To determine the minimum allowed phase spacing for a transmission line, a number of variables need to be taken into consideration including:

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

References [10, 11] discuss these factors further. The National Electrical Safety Code (NESC) [12, 13] gives minimum conductor spacing (see Table II). This minimum spacing must be found during the maximum sag and during wind and ice conditions. Many operating companies and some jurisdictions (e.g., California [14], or the U. S. Department of Agriculture requirements [15]) 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 realize the benefits of compact designs.

Table II NESC minimum conductor spacing for specific operating voltages at elevations under 1500 ft [12]

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Minimum Conductor Spacing*</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 kV</td>
<td>13.6 ft</td>
</tr>
<tr>
<td>345 kV</td>
<td>9.4 ft</td>
</tr>
<tr>
<td>230 kV</td>
<td>7.1 ft</td>
</tr>
</tbody>
</table>

*For higher elevations, add 3% spacing for every 1000 ft above 1500 ft.

If a line is thermally overloaded it may be a target to be reconducted to HTLS. Once reconducted to HTLS, it is possible the line will no longer be thermally limited, but now security limited. Therefore, the extra current capacity of the HTLS line would go unused. Since the maximum current would not be flowing through the line, it would sag less. Therefore, the phase spacing could be decreased and the security rating could be increased. This would boost the power capacity of the line further and utilize the line to its full potential.

If the conductors are placed closer together, it would not only decrease ROW, but it would increase the mutual reac-
tance between phases. The increase in the mutual reactance would decrease the total positive sequence reactance in the line since total $X^+$ is equal to the self-reactance of the line less the mutual reactance between the lines in the balanced case,

$$X^+ = X_S - X_M.$$  \hfill (2)

This decrease in total $X^+$ would increase the security limit of the line, increasing the power flow capacity of the line. The power flow security limit in MW in the line can be calculated using (1).

In addition to the enhanced power marketing capabilities and decreased land costs and/or tower construction costs, there is another benefit to HTLS compact designs. The lower $X$ will cause more power to flow on the phase compact line causing decreased power flow on neighboring lines. The change to compact design instead of traditional spacing for a line in a congested power flow area could increase the power flow capabilities of neighboring lines, whose load was reduced due to the increased power flow on the new compact line.

V. INCREASE IN SECURITY RATING

The relationship between phase separation and positive sequence reactance of a transmission line is given by [16],

$$X^+ = X_1foot\ spacing + X_d$$ \hfill (3)

$$X_1foot\ spacing = 0.2794 \frac{f}{GMR} \ln \left( \frac{1}{GMD} \right)$$ \hfill (4)

$$X_d = 0.2794 \frac{f}{GMD} \log_{10} GMD$$ \hfill (5)

$$GMD = \sqrt{\frac{d_{ab} d_{bc} d_{ca}}{GMR}}$$ \hfill (6)

where (4)-(6) are for a lumped parameter three phase overhead line of geometric mean radius and geometric mean distance GMR, GMD respectively. Also, $X_d$ is the mutual reactance and $f$ is the operating frequency in Hz. For example, the reactance at one foot spacing for a 60 Hz Drake conductor with a GMR of 0.0375 ft is 0.3984 Ω/mi. The reactance of the line in Ω/mi with the GMD in feet is,

$$X_{per\ length} = 0.3984 + 0.2794 \log_{10} GMD.$$ \hfill (7)

A vertical or horizontal equally spaced line (i.e., phase spacing A-B is $d$, B-C is $d$, and A-C is 2$d$) has

$$GMD = \sqrt{2}d.$$ \hfill (8)

If the line has spacing 30 ft, the positive sequence reactance is 0.8391 Ω/mi.

In order to assess the impact of reduced spacing, note that the rate of change of positive sequence reactance with respect to spacing is,

$$\frac{\partial X}{\partial d} = 0.12134 \frac{d}{d}.$$ \hfill (9)

The change in $X^+$ with respect to $d$ is

$$\Delta X = \Delta d \frac{0.12134}{d}.$$ \hfill (10)

Equation (10) is depicted graphically in Fig. 1.

To illustrate the typical reduction in positive sequence line reactance, if $d = 30$ ft, the nominal 0.8391 Ω/mi will decrease to 0.7784 Ω/mi at 15 ft spacing. Since $X^+$ is roughly inversely proportional to active power flow in the line under representative conditions, for every 1% decrease in spacing there would be a 0.1446% increase in line active power flow. For example, 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 to 536.15 MW. Using Table III the increase in power capacity from a certain decrease in phase spacing can be calculated. If
restrictions on phase spacing were relaxed the line power capacity could be increased.

Then (12) becomes

\[ X^+ = S + \frac{(1 - \Delta)M_1}{2} - \frac{\sqrt{BM_1^2 + (1 - \Delta)^2M_1^2}}{2} \]  

(17)

Expanding the square root terms in a Taylor series around \( \Delta = 0 \),

\[ \sqrt{1 - \frac{2\Delta}{9}} = 1 - \frac{\Delta}{9} \]  

(19)

In (19), the high order terms in the Taylor series are assumed to be small and the series is truncated. Then,

\[ X^+ = S + \frac{M_1}{2} - \frac{\Delta M_1}{2} - \frac{2M_1}{3} (1 - \frac{\Delta}{9}) \]  

(20)

\[ X^+ = S - \frac{4}{3} M_1 + \frac{1}{3} M_2 \]  

(21)

The negative sequence simplification under the same assumptions follows from the same logic with the result as,

\[ X^- = S + \frac{4}{3} M_1 + \frac{2}{3} M_2. \]  

(22)

VI. APPROXIMATION TO THE POSITIVE AND NEGATIVE SEQUENCE LINE REACTANCES

The positive, negative, and zero sequence reactances of a transmission line can be expressed in terms of the mutual and self reactances of the three phase conductors. For example, consider the case of equal self reactances in the phases denoted as \( S \); and mutual reactances \( M_i \) between phases A and B and also B-C; and \( M_j \) between phases A and C,

\[ X_{3p} = \begin{bmatrix} S & M_1 & M_2 \\ M_1 & S & M_3 \\ M_2 & M_3 & S \end{bmatrix}. \]  

(11)

The positive, negative, and zero sequence reactances can be found from \( X_{3p} \) by computing the eigenvalues,

\[ X^+ = S + \frac{M_2}{2} - \frac{\sqrt{BM_1^2 + M_2^2}}{2} \]  

(12)

\[ X^- = S + \frac{M_2}{2} + \frac{\sqrt{BM_1^2 + M_2^2}}{2} \]  

(13)

\[ X^0 = S - M_2. \]  

(14)

These expressions can be simplified for the special case that \( M_j \) and \( M_3 \) are nearly equal. To illustrate the simplification, let

\[ \frac{M_2}{M_3} = 1 - \Delta, \]  

(15)

where \( \Delta \) is a very small (i.e., \( M_j \) and \( M_3 \) are nearly equal and \( \Delta \approx 0 \)). Therefore,

\[ M_2 = (1 - \Delta)M_1. \]  

(16)

Then (12) becomes

\[ X^+ = S + \frac{(1 - \Delta)M_1}{2} - \frac{\sqrt{BM_1^2 + (1 - \Delta)^2M_1^2}}{2} \]  

(17)

\[ X^+ = S + \frac{M_1}{2} - \frac{\Delta M_1}{2} - \frac{3M_1}{2} \sqrt{1 - \frac{2\Delta}{9}}. \]  

(18)

Fig. 1 The decrease in positive sequence line reactance illustrating reduced \( X^+ \) with decreasing phase separation

<table>
<thead>
<tr>
<th>Original phase spacing</th>
<th>Change in phase spacing</th>
<th>Change in ( X^+ )</th>
<th>Change in line power capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>35 ft</td>
<td>↑</td>
<td>-0.1414%</td>
<td>+0.1414%</td>
</tr>
<tr>
<td>30 ft</td>
<td>↑</td>
<td>-0.1446%</td>
<td>+0.1446%</td>
</tr>
<tr>
<td>25 ft</td>
<td>↑</td>
<td>-0.1485%</td>
<td>+0.1485%</td>
</tr>
<tr>
<td>20 ft</td>
<td>↑</td>
<td>-0.1536%</td>
<td>+0.1536%</td>
</tr>
<tr>
<td>15 ft</td>
<td>↓</td>
<td>-0.1607%</td>
<td>+0.1607%</td>
</tr>
<tr>
<td>10 ft</td>
<td>↓</td>
<td>-0.1719%</td>
<td>+0.1719%</td>
</tr>
</tbody>
</table>

Table III Change in power capacity vs. change in phase spacing for different phase spacing

Several companies have used HTLS conductors, reconductoring old circuits in need of higher power capacity. Alternatives for raising the line capacity include:

A. Add an additional conductor to the tower
B. Add a second circuit on a separate tower
C. Reconductor to a higher ampacity conductor
D. Reconductor the old circuit to HTLS.

These options are compared in Table V. 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, the Southern Company reconducted a 16 mile line to HTLS. Construction took ten weeks [17]. In that case, the cost of the HTLS conductor was assessed as tolerable considering labor costs, outage time (and costs), tower costs, and ROW costs.
VIII. ILLUSTRATIVE APPLICATIONS

The software PowerWorld was used to simulate steady state cases with HTLS, compact designs, and a mixture of the two [2]. For example purposes, two separate circuits will be analyzed; one is a short line, Rinaldi – Tarzana; and one is a long line, Bridger – West. In practice, HTLS has been used primarily on short lines for thermal rating upgrade. However, a long line will be 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 re-designed to HTLS with compact phase spacing.

A. Short line in Southern California, North - Tarzana.

The double circuit line between buses Rinaldi and Tarzana is approximately 9.7 miles long, 230 kV, and often heavily loaded. The line is located in Los Angeles, CA. 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 (summer 2009 peak). In Tables VI – VIII 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 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. Reconducted to HTLS

Once the three lines are reconductored, the violations disappear 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 reconductored 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.

Table IV 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>&lt; 65</td>
<td>65 &lt; l &lt; 128</td>
<td>128 &lt; l</td>
</tr>
<tr>
<td>345</td>
<td>1 &lt; 97</td>
<td>97 &lt; l &lt; 195</td>
<td>195 &lt; l</td>
</tr>
<tr>
<td>500</td>
<td>1 &lt; 140</td>
<td>140 &lt; l &lt; 280</td>
<td>280 &lt; l</td>
</tr>
</tbody>
</table>

*Under the assumed conditions of thermal and security limits stated in the text.

Table V 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</td>
</tr>
<tr>
<td>B</td>
<td>May retain original circuit in service during construction</td>
<td>High cost, longer construction time, wide right of way</td>
</tr>
<tr>
<td>C</td>
<td>Could be a minimum cost solution</td>
<td>Potential problem in supporting a larger conductor</td>
</tr>
<tr>
<td>D</td>
<td>Allows use of same towers</td>
<td>High cost for HTLS conductor</td>
</tr>
</tbody>
</table>

Table VI Base case thermal ratings and voltage rating, North – Tarzana

<table>
<thead>
<tr>
<th>No outage</th>
<th>N-1</th>
<th>N-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarzana voltage (pu)</td>
<td>1.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Circuit voltage magnitude closest to voltage violation (pu)</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>Tarzana line MVA</td>
<td>62.4%</td>
<td>92.0%</td>
</tr>
<tr>
<td>Start of line MVA</td>
<td>62.2%</td>
<td>92.4%</td>
</tr>
<tr>
<td>Maximum load at Tarzana (MW)</td>
<td>1221</td>
<td>416*</td>
</tr>
<tr>
<td>Bus voltage phase angle difference</td>
<td>1.1°</td>
<td>1.6°</td>
</tr>
</tbody>
</table>

693 MW can be accommodated but under N-1, a bus tie at Rinaldi overloads. The 416 MW cited results in no overloads.

Table VII HTLS case thermal ratings and voltage rating North – Tarzana

<table>
<thead>
<tr>
<th>No outage</th>
<th>N-1</th>
<th>N-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarzana voltage (pu)</td>
<td>1.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Circuit voltage magnitude closest to a voltage violation (pu)</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>Tarzana line MVA</td>
<td>31.1%</td>
<td>46.0%</td>
</tr>
<tr>
<td>Start of line MVA</td>
<td>31.2%</td>
<td>46.2%</td>
</tr>
<tr>
<td>Maximum load at Tarzana (MW)</td>
<td>1603</td>
<td>1583</td>
</tr>
<tr>
<td>Bus voltage phase angle difference</td>
<td>1.1°</td>
<td>1.6°</td>
</tr>
</tbody>
</table>

Table VIII HTLS compact designs case thermal ratings and voltage rating North – Tarzana

<table>
<thead>
<tr>
<th>No outage</th>
<th>N-1</th>
<th>N-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarzana bus voltage (pu)</td>
<td>1.01</td>
<td>1.00</td>
</tr>
<tr>
<td>Circuit voltage magnitude closest to a voltage violation (pu)</td>
<td>1.01</td>
<td>1.01</td>
</tr>
<tr>
<td>Tarzana line MVA</td>
<td>41.9%</td>
<td>62.3%</td>
</tr>
<tr>
<td>Start of line MVA</td>
<td>42.0%</td>
<td>62.6%</td>
</tr>
<tr>
<td>Maximum load at Tarzana (MW)</td>
<td>1604</td>
<td>1461</td>
</tr>
<tr>
<td>Bus voltage phase angle difference</td>
<td>1.0°</td>
<td>1.3°</td>
</tr>
</tbody>
</table>

The results of reconductoring these lines are shown in Tables VI - VIII. Reconductoring these three lines would increase the power consumption capacity of Tarzana by 380% in the N-1 case for no violations. 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 the advantages would be smaller towers and less use of ROW.

B. Long line in Wyoming and Idaho, Bridger - West

From the WECC critical path report [18] 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. 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. This circuit path is identified in [18] as a criti-
cal 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 a line outage.

The three lines in the cited path are approximately 190 miles long, are assumed to be heavily loaded, and have caused problematic operating conditions in the past [19]. For example purposes, the HTLS conductor will result in twice the ampacity of the conventional conductor presently in place.

The values in Tables IX - XI illustrate the results of reconductoring and utilization of phase compact design. Note the following:

1. Base case (present construction)

During the base summer 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. Reconducted to HTLS

Again consider the same Bridger – Populus circuits. If the lines were reconducted using HTLS conductors, reconductoring would double the thermal ratings. HTLS design reduces the thermal loading to reasonable 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.

3. HTLS and compact spacing

Consider the case where the three lines are reconducted 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 IX. Base case thermal ratings and voltage rating, Bridger – West Path

<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 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 X. HTLS case thermal ratings and voltage rating, Bridger – West Path

<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 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>

The results of reconductoring these lines are shown in Tables IX-XI. 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.

IX. 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 VIII for the Rinaldi - Tarzana 230 kV line is a case of a short line. As shown in Fig. 2, short lines are generally thermally limited. To illustrate the dynamic consequences of reconductoring, consider only the Bridger West critical path discussed in Section VIII(B). The Bridger West critical path is illustrated in Fig. 3. Note the series compensated segment of the Bridger –Three Mile Knoll line.

![Fig. 3 Pictorial of the Bridger – West critical path in Idaho and Wyoming](image)

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 Fig. 3. In Case 3, it is assumed that the use of HTLS allows the compaction of the phase spacing so that the original right of way 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 TSAT analysis packages, commercially available software tools in common use in the electric power industry today. The case study results are shown in Table XII.

Note that in the results shown in Table XII 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 XII. Because the RASs are not implemented in the 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 [20]. Note that the two double line outage contingencies are nearly identical because the circuit reactances outaged are very similar. Inspection of Table XII shows that both double line contingencies are much better damping of critical modes is enhanced and the addition of a new 345 kV circuit can be accomplished without widening the existing right of way.

Table XII Results of dynamic studies for three cases of double line outage contingencies (Bridger West critical path)

<table>
<thead>
<tr>
<th>Case**</th>
<th>Case 1: present construction</th>
<th>Case 2: HTLS reconductoring plus compaction of phase spacing by 25%*</th>
<th>Case 3: HTLS + compact phase spacing to 50% plus new circuit addition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limitation</td>
<td>Transient voltage dips and voltage magnitude stability</td>
<td>Transient voltage dips and voltage magnitude stability</td>
<td>Transient voltage dips and voltage magnitude stability</td>
</tr>
<tr>
<td>TSAT solution characteristics</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>
</tbody>
</table>

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

X. CONCLUSIONS

Transmission expansion is mainly motivated by load growth (often in localized regions) and by the integration of solar and wind generation resources (often long distance circuits). The short lines proposed in transmission expansion are often thermally limited, while long lines are often security limited. HTLS conductors seem especially suited for applications in which thermal limitations occur; and compaction of overhead spacing of phases seems particularly suited for improving security limits and allowing additional circuits to be placed on existing right of way. HTLS designs have the potential of allowing compaction of phase spacing below commonly accepted levels due to the lower sag in HTLS designs.

Several examples are shown in this paper: a short 230 kV circuit in the Los Angeles area illustrates the benefits of HTLS from the point of view of improvement of ampacity, while a long line application in Wyoming and Idaho illustrates the value of phase compaction with HTLS.

XI. ACKNOWLEDGEMENTS

This work was funded in part by the United States Department of Energy under an agreement with the Power Systems Engineering Center (PSerc). PSerc is an Industry University Cooperative Research Center, funded by the National Science Foundation under awards EEC-0001880 and EEC-0968993. The authors thank Dr. Jaime Quintero for running the TSAT studies reflected in Table XIII.

XII. REFERENCES


XIII. BIOGRAPHIES

Brian Joseph Pierre (StM '09) is from Laramie, WY. Mr. Pierre holds the BSEE from Boise State University, Boise, ID (2011). He is presently a doctoral student at Arizona State University, Tempe, AZ.

Gerald Thomas Heydt (StM '62, M '64, SM '80, F '91) is from Las Vegas, NV. He holds the Ph.D. in Electrical Engineering from Purdue University. He is a Regents’ Professor at Arizona State University.