Transmission Design 201
MIPSYCON Tutorial – 2017

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Stanley Consultants INC.
Objectives

- Walk through the associated design considerations associated with transmission line design


- Additional design considerations
Transmission Design 201 – Key Topics

- Route Selection Concepts
- Material Testing Concepts
- Electrical Studies
Route Selection

- **Purpose:** develop and define a viable route centerline for design and construction of transmission facility

- **Viable means an acceptable route that can be permitting and constructed**
Siting Definitions

- **Study Area**: geographical area small enough to encompass feasible alternatives, but large enough to include adequate number of corridors.

- **Macro-Corridor**: broad linear area of land within which alternative corridors can be located.
Micro-Corridor: linear areas within macro-corridor suitable of locating transmission line when natural environment, built environment, and engineering requirements are considered
Siting Definitions

- **Route**: contiguous constructable right-of-way within alternative micro-corridor

- **Siting**: process of determining location for proposed action
Corridor & Route Selection

- Environmental
- Land Use Limitations
- Land Owners
- Availability of Property
- Public Opinion/Opposition
Macro-Corridor Study

- Initiated following determination of project need and feasibility
- Ends with identification of one or more macro-corridors
Macro-Corridor Study

- Completion of macro-corridor study signals beginning of scoping and permitting processes

- Interdisciplinary study involving engineering, environmental, land acquisition, permitting, etc.
Corridor Selections
Land Use Determinations

- **Exclusion:** areas that cannot be crossed by linear projects unless specific written authorization made from approving official

- **Avoidance:** areas that should be avoided or not crossed by linear projects
Route Determination

- Line Draw
- Weighted Methodology
- GIS Tier Methodology
Weighted Value Method

- **Land segments are assigned weighted value for each segment based on land usage**
  - 1-3 high suitability
  - 4-6 moderate suitability
  - 7-9 low suitability

- **Route alternative determined by contiguous paths of lowest value**
# Weighted Land Use Chart

<table>
<thead>
<tr>
<th>Land Cover Classification</th>
<th>Source</th>
<th>X-Country</th>
<th>Roads</th>
<th>T/Ls</th>
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<tbody>
<tr>
<td>Open Water</td>
<td>LANDSAT</td>
<td>7</td>
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<tr>
<td>Secondary Roads</td>
<td>LANDSAT</td>
<td>5</td>
<td>1</td>
<td>5</td>
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<tr>
<td>Other Utility Corridors</td>
<td>LANDSAT</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Urban</td>
<td>LANDSAT</td>
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<tr>
<td>Open Land</td>
<td>LANDSAT</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Surface Mining/ Rock Outcrop</td>
<td>LANDSAT</td>
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<td>9</td>
<td>9</td>
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<tr>
<td>Forest</td>
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<td>2</td>
<td>2</td>
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<td>Agriculture</td>
<td>LANDSAT</td>
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<td>2</td>
<td>2</td>
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<tr>
<td>Wetland</td>
<td>LANDSAT</td>
<td>9</td>
<td>9</td>
<td>9</td>
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<tr>
<td>Transmission Corridors</td>
<td>ITS*</td>
<td>5</td>
<td>5</td>
<td>1</td>
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<tr>
<td>Primary Roads</td>
<td>GDT**</td>
<td>5</td>
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<td>5</td>
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<td>Interstate</td>
<td>GDT</td>
<td>9</td>
<td>9</td>
<td>9</td>
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<tr>
<td>Slopes &gt; 30 degrees</td>
<td>USGS</td>
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<td>9</td>
<td>9</td>
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<td>Avoidance Features</td>
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<td></td>
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<tr>
<td>Airports</td>
<td>GDT</td>
<td></td>
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<td>Military Facilities</td>
<td>GDT</td>
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<td>NRHP Listed Historic Structures</td>
<td>NPS</td>
<td></td>
<td></td>
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<tr>
<td>NRHP Listed Historic Districts</td>
<td>NPS</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Weighted Land Summation
Weighted Land Summation

Start Point A

4  5  7  6  3
14 20 10  1  2
  8  4 20  6  9
  6  8  1 12 10
  3  7  8  2  4

End
GIS Tier Method

- Land segments are categorized by land use classification, built environment, natural environment, and engineering considerations into layers.

- Each data layer is assigned a weighted value based on relative importance to linear project specifications.
Data Layers

Avoidance Areas - Data Layers
- Buildings + Buffer
- Special Places
- Sensitive Areas
- Physical Barriers

Can’t go there...

Engineering Requirements Perspective - Data Layers
- Linear Infrastructure (48%)
- Slope (16%)
- Intensive Ag (43%)

Group Perspective Layers
- Group Avoided Areas
- Avoid if possible...

Natural Environment Perspective - Data Layers
- Floodplain (8%)
- Streams/Wetlands (21%)
- Public Lands (15%)
- Land Cover (21%)
- Wildlife Habitat (36%)

Built Environment Perspective - Data Layers
- Proximity Buildings (12%)
- NRHP Historic (14%)
- Building Density (37%)
- Proposed Development (6%)
- Spannable Water bodies (4%)
- Land Divisions (8%)
- Land Use (15%)

Wt. Average Natural

Wt. Average Built

Wt. Average Criteria

Phase 2: Alternative Corridors
- Avoidance Areas
- Siting Criteria:
  - Engineering
  - Natural
  - Built
- Overall Preference Surface

Figure 2-19
Phase 2: Alternative Corridor GIS Data Layers Least Cost Path Algorithm
Once weighted, data layers are combined to form group perspective (alternative routes)

Each group is then graded based on combined weighting
## Data Layers Weighting

### Evaluating Alternative Routes

<table>
<thead>
<tr>
<th>Feature</th>
<th>Route A</th>
<th>Route B</th>
<th>Route C</th>
<th>Route D</th>
<th>Route E</th>
<th>Route F</th>
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<td>0.09</td>
<td>0.05</td>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
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<td>0.05</td>
<td>0.00</td>
<td>1.00</td>
<td>1.00</td>
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<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
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<td>0.00</td>
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<tr>
<td>Weighted</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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</tbody>
</table>

**FOR TOP 3-5 ROUTES (INTERNAL)**

<table>
<thead>
<tr>
<th>Sample Weights</th>
<th>Route A</th>
<th>Route B</th>
<th>Route C</th>
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<tbody>
<tr>
<td>Visual Issues</td>
<td>5%</td>
<td>1%</td>
<td>1%</td>
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<tr>
<td>Weighted</td>
<td>0.05</td>
<td>0.25</td>
<td>0.05</td>
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<tr>
<td>Community Concerns</td>
<td>25%</td>
<td>1%</td>
<td>1%</td>
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<tr>
<td>Weighted</td>
<td>0.25</td>
<td>1.25</td>
<td>0.75</td>
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<tr>
<td>Schedule Delay Risk</td>
<td>30%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>Weighted</td>
<td>0.50</td>
<td>1.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Special Permit Issues</td>
<td>30%</td>
<td>4%</td>
<td>1%</td>
</tr>
<tr>
<td>Weighted</td>
<td>1.20</td>
<td>1.50</td>
<td>1.00</td>
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<tr>
<td>Weighted Construction/Maintenance Accessibility</td>
<td>10%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Weighted</td>
<td>0.50</td>
<td>0.10</td>
<td>0.20</td>
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</table>

**Total**

<table>
<thead>
<tr>
<th>Route A</th>
<th>Route B</th>
<th>Route C</th>
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</thead>
<tbody>
<tr>
<td>2.6</td>
<td>4.6</td>
<td>1.6</td>
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</tbody>
</table>

### Expert Judgment

- Visual Concerns (5%)
- Community Concerns (25%)
- Schedule Delay Risk (30%)
- Special Permit Issues (30%)
- Construction/Maintenance Accessibility (10%)
Route Selection

- Multiple alternative routes identified for each macro-corridor
- Alternative routes are further evaluated for same considerations used for weighting → at more detailed level
- Selected route is contiguous path with lowest scoring and most feasible construction
Corridor Selections
Route Selections
Route Selections
Material Testing
Purpose of Material Testing

- Verification that proposed materials will perform adequately and meet design specifications
- Implied warrantee for design function of assembly
Definitions

- **Hardware**: any single piece or item of material used in support of transmission facility functions and purpose.

- **Assembly**: grouping of multiple items of hardware to form a functional arrangement with designed purpose.
Types of Testing

- Mechanical Strength
- Electrical
- Fit & Function
Mechanical Strength

- Functional mechanical strength is load at which any part of hardware will not perform its design function...

- ...or that causes sufficient deformation or destruction of any part that will prevent its proper operational function
Mechanical Strength

- **Ultimate Break Strength**
  - Maximum stress can be withstood before mechanical failure occurs (breaks)

- **Ultimate Yield Strength**
  - Maximum stress can be withstood before plastic deformation occurs

- **Ultimate Mechanical Strength**
  - Maximum stress can be withstood before deformation occurs preventing ability to perform designed function
**Mechanical Strength**

- **Ultimate mechanical strength** is the load at which failure of a part occurs.

- Most materials are classified based on their **ultimate mechanical strength rating** (lbs).
Manufacture Testing

- Mechanical strength testing & ratings determined by manufacturer through use of independent certified testing

- Testing results should be less than 5 years old to ensure inclusion of any manufacturing process, materials, or design modifications
Assembly Testing

- Construct assembly of designed materials and load to ultimate breaking strength
  - Identifies weak link
  - Predictor of where failures should occur
  - Allows adjustment for design of least impacting weak link

- Assembly does not have to be full assembly → but should include all hardware (i.e. 2-3 insulator bells vs 23)
Electrical Testing

- Purpose is to ensure that the design assembly will perform adequately during electrical conditions

- Main types:
  - Flashover
  - Withstand
  - Corona/Radio-Induced Voltage (RIV)
Flashover

- Application of voltage quickly to 75%, then increase such that flashover conditions reached in 5-30 seconds

- Flashover value is arithmetical mean of not less than 5 individual flashovers taken consecutively

- Types: dry & wet (under water spray)
Withstand

- Application of voltage quickly to 75%, then increased to 100% in 5-30 seconds
- Voltage at 100% held at least 1 minute
- Types: dry (1 min), wet (10 secs), dew (20 secs under 100% humidity), Impulse (no flashover)
Corona/RIV

- Corona: ionization of air caused by intense electric field
- RIV: high frequency voltage generated by source of ionization current at terminals of power circuits
- Produces audible noise and causes tracking, pitting, cracking, and damage to hardware & assemblies
Corona Damage
Corona Damage
Corona/RIV Testing

- Application of voltage well above corona point (up to 1.9 times rated voltage) → then lowered until corona disappears as inspected with ultraviolet cameras or visually in darkened room

  - High levels of corona indicate inadequate design & material selection
  - Long term high corona decreases life expectancy of hardware & assemblies
Corona Discharge
Fit & Function Testing

- Construction and assembly of design hardware into proper configuration or assembly

- Assembly is then maneuvered into expected conditions and alignments

- Assembly is verified for freedom of movement, proper fit of hardware, assembly dimensions, & constructability
Electrical Studies
Purpose

Electrical studies provides verification of transmission facility operating conditions and coordination of design elements.

Groups: Interactive & Design
Interactive Studies

- Interconnection
  - Feasibility
  - System Impact
  - Interconnection Facilities

- Transient Response (TRV)

- Transient Overvoltage (TOV)
Interconnection

- Determine the impact of connecting additional facilities to existing operating systems

- 3 analytical steps:
  - Feasibility
  - System Impact
  - Interconnection Facilities
Feasibility

- Practicality and cost of incorporating requested interconnection facility into existing operating system
- Limited to load flow and fault analysis
- Provides preliminary estimates for type, scope, cost, construction lead time of facilities required to interconnect
System Impact

- Relationship between new facility, other planned new facilities (queue), and existing system

- Model based analysis of operating system
  - Manufacturer models and operating system parameters identified and agreed upon as basis for study
System Impact

- Comprehensive regional analysis of impact of adding facility on operating conditions and deliverability to load

- Identifies constraints, required attachment facilities, local and/or network upgrades, detailed estimates with cost responsibility
Interconnection Facilities

- Identifies the engineering design work necessary to begin construction
- Good faith estimate as to cost for required upgrades or alterations (from System Impact Study)
- Detailed design and construction schedules
- Result is defined 1-line with annotated changes & interconnection agreement
1-Line Example
MISO Interconnection

For study start dates, milestone deadlines, and deposit deadlines, refer to the [Generator Interconnection Study Calendar](#).

```
IC: 1. Sumit IR
    2. Provide M1
    3. D1 and D2

MISO:
1. Verify Application
2. Assign Project Number
3. Establish Initial Queue Date

MISO: FeS/M2 Entry Milestone Calculated

IC: Enter DPP?
   Yes
   IC: 1. Provide M2
       2. D3 Deposit
       3. Establish DPP Queue Date

IC: SPA Study?
   Yes
   SPA Study Required
   6 Months**
   MISO:
   IC: SPA Study?
   Yes
   > 18 Months
   Withdraw
   No
   Park

At any time the customer may enter the DPP

Notes:
IC = Interconnection Customer
TO = Transmission Owner
IR = Interconnection Request
M1, M2 = Milestone Requirements
D1, D2, D3 = Deposit Requirements
FeS = Feasibility Study
DPP = Definitive Planning Phase
SPA = System Planning and Analysis
GIA = Generator Interconnection Agreement
SIS = System Impact Study
NU = Network Upgrade
IF = Interconnection Facilities
FS = Facilities Study
** = Estimated
= Optional
```
Impact on Design

- Capacity based → configuration, conductor, structures
- Operating condition based → configuration, insulation coordination
- Facility based → interconnection facilities & upgrades
Transient Response Voltage

- Voltage potential across terminals of circuit breaker/terminus following interruption of fault current
- Reactions to fault interruptions
Models based which expand out multiple levels & incorporates ‘case based’ scenarios (interconnection)

Model based from facility/component ratings & operating conditions

Multiple fault types/levels
  > LG, LLL, LLG, N-0, N+1, etc.

Models resultant voltage from fault to trips (typically 3 cycles)
## TRV Results

### Table 1: TRV Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Kpp at T100</th>
<th>U1 (kV)</th>
<th>T1 (us)</th>
<th>Uc (kV)</th>
<th>T2 (us)</th>
<th>T3 (us)</th>
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<tbody>
<tr>
<td>T100</td>
<td>1.3</td>
<td>288</td>
<td>144</td>
<td>538</td>
<td>576</td>
<td></td>
</tr>
<tr>
<td>T60</td>
<td>1.3</td>
<td>288</td>
<td>96</td>
<td>576</td>
<td>288</td>
<td></td>
</tr>
<tr>
<td>T30</td>
<td>1.3</td>
<td></td>
<td></td>
<td>592</td>
<td></td>
<td>118</td>
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<td>1.5</td>
<td>333</td>
<td>166</td>
<td>621</td>
<td>664</td>
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<td>T60</td>
<td>1.5</td>
<td>333</td>
<td>111</td>
<td>665</td>
<td>333</td>
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<tr>
<td>T30</td>
<td>1.5</td>
<td></td>
<td></td>
<td>701</td>
<td></td>
<td>140</td>
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<tr>
<td>Short Line</td>
<td>1.3</td>
<td>222</td>
<td>111</td>
<td>414</td>
<td>444</td>
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### Table 7: Results

<table>
<thead>
<tr>
<th>Case #</th>
<th>Breaker</th>
<th>Fault Location</th>
<th>Fault Type</th>
<th>Contingency</th>
<th>Observed Fault Current (pu on 60 A base)</th>
<th>Criteria Used</th>
<th>Criteria Passed</th>
<th>Criteria Failed</th>
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<tbody>
<tr>
<td>1</td>
<td>Centre</td>
<td>Terminal</td>
<td>SLG</td>
<td>N-0</td>
<td>0.256326208</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Centre</td>
<td>Terminal</td>
<td>SLG</td>
<td>1 Line out</td>
<td>0.235201393</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Centre</td>
<td>Terminal</td>
<td>SLG</td>
<td>2 Lines out</td>
<td>0.179958676</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
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<tr>
<td>4</td>
<td>Centre</td>
<td>Terminal</td>
<td>SLG</td>
<td>1 transformer out</td>
<td>0.220705704</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
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<tr>
<td>5</td>
<td>Centre</td>
<td>Terminal</td>
<td>LLLG</td>
<td>N-0</td>
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<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
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<td>6</td>
<td>Centre</td>
<td>Terminal</td>
<td>LLLG</td>
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<td>Terminal</td>
<td>LLLG</td>
<td>2 Lines out</td>
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<td>Pass T60</td>
<td>Fail T100</td>
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<td>8</td>
<td>Centre</td>
<td>Terminal</td>
<td>LLLG</td>
<td>1 transformer out</td>
<td>0.214164966</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
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<tr>
<td>9</td>
<td>Centre</td>
<td>Terminal</td>
<td>LLL</td>
<td>N-0</td>
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<td>T100/T60/T30(Kpp = 1.5)</td>
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<td></td>
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<tr>
<td>10</td>
<td>Centre</td>
<td>Terminal</td>
<td>LLL</td>
<td>1 Line out</td>
<td>0.245277665</td>
<td>T100/T60/T30(Kpp = 1.5)</td>
<td>Pass All</td>
<td></td>
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<tr>
<td>11</td>
<td>Centre</td>
<td>Terminal</td>
<td>LLL</td>
<td>2 Lines out</td>
<td>0.181549666</td>
<td>T100/T60/T30(Kpp = 1.5)</td>
<td>Pass T60</td>
<td>Fail T100</td>
</tr>
<tr>
<td>12</td>
<td>Centre</td>
<td>Terminal</td>
<td>LLL</td>
<td>1 transformer out</td>
<td>0.214164966</td>
<td>T100/T60/T30(Kpp = 1.5)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Centre</td>
<td>1 Km Down Line</td>
<td>SLG</td>
<td>N-0</td>
<td>0.24660349</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
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<tr>
<td>14</td>
<td>Centre</td>
<td>1 Km Down Line</td>
<td>SLG</td>
<td>1 Line out</td>
<td>0.22945615</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
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<tr>
<td>15</td>
<td>Centre</td>
<td>1 Km Down Line</td>
<td>SLG</td>
<td>2 Lines out</td>
<td>0.17545087</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Centre</td>
<td>1 Km Down Line</td>
<td>SLG</td>
<td>1 transformer out</td>
<td>0.198166675</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Centre</td>
<td>20% Down Line</td>
<td>SLG</td>
<td>N-0</td>
<td>0.07601397</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
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<tr>
<td>18</td>
<td>Centre</td>
<td>20% Down Line</td>
<td>SLG</td>
<td>1 Line out</td>
<td>0.074953319</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Centre</td>
<td>20% Down Line</td>
<td>SLG</td>
<td>2 Lines out</td>
<td>0.067167086</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Centre</td>
<td>20% Down Line</td>
<td>SLG</td>
<td>1 transformer out</td>
<td>0.070445513</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Prairie</td>
<td>Terminal</td>
<td>SLG</td>
<td>N-0</td>
<td>0.087327687</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Prairie</td>
<td>Terminal</td>
<td>SLG</td>
<td>1 transformer out</td>
<td>0.065644814</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Prairie</td>
<td>Terminal</td>
<td>LLLG</td>
<td>N-0</td>
<td>0.080521785</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Prairie</td>
<td>Terminal</td>
<td>LLLG</td>
<td>1 transformer out</td>
<td>0.067793863</td>
<td>T100/T60/T30(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Prairie</td>
<td>Terminal</td>
<td>LLL</td>
<td>N-0</td>
<td>0.080521785</td>
<td>T100/T60/T30(Kpp = 1.5)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Prairie</td>
<td>Terminal</td>
<td>LLL</td>
<td>1 transformer out</td>
<td>0.067705474</td>
<td>T100/T60/T30(Kpp = 1.5)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Prairie</td>
<td>1 Km Down Line</td>
<td>SLG</td>
<td>N-0</td>
<td>0.086443084</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Prairie</td>
<td>1 Km Down Line</td>
<td>SLG</td>
<td>1 transformer out</td>
<td>0.066205096</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Prairie</td>
<td>20% Down Line</td>
<td>SLG</td>
<td>N-0</td>
<td>0.046315494</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Prairie</td>
<td>20% Down Line</td>
<td>SLG</td>
<td>1 transformer out</td>
<td>0.039509591</td>
<td>Short Line/T100(Kpp = 1.3)</td>
<td>Pass All</td>
<td></td>
</tr>
</tbody>
</table>
Impacts to Design

- Results within criteria → no further action
  - Validation

- Results exceed criteria → additional review & design
  - Circuit breaker design (live tank, dead tank)
  - Configuration changes
  - Insulation coordination
Transient Overvoltage

- Voltage present across line and terminal arrestors during switching surges/operational transients

- Factors in impedance, capacitance, and line & system characteristics
Methods

- Models based which expand out multiple levels & incorporates ‘case based’ scenarios (interconnection)
- Model based from facility/component ratings & operating conditions
- Multiple fault types/levels
  - LG, N-1, N-2, N-0, N+1, etc.
Methods

- Facility type (generator type, configuration) has larger impact than with TRV
- Assumptions include re-closing scenarios
# TOV Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Centre Transformer Arrester Voltage (L-G pu)</th>
<th>Centre Line Arrester Voltage (L-G pu)</th>
<th>Prairie Line Arrester Voltage (L-G pu)</th>
<th>Prairie Transformer Arrester Voltage (L-L pu)</th>
<th>Centre Transformer Arrester Voltage (L-L pu)</th>
<th>Centre Line Arrester Voltage (L-L pu)</th>
<th>Prairie Line Arrester Voltage (L-L pu)</th>
<th>Prairie Transformer Arrester Voltage (L-L pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer Off-Peak</td>
<td>1.813</td>
<td>1.813</td>
<td>1.824</td>
<td>1.824</td>
<td>2.012</td>
<td>2.012</td>
<td>2.020</td>
<td>2.020</td>
</tr>
<tr>
<td>Winter Peak</td>
<td>1.685</td>
<td>1.685</td>
<td>1.817</td>
<td>1.772</td>
<td>1.664</td>
<td>1.664</td>
<td>2.021</td>
<td>2.021</td>
</tr>
</tbody>
</table>
# TOV Results

<table>
<thead>
<tr>
<th>Case</th>
<th>Centre Line Arrester Energy (pu)</th>
<th>Prairie Line Arrester Energy (pu)</th>
<th>Centre Transformer Arrester Energy (pu)</th>
<th>Prairie Transformer Arrester Energy (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer Off-Peak</td>
<td>0.047</td>
<td>0.077</td>
<td>0.120</td>
<td>0.178</td>
</tr>
<tr>
<td>Winter Peak</td>
<td>0.009</td>
<td>0.074</td>
<td>0.014</td>
<td>0.061</td>
</tr>
</tbody>
</table>
Arrestor Condition

Graphs:
- PrairieVRM1pu
- PrairieV12pu
- PrairieV11pu
- PrairieE2pu
- PrairieET2pu

Y (pu) vs Time (pu)
Impacts to Design

- Results within criteria → no further action
  - Validation

- Results exceed criteria → additional review & design
  - Arrestor or insulator design
  - Configuration or facility changes
  - Insulation coordination
Design Studies

- Design studies are studies which will impact physical design of transmission facility to meet design parameters.

- Can be used to aid in design determination or verification of designs.
Electrical Studies

- Economic Conductor
- Insulation Coordination
- Electric & Magnetic Field Interaction
- Induction
- Parallel Circuit
- Grounding
- Transposition
- Shield Wire
Economic Conductor
Purpose & Function

- Comparison of conductor alternatives to design most cost-effective conductor size given the life cycle of line

- Mean of analysis to aid in conductor selection
Factors Impacting Selection

- **Cost**
  - Conductor, design & construction, losses, maintenance

- **Ampacity**
  - Current carrying capacity (power)

- **Line Losses**
  - Cost, impact to operations, thermal

- **Life Cycle**
  - Assumed life of facility, O&M considerations
Methods

- Calculation based approach based on given data from design criteria

- \[ I_L = \frac{P_{cf}}{\sqrt{3} V_L B} \] = amps/ conductor

- \[ P_{loss} = \frac{I_L^2 R N B}{1000} \] = kw/mile

- Numerical comparison
## Economic Conductor Results

<table>
<thead>
<tr>
<th>Size &amp; Type of Conductor</th>
<th>Losses (kwh/year) (1)(2)</th>
<th>Cost of Losses ($/2yrs)(3)</th>
<th>Incremental Cost ($/2yrs)(5)</th>
<th>Cost of Construction ($/2yrs)(4)</th>
<th>Incremental Cost ($/2yrs)(5) Total</th>
<th>Incremental Cost ($/2yrs)(5) Conductor Only</th>
<th>Cost Benefit Ratio (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>795 Drake ACSR</td>
<td>115,666,856</td>
<td>$9,392,149</td>
<td></td>
<td>$261,045,079</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>954 Rail ACSR</td>
<td>98,604,691</td>
<td>$8,006,701</td>
<td>(1,385,448.00)</td>
<td>$283,063,441</td>
<td>$22,018,362</td>
<td>$732,423</td>
<td>15.9</td>
</tr>
<tr>
<td>1272 Bittern ACSR</td>
<td>75,203,798</td>
<td>$6,106,548</td>
<td>(3,285,601.00)</td>
<td>$304,294,469</td>
<td>$43,249,390</td>
<td>$4,860,486</td>
<td>13.2</td>
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<tr>
<td>795 Drake ACSS</td>
<td>112,682,041</td>
<td>$9,149,782</td>
<td>(242,367.00)</td>
<td>$268,132,423</td>
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</tr>
<tr>
<td>954 Rail ACSS</td>
<td>96,071,092</td>
<td>$7,800,973</td>
<td>(1,591,176.00)</td>
<td>$290,768,573</td>
<td>$29,723,494</td>
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<tr>
<td>1272 Bittern ACSS</td>
<td>73,344,190</td>
<td>$5,955,548</td>
<td>(3,436,601.00)</td>
<td>$311,374,806</td>
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<td>$6,961,786</td>
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</tr>
<tr>
<td>900 Ruddy ACSR</td>
<td>104,327,007</td>
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<td>(920,796.00)</td>
<td>$282,459,804</td>
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<tr>
<td>900 Canary ACSR</td>
<td>103,507,654</td>
<td>$8,404,822</td>
<td>(987,327.00)</td>
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<tr>
<td>959.6 Suwannee ACSR/TW</td>
<td>95,773,739</td>
<td>$7,778,828</td>
<td>(1,615,321.00)</td>
<td>$282,545,157</td>
<td>$21,500,078</td>
<td>$4,102,630</td>
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</tr>
<tr>
<td>959.6 Suwannee ACSS/TW</td>
<td>93,207,101</td>
<td>$7,568,417</td>
<td>(1,823,732.00)</td>
<td>$290,234,245</td>
<td>$29,189,166</td>
<td>$5,560,764</td>
<td>16</td>
</tr>
</tbody>
</table>
Impacts to Design

- Conductor selection
- Structure design & configuration from conductor loading
- EHV bundling driven by corona performance vs. ampacity
MN Conservation Improvement Program (CIP)

- **Purpose**: realize annual energy savings based on percentage of utility’s annual retail sales
- Energy savings realized from alternative designs of new transmission projects is option available
- Adds an additional cost comparison for line losses factor
### MN CIP Example

<table>
<thead>
<tr>
<th>Size &amp; Type of Conductor</th>
<th>Losses (kwh/year) (1)(2)</th>
<th>Cost of Losses ($/2yrs)(3)</th>
<th>Incremental Cost ($/2yrs)(5)</th>
<th>Cost of Construction ($/2yrs)(4)</th>
<th>Incremental Cost ($/2yrs)(5)</th>
<th>Cost Benefit Ratio (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>795 Drake ACSR</td>
<td>115,666,856</td>
<td>$9,392,149</td>
<td>--</td>
<td>$245,239,777</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>959.6 Suwannee ACSR/TW</td>
<td>95,773,739</td>
<td>$7,776,828</td>
<td>(1,615,321.00)</td>
<td>$254,420,798</td>
<td>$9,181,021</td>
<td>$4,102,630 5.7</td>
</tr>
</tbody>
</table>
Insulation Coordination
General Review

- Basic goal is to be above stress/strength curve
- Power system is contiguous when connected → each part/facility affects anything else connected to
Electrical Stress vs Strength

Stress Density Distribution

Cumulative Strength Distribution

F(V)

P(V)

CFO

Voltage

Frequency of Occurrence

Insulation Flashover Probability

Statistical Representation of Insulation Stresses and Strengths
Purpose & Function

- Select insulator characteristics that accommodate the expected over voltages within an acceptable risk of failure

- Coordinate physical & electrical requirements with voltage stresses, protective devices, substation equipment
Factors Considered

- Operating Voltage
- Conductors & shield wires
- Contamination
- Insulator selection
- Voltage drop across insulator materials
  - Voltage stresses are non-linear
Flashover Considerations

- **Power Frequency**
  - Considers environmental conditions specific to line (contamination, air density)

- **Lightning Surge**
  - Based on ground fault distribution, assumed risk/acceptable outage rate
  - Based on surge analysis (ground resistance, shield wire capacity)
Flashover Considerations

- **Switching Surge**
  - Statistical analysis of anticipated electrical stresses
  - Determined from transient studies (TRV, TOV)

- Limiting condition will establish electrical stress level to be designed to
CFO Distance

- $D_0 = 39.37 \ (V_{pu \ a})^{1.667} \ b = \text{distance} \ (500 \ k) \ (\text{in inches})$

- $D_{atmos} = 3\% \uparrow \text{for each 100 ft > sea level}$

- $D_F = D_0 + D_{atmos}$

- $CFO = \frac{3400}{1 + 8/D_F} = \text{Volts}$
Electrical Clearance

- Physical clearance distance between energized components & structure (grounded components)
- From highest CFO calculation
  - Reverse with CFO value as V and calculate distance
- Establishes air gap required for use in design (tower window)
Coordination of Results

- Clearance envelope for power frequency
- Clearance envelope for switching surges
- Clearance envelope for lightning
- String length determined by contamination
Electrical & Magnetic Field Interaction

EMF
EMF

- Electric → based on voltage levels
- Magnetic → based on current flow (load)

Concerns
- Induction  (Induction Study)
- Public perception (health, livestock, safety)
Methods

- Model based on system operating characteristics
- Configuration & proximity based
- Guidelines or limits vary based on region (Design Criteria)
- Result: Electric (kV/m), Magnetic (mG), Audible (dBA)
Electric Field Results

Unperturbed Electric Field
Maximum Sag Condition at Midspan
(1m scan height)

Distance From Structure Centerline (ft)
Magnetic Field - Maximum

Magnetic Field
At Maximum Expected Load (404 MVA)
(1m scan height)

Distance From Structure Centerline (ft)

Magnetic Field (mG)

Edge of ROW

Edge of ROW
Magnetic Field - Emergency

Magnetic Field
At Thermal Limit Emergency Rating (1,686 MVA)
(1m scan height)

Distance From Structure Centerline (ft)

Edge of ROW

Edge of ROW
Audible Noise Results

Audible Noise - L50 Rain
Conductor at average height - 60deg Ambient
(2m scan height; 1970ft Elevation)
Impacts to Design

- Results within criteria → no further action
  - Validation

- Results exceed criteria → additional review & design
  - Configuration changes (height, layout, ROW)

- Public/Safety perception → V vs. mA
Induction Study
Potential conductors that exist within electrical fields can have voltage generated in them.

Voltage potentials create touch potentials and current flow.

Concern for safety (touch) & other facility operations.

Common: fence, pipeline, railroad, structures, facilities.
Methods

- Model based on operating characteristics, scenario based, and configuration & proximity
- Case based so magnitude can be reviewed for mitigation methods
- Some safety limits (NESC) as well as facility & regional based guidelines
Pipelines - Normal

Unmitigated Induced Voltage on Pipelines Under Steady-State Normal Load
Figure 8-1
Pipeline - Emergency

Emergency Load Pipelines

Unmitigated Induced Voltage on Pipelines Under Steady-State Emergency Load
Figure 8-3
Railroads - Normal

Normal Load Railroads

Unmitigated Induced Voltage on Railroads Under Steady-State Normal Load

Figure 8-2
Figure 8-4: Unmitigated Induced Voltage on Railroads Under Steady-State Emergency Load
Pipeline – Fault (Touch)
Railroad – Fault (Touch)
Impacts to Design

- Mitigation of impacts from induced voltage (normal & fault/emergency)
- Coordination with other facility designs (pipelines, railroads, power lines)
Mitigation of Induction

- **Voltage Mitigation**
  - Grounding (mats/grids, rods, wire)
  - Configuration & materials

- **Current**
  - Filters, insulators, materials

- Mitigation level varies based on scenario & facility
Parallel Circuit
Subset of Induction Study
Purpose & Function

- Modified induction study between parallel circuits

- Parallel is on same system facility, interconnection or induction if on different systems

- Geometry & configuration based (model or calculation)
Methods

- Model built (CDEGS) based on operating characteristics, scenario based, and configuration & proximity

- Case based so magnitude can be reviewed for mitigation methods
Impacts to Design

- No or tolerable interference → no further action
  - Validation

- Measureable interference
  - Configuration
  - Layout/location
  - Facility changes (mitigation)
Purpose & Function

- Adequacy of grounding methods to carry fault conditions
- Maintain NESC safety criteria during any conditions
Methods

- Comparison of fault current vs. ground current capabilities

Computation based with respect to grounded conditions (soil resistivity, ground wire)
Impacts to Design

- Determines ground configuration
- Determines ground wire size/type
- Verification of selected grounding materials
Transposition
Purpose & Function

- Determine induction based voltage imbalance along line length
- Determination if mitigation required to minimize imbalances
- Eliminates potential relay sensing errors (calculating mho element)
Methods

- Calculation of impedance matrix (self, mutual, sequence)
- Imbalances calculated from sequence imbalances, compared as ratio
- Calculated by line length and line segments
Impact to Design

- Requirement of line transpositions
- Addition of transposition structures or alternate methods
Shield Wire
Adequacy of shielding methods to carry fault conditions

Combined with Grounding study determines fault current mitigation

Maintain NESC safety criteria during any conditions
Shield Angle Example
Methods

- Comparison of fault current vs. shield wire current capabilities
- Computation based with respect to grounded conditions (soil resistivity, ground wire, ground rods)
- Comparison of cost of shielding materials (height vs. 2nd wire)
Impact to Design

- Determines shield wire configuration
- Determines shield wire size/type
Application

Thoughts on Design Approaches
Standard vs. Detailed

- **Standard designs** are those designs based on previous application in which the base design work (including studies & calculations) has already been performed.

- Standard designs are more typical for HV applications (41.6 kV thru 115 kV, 230 kV)
Standard vs. Detailed

- **EHV standard designs should be validated**
  - Changing conditions such as location, environmental, etc. can invalidate a standard design
  - Changing regulatory or permitting conditions may also invalidate standard designs
Chicken or Egg?

- Studies can determine values to be used in design criteria - or - utility standards can dictate design criteria then design to meet standards

- Do electrical (studies) then physical → or perform physical design and adjust/validate from electrical studies
Questions?
Need/Want More?
Additional Questions, Thoughts, or General Discussion

Duane Phillips
Senior Project Manager

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303.649.7831

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