Transmission Line Ratings Workshop

Typical Industry Practices

January 15, 2021

Purpose & Key Takeaways

Purpose:

- Workshop to provide an overview of typical industry practices surrounding the establishment of Transmission Line Ratings

Key Takeaways:

- There are many factors that impact the development of Transmission Line Ratings.
- There must be an appropriate balance in considering economics vs. reliability when developing Transmission Line Ratings.
- Ratings must be compliant with laws, regulations and applicable industry standards.
- Rating development is often an exercise in risk management.

PART 1
Introduction to Ratings

Definitions

- **Facility Rating (NERC Definition):** *"The maximum or minimum voltage, current, frequency, or real or reactive power flow through a facility that does not violate the applicable equipment rating of any equipment comprising the facility."*

- **Transmission Load Rating:** *A subset of a facility rating focused on the maximum allowable power flow for any two-terminal transmission branch.*

- **Transmission Line Rating:** *A subset of a transmission load rating focused on the maximum allowable power flow for overhead transmission line branches only (including terminal equipment in series with the overhead transmission line branch).*

Transmission Load Rating Parameters

- **Rating Magnitude:** *The maximum loading level permitted for a transmission branch under prescribed conditions, typically specified in MW, MVA, MVAR or Amperes.*

- **Rating Duration:** *The maximum amount of time transmission branch loading can be maintained at the load rating magnitude specified.*

  Note: Continuous ratings do not have duration limits, and thus represent the maximum loading level that is permitted continuously.

- **Applicable Operating Conditions:** Applicable operating conditions include ambient conditions (temperature, wind speed, etc.) and system conditions (preloading, cooling equipment status, etc.).

Transmission Loading Limits Drive Transmission Load Ratings

- **Hard Transmission Loading Limits.** *Limits that cannot be exceeded for any duration based on the laws of physics, and typically include:*
  - *Maximum Power Transfer Limits*
  - *Relay Trip Limits*
- **Soft Transmission Loading Limits.** *Limits that can be exceeded, but exceeding such limits could compromise safety, violate laws and regulations, reduce facility life span, degrade reliability or introduce other operational risks. Soft limits typically include:*
  - *Thermal Limits*
  - *Voltage and Stability Limits*
- Hard Transmission Loading Limits tend to be greater than Soft Transmission Loading Limits, so most Transmission Load Ratings are driven by Soft Transmission Loading Limits.

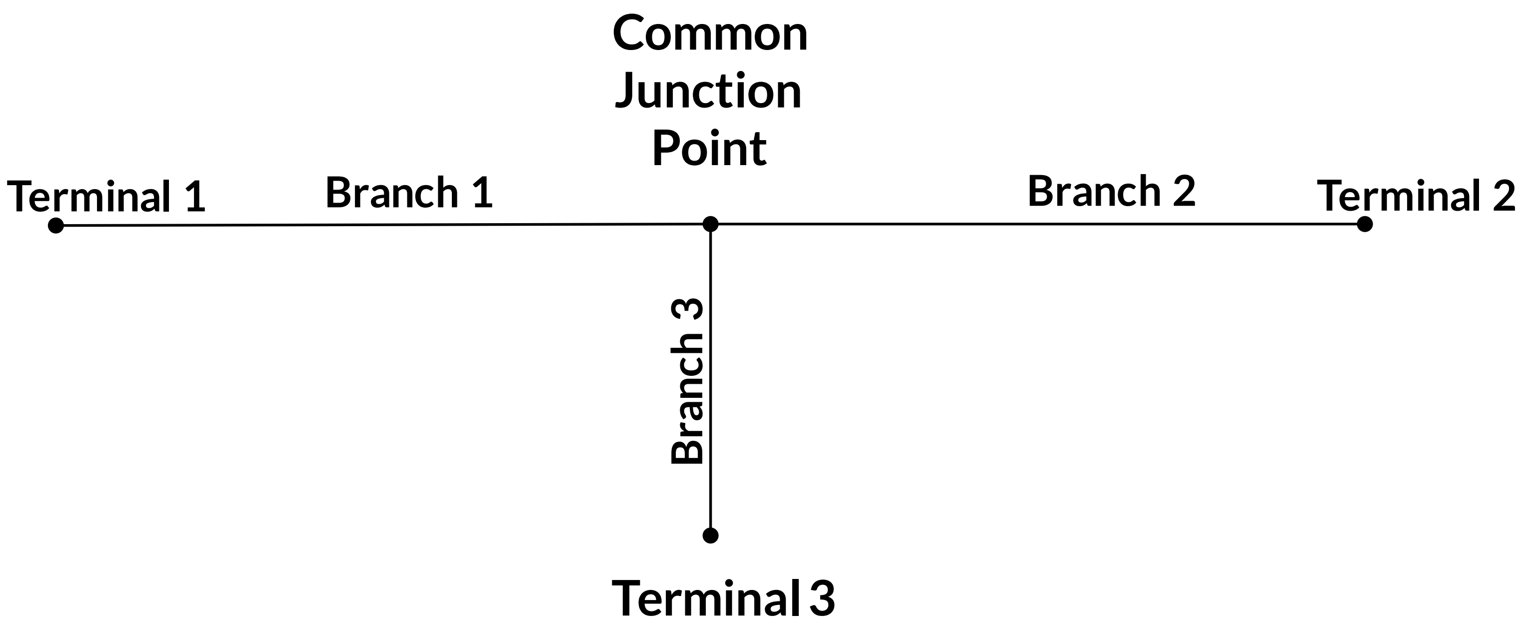
Ratings Apply to Transmission Branches

- A transmission branch is defined as any portion of the transmission system which contains only two terminals where such terminals are located at the endpoints.

- Theoretically the loading within a transmission branch is constant since real and reactive power cannot be injected into or withdrawn from the branch at any location but the end-point terminals.
- However, this is not entirely true since distributed capacitance will inject reactive power into the branch, distributed inductance will withdraw reactive power from the branch and conductor resistance will withdrawal real power from the branch, thus the real and reactive power flow at each of the two end-point terminals of a branch will be slightly different.
- Therefore, power flow must be measured at both terminals to get a worst case loading for the transmission branch.

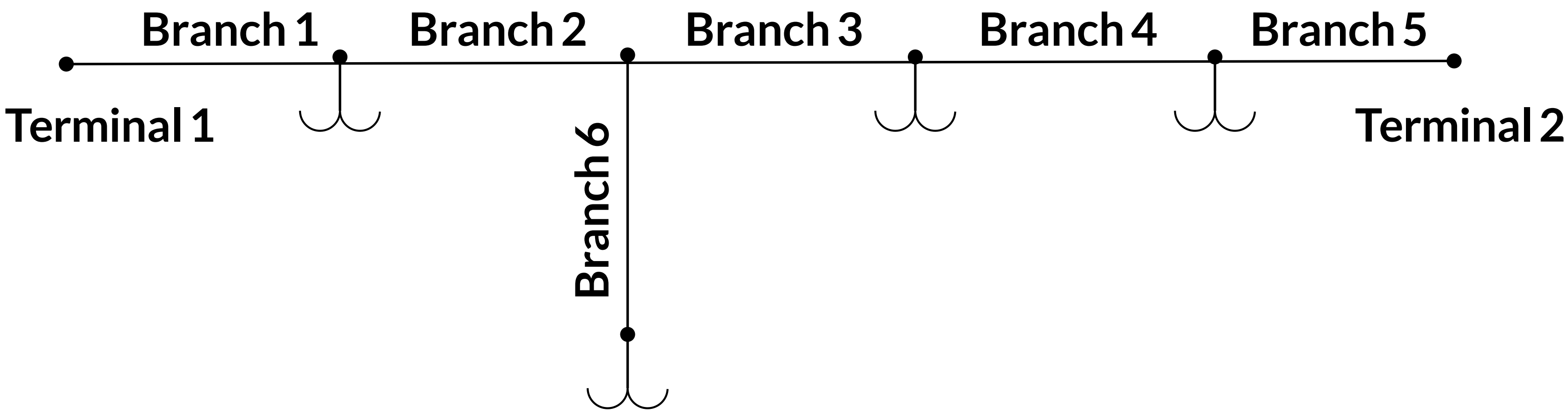
Example 1
Three-terminal Line Circuit with Three Branches

Independent ratings are established for Branch 1, Branch 2 and Branch 3 since the flows on these branches will be different in general.



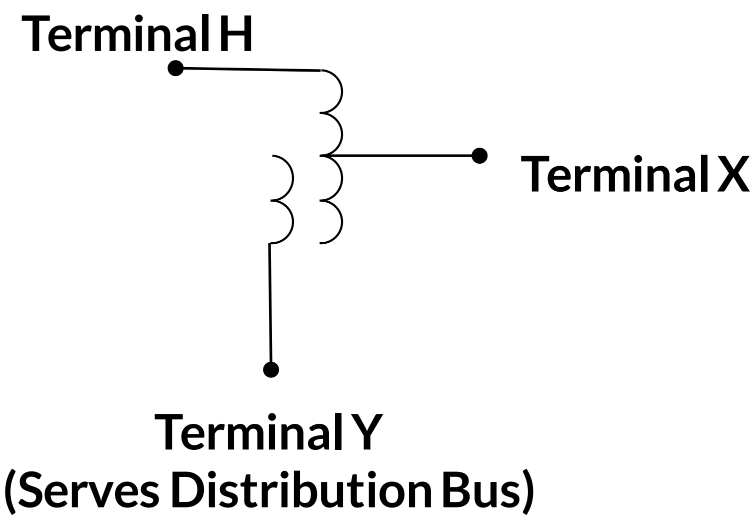
Example 2
Two-terminal Line Circuit with Radial Taps and Loads

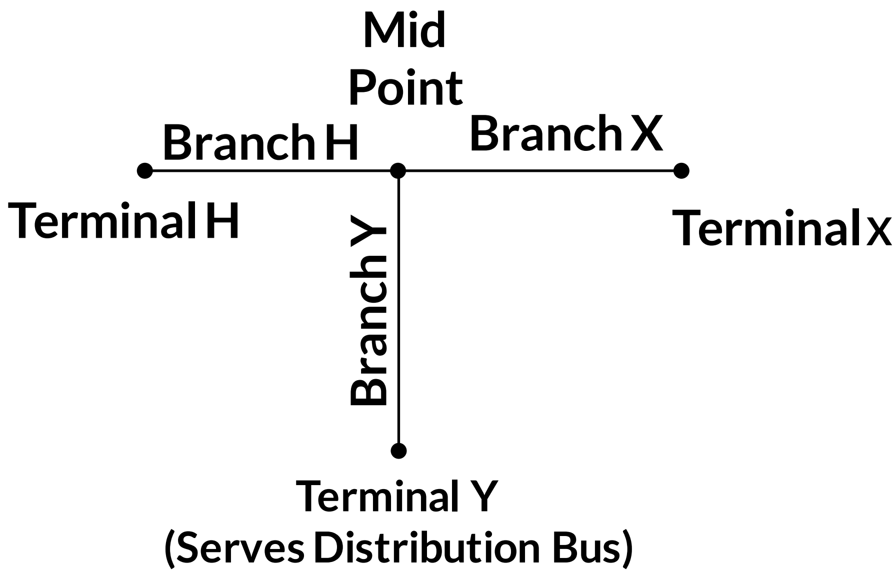
Independent ratings are established for Branch 1, Branch 2, Branch 3, Branch 4, Branch 5 and Branch 6 since the flows on these branches will be different in general.



Example 3
Transmission Autotransformer with Tertiary Load

Independent ratings are established for Branch H, Branch X and Branch Y since the flows on these branches will be different in general.





PART 2
Normal vs. Emergency Ratings

Normal Rating

- **NERC Definition.** *"The rating as defined by the equipment owner that specifies the level of electrical loading, usually expressed in megawatts (MW) or other appropriate units that a system, facility, or element can support or withstand through the daily demand cycles without loss of equipment life."*

- Normal Ratings are generally continuous ratings and do not have duration limits.

- Normal ratings are applied under normal operating conditions and not under emergency operating conditions.

Emergency Rating

NERC Definition. *"The rating as defined by the equipment owner that specifies the level of electrical loading or output, usually expressed in megawatts (MW) or Mvar or other appropriate units, that a system, facility, or element can support, produce, or withstand for a finite period. The rating assumes acceptable loss of equipment life or other physical or safety limitations for the equipment involved."*

- Emergency ratings are typically duration limited, where the duration limit is designed to minimize i) cumulative loss-of-life of equipment and ii) other operating risks by limiting loading above the normal rating to abnormal conditions and very short durations.

- Emergency ratings are applied under emergency operating conditions only.

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Application of Normal vs. Emergency Ratings

- Emergency ratings are generally used to constrain the system during emergencies, where emergencies are often characterized as a short period of time following a generation or transmission forced outage.
- The short period of time for which an emergency rating is applicable is generally set equal to the duration of the emergency rating.
- Normal ratings apply at all other times.
- The primary purpose of emergency ratings is to allow time for system adjustments following a forced outage to get transmission loading back down under normal ratings.
- Normal daily load cycles will also assist in reducing loading back below normal ratings if the forced outage occurs during the daily peak and the emergency rating duration allows sufficient time for the load to cycle down.

NERC FAC-008 Requirements for Normal and Emergency Ratings

- NERC FAC-008 **requires** both a normal rating and an emergency rating.

NERC FAC-008 **does not** specify any duration requirements for the emergency rating.

NERC FAC-008 **does not** specify how the normal vs. the emergency rating is to be applied in operations and planning.

NERC FAC-008 **does not** specify that the emergency rating must be greater than the normal rating.

Can Normal Rating Magnitudes be the same as Emergency Rating Magnitudes?

Absolutely…………but in these cases, there would be no duration limit on the emergency rating since the normal rating does not have a duration limit.

- **Normal rating magnitudes will equal emergency rating magnitudes** when the limits that drive the ratings are instantaneous limits that do not allow for duration-limited excessive loading (e.g., conductor sag limits, etc.).
- **Normal rating magnitudes will also equal emergency rating magnitudes when:**
  - the limit that drives the rating is the manufacturer's continuous Ampere or MVA rating (or nameplate rating), and
  - there is no other manufacturer rating, industry standard, manufacturer statement or other technical basis that can support a higher duration-limited emergency rating.
- Any requirement to force a difference between normal and emergency ratings will drive down the normal rating under the above scenarios, which in turn will increase congestion and reduce operating flexibility.
- More on this later.

PART 3
Absolute Ratings

The Absolute Rating

- **Definition.** *The absolute rating is the theoretical maximum level of power transfer possible through a transmission branch for any length of time. It is not theoretically possible to exceed the absolute rating.*

- The absolute rating is typically the lesser of the Maximum Power Transfer Limit and the Relay Trip Limit, or the lowest hard limit.
- The absolute rating is typically greater than the thermal rating for most transmission lines and transformers, and thus does not drive the rating.
- Furthermore, the absolute rating can vary as system conditions vary, so it is difficult to get a handle on what the absolute rating actually is at any point in time.
- For these two reasons, the absolute rating is not typically calculated, but it is important to understand that it exists.

Absolute Ratings

Part A

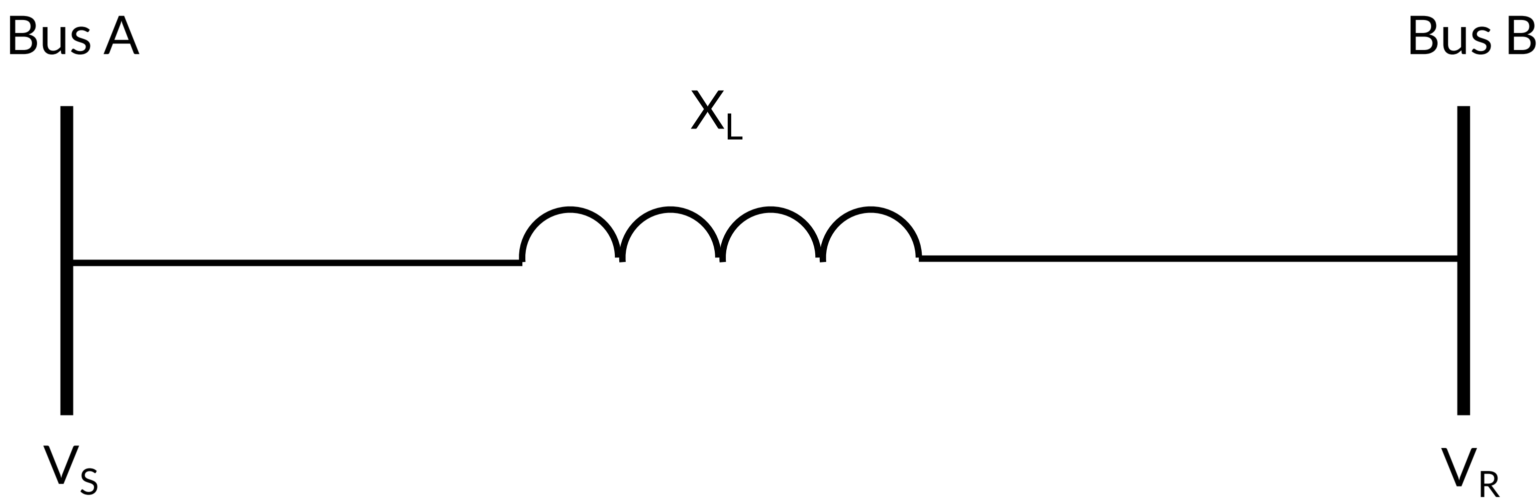
Maximum Power Transfer Limit

Power Transfer Through A Transmission Branch

The power flow in per unit through a transmission branch connected to Bus A at the source terminal and Bus B at the receiving terminal can be approximated by the following formula:

Power Flow = $[|V_S||V_R|\sin(\delta)] / |X_L|$

where
- V_S = Voltage at Bus A in per unit
- V_R = Voltage at Bus B in per unit
- X_L = Series reactance of line in per unit
- δ = Angle by which V_S leads V_R in radians

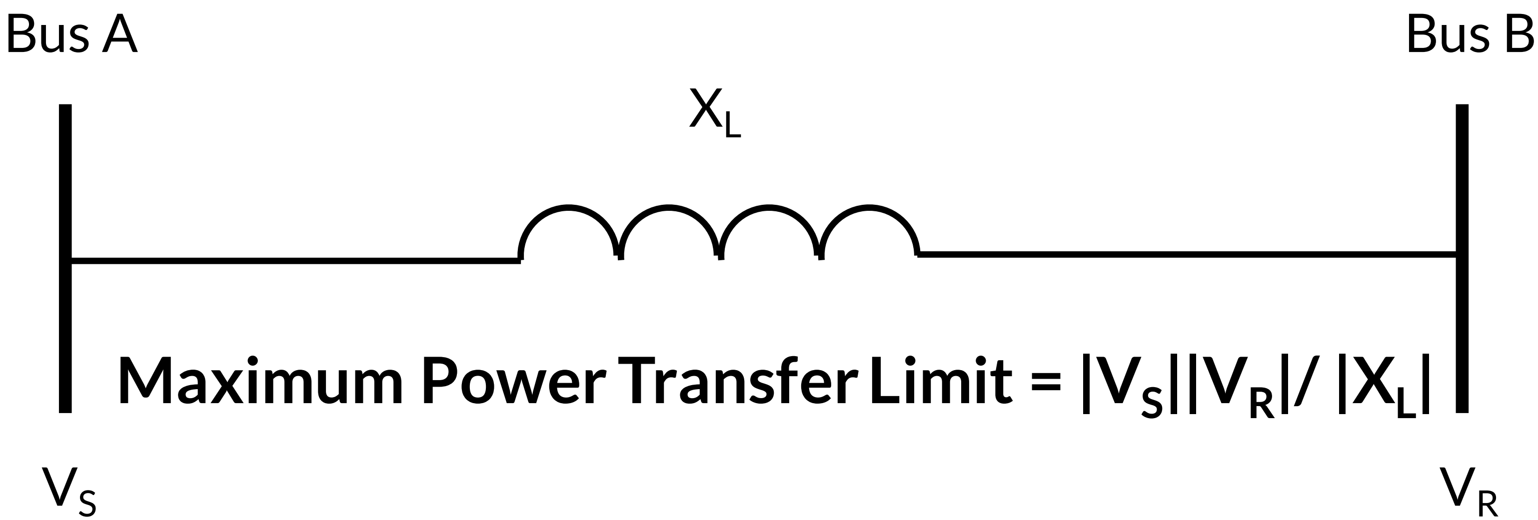


Maximum Power Transfer Limit

Since the maximum value of the sine function is 1.0 and occurs when the angle is 90°, the maximum power flow through a transmission branch occurs when the source voltage leads the receiving voltage by 90° and is equal to the following:

Maximum Power Flow = $|V_S||V_R|/|X_L|$

where
- V_S = Voltage at Bus A in per unit
- V_R = Voltage at Bus B in per unit
- X_L = Series reactance of line in per unit



Maximum Power Transfer Limit = $|V_S||V_R|/|X_L|$

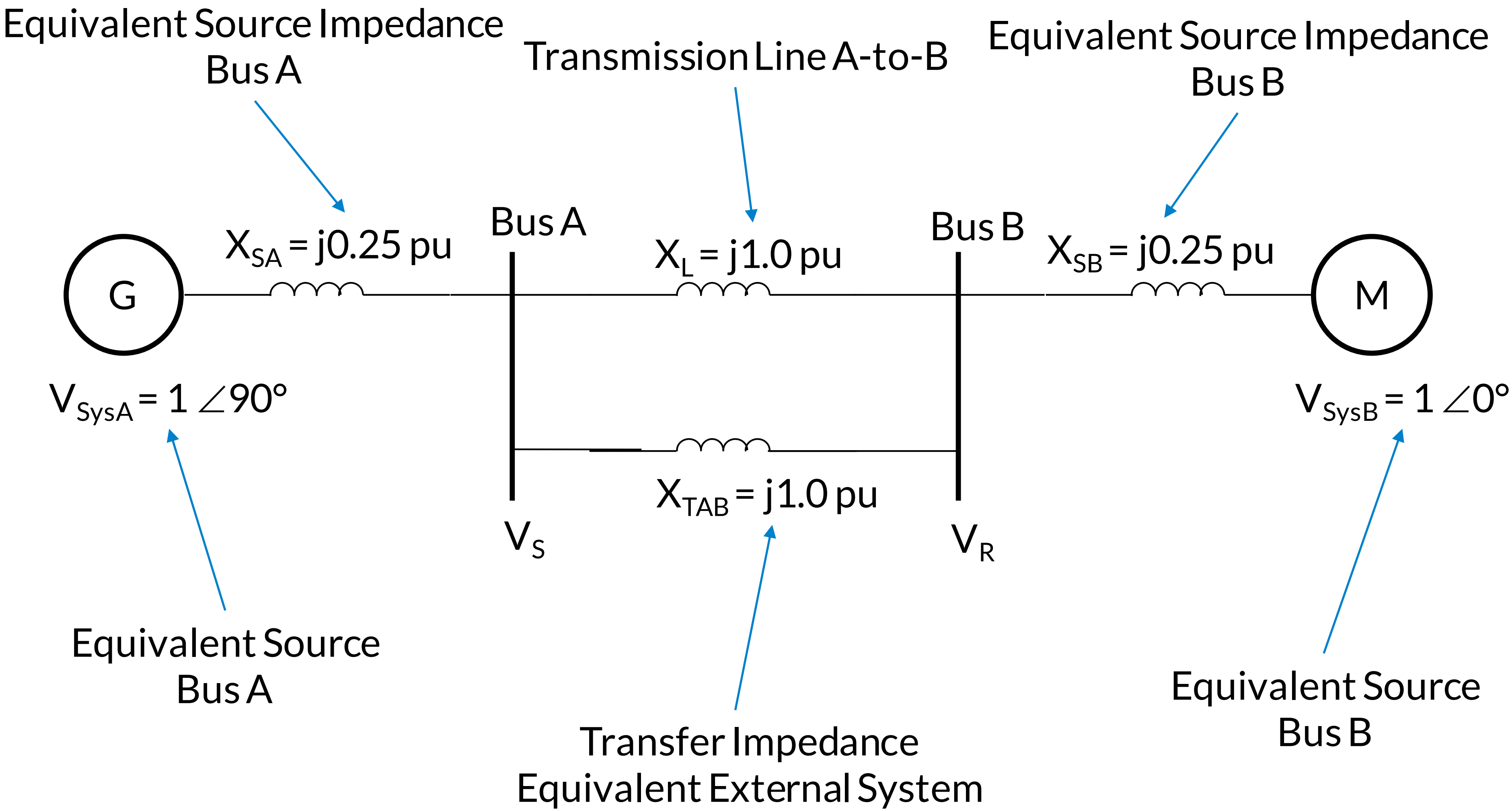
Maximum Power Transfer Limit
With and Without Consideration of External System

The transmission branch maximum power transfer limit shown on the previous slide is a true maximum power transfer limit for a transmission impedance branch, but not necessarily the most conservative maximum power transfer limit for a given transmission impedance branch.

The most conservative maximum power transfer limit for a branch must consider the impact of the external system.

The external system can be considered in developing a maximum power transfer limit by connecting the transmission branch to a two-bus equivalent network as shown on the following slide.

Maximum Power Transfer Through A Transmission Line Example with External System Considered



Maximum Power Flow Across System Further Limits Maximum Power Flow of Branch

- Considering the branch and the external system modeled on the previous slide, the maximum power transfer possible across the system would occur when the phase angles of the equivalent source voltages are displaced by 90°, and would be calculated as follows:

Max Power Across System

$$= [|V_{SA}||V_{SB}|] / |[X_{SA} + X_L||X_{TAB} + X_{SB}]|$$
$$= [1.0 * 1.0] / [0.25 + 1.0||1.0 + 0.25]$$
$$= 1.0 / [0.25 + 0.5 + 0.25] = 1.0 \text{ p.u.}$$

- Since the line impedance is equal to the external system transfer impedance, the maximum power flow through the line occurs when there is maximum power flow across the system and would be equal to 50% of the maximum power flow across the system based on simple current division between the line and transfer impedance, which implies a maximum power transfer limit for the branch of 0.5 per unit.
- When the external system is ignored, the maximum power transfer limit of the branch is calculated as:
  - Max Power Transfer Limit = $|V_S||V_R| / |X_L|$ = (1.0)(1.0)/(1.0) = 1.0 p.u. (overstated by 100%)

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Two Maximum Power Transfer Limits for a Branch

- A transmission impedance branch has two maximum power transfer limits:
  - **$MPTL_{Branch}$** = The calculated limit when the external system is ignored.
  - **$MPTL_{BranchSystem}$** = The calculated limit when the external system is considered.
- The formulae for each type of maximum power transfer limit are as follows:
  - **$MPTL_{Branch}$** = $|V_S||V_R|/|X_L|$
  - **$MPTL_{BranchSystem}$** = $\{|V_{SA}||V_{SB}| / |[X_{SA} + X_{SB} + X_L||X_{TAB}]|\} * DF$

Where

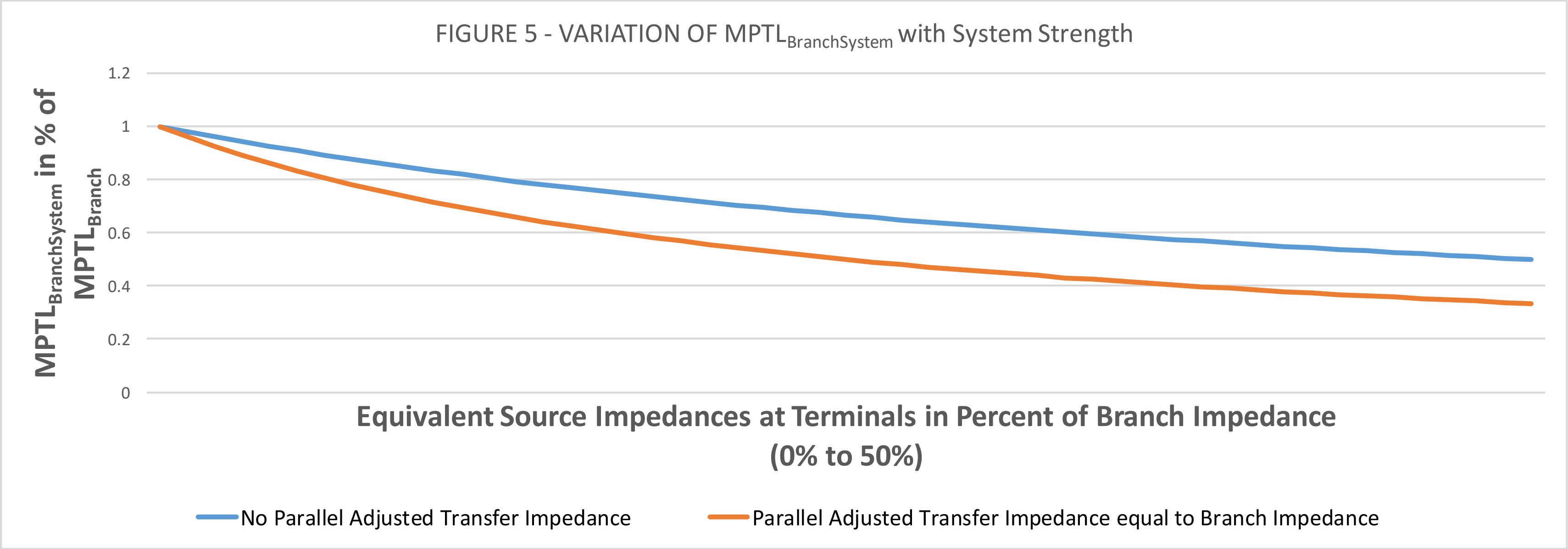
DF = 1.0 if there is infinite external transfer impedance between Bus A and B

DF = $|X_{TAB} / [X_L + X_{TAB}]|$ if external transfer impedance is less than infinite

- $MPTL_{Branch} = MPTL_{BrnachSystem}$ when $X_{SA} = X_{SB} = 0$ (Infinite System Strength)

Plot of $MPTL_{Branch}$ vs. $MPTL_{BranchSystem}$

- For $X_{SA} = X_{SB} = X_S$
  - **Blue Plot:** Plot of $MPTL_{BranchSystem}$ as a percent of $MPTL_{Branch}$ assuming X_S varies from 0% to 50% of X_L with no external transfer impedance (i.e., infinite external transfer impedance)
  - **Red Plot:** Plot of $MPTL_{BranchSystem}$ as a percent of $MPTL_{Branch}$ assuming X_S varies from 0% to 50% of X_L with $X_{TAB} = X_L$



Summary of Maximum Power Transfer Limits

- Each branch has two maximum power transfer limits: $MPTL_{Branch}$ and $MPTL_{BranchSystem}$ if the transmission branch has a non-zero series reactance.

- Zero impedance branches such as circuit breakers do no have maximum power transfer limits but do have thermal limits.

- $MPTL_{Branch} \geq MPTL_{BranchSystem}$, so $MPTL_{BranchSystem}$ is the most conservative limit.

- It is easy to calculate $MPTL_{Branch}$,

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Summary of Maximum Power Transfer Limits, continued

- $MPTL_{BranchSystem}$ changes as system conditions change (i.e., topology and/or generation commitment), thus it is not practical to calculate $MPTL_{BranchSystem}$.
- For longer lines with higher impedances relative to the equivalent source impedances, $MPTL_{Branch}$ is a good approximation of $MPTL_{BranchSystem}$, but not worst case.
  - Since longer lines have lower maximum power transfer limits, the thermal limit may not be lower than the maximum power transfer limit for longer lines.
  - The good news is that $MPTL_{Branch}$ is closer to $MTP_{BranchSystem}$ on longer lines, thus $MPTL_{Branch}$ is a good proxy for the maximum power transfer limit for longer lines (but not worst case).
- For shorter lines with lower impedances,

  $MPTL_{Branch} >> MPTL_{BranchSystem} >>$ Thermal Limit

  so it has not generally been necessary to calculate maximum power transfer limits for shorter lines, since thermal limits are well below maximum power transfer limits.

The “So What” of Maximum Power Transfer Limits in a World of Ambient Adjusted Ratings and Dynamic Line Ratings

While AARs and DLRs allow for reductions in production cost and increases in operating flexibility, they will tend to drive lower safety margins between thermal limits and maximum power transfer limits if the transmission line is long.

Attempting to load a long line near or beyond a maximum power transfer limit typically will introduce angular stability issues, which could have adverse impacts on reliability.

In the new world of renewables where power may travel longer distances on average and system strength will be lower on average, it is even more important to be aware of the existence of maximum power transfer limits.

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The “So What” of Maximum Power Transfer Limits in a World of Ambient Adjusted Ratings and Dynamic Line Ratings (continued)

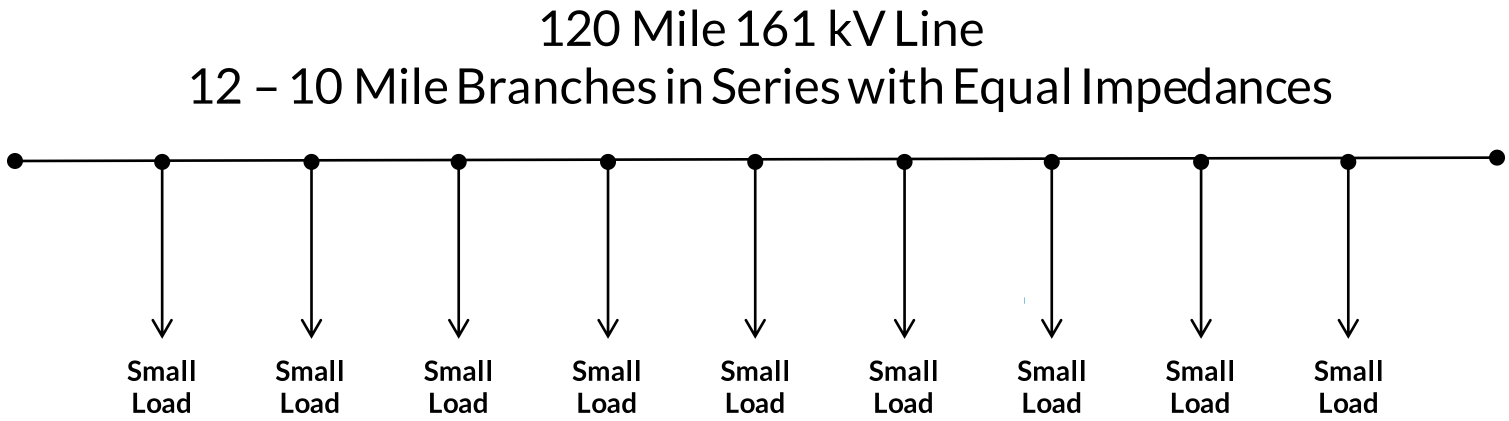
It may be prudent to consider capping AARs and DLRs at some value to ensure operation never approaches maximum power transfer limits.

One such idea would be to use the St. Clair Curve which provides for a loadability limit based on the Surge Impedance Loading (SIL) of the line and the line length.

The St. Clair Curve incorporates a 30% steady state stability margin (maximum angular displacement of 44°) applied to the $MPTL_{Branch}$ to account for the impact of the external system.

Such a cap would be more restrictive for longer lines than shorter lines, which is appropriate.

Example of when $MPTL_{BranchSystem}$ is much lower than $MPTL_{Branch}$



- $MPTL_{Branch}$ for each 10 Mile branch is very high due to low branch reactance.
- However, $MPTL_{BranchSystem}$ is much lower than $MPTL_{Branch}$ since the reactance values of the other series branches in the line would likely drive very high equivalent source reactance relative to the reactance of any one branch (i.e., the reactance of the other series branches are part of the external system).
- Applying a 30% steady state stability margin to $MPTL_{Branch}$ would not be sufficient to take into consideration the external system.
- A better approach would be to calculate $MPTL_{Branch}$ for the entire line (ignoring the load points) and then apply a 30% steady state stability margin to that value and assign to each of the individual branches.

ABSOLUTE RATINGS

Part B

Relay Trip Limits

Relay Trip Limits

A transmission branch may have a relay trip limit if:

- One or both branch terminals contains a circuit breaker.
- The circuit breaker is tripped by one or more load sensitive relay element(s).

Load sensitive relay elements include the following:

- Overcurrent relays sensitive to transmission branch loading
- Impedance or distance relays sensitive to transmission branch loading

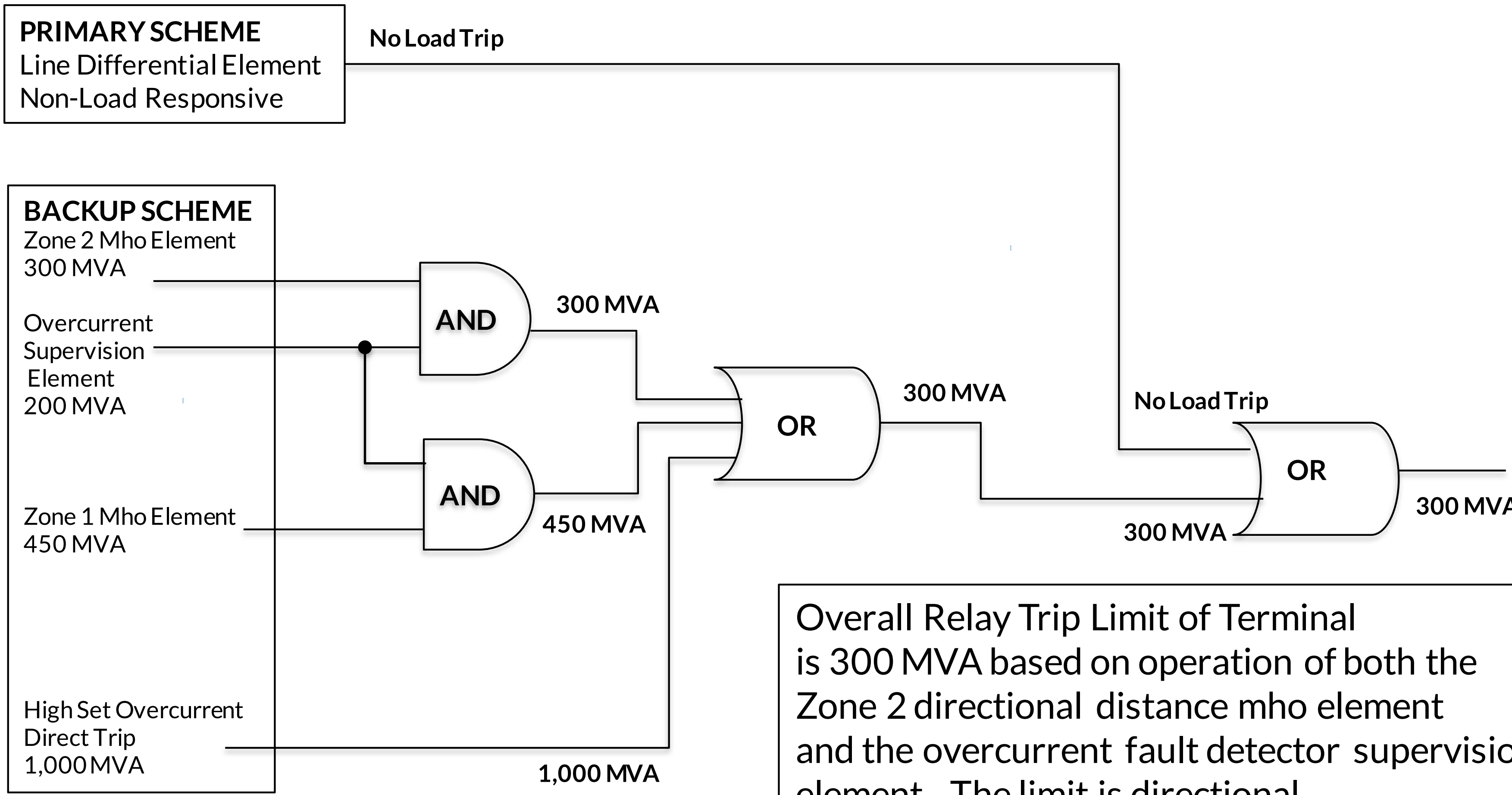
The following relay elements would not be considered load sensitive:

- Ground relays (cannot protect 3ϕ or ϕϕ faults – so cannot fully protect a line)
- Negative sequence relays (cannot protect 3ϕ faults – so cannot fully protect a line)
- Line differential relays
- Transformer differential relays
- Bus differential relays
- Phase comparison relay
- Impedance or distance relays with load encroachment features

Determining a Relay Trip Limit

- To initiate a relay trip, several relay elements must typically operate within a given relay scheme, and if any of these relay elements are not sensitive to branch loading, then the relay scheme is considered non-load responsive and there is no relay trip limit for the scheme.
- The MVA load necessary to operate a relay element is referred to as the relay element load pickup level, and operation of a relay element does not necessarily mean a relay trip has occurred.
- If a protection scheme is load responsive, the relay trip limit is based on the least sensitive relay element load pickup level for all relay elements that must operate to initiate a relay trip.
- If multiple protective relay schemes exist for a given transmission branch, the overall relay trip limit is the most sensitive relay trip limit for each of the relay schemes.
- Relay trip limits are generally directional for network transmission lines thus the relay trip limit will be different for each terminal, and thus each power flow direction.

Example of How to Determine a Relay Trip Limit For a Specific Branch Terminal



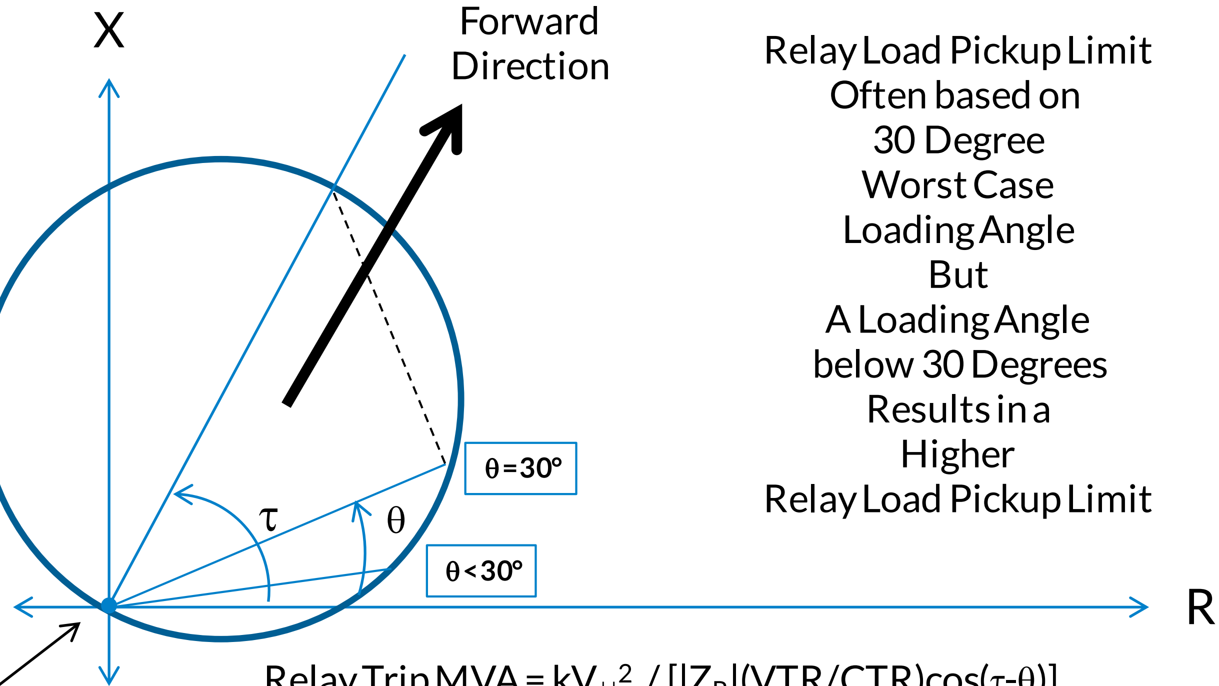
Overall Relay Trip Limit of Terminal is 300 MVA based on operation of both the Zone 2 directional distance mho element and the overcurrent fault detector supervision element. The limit is directional.

Determining a Distance Relay Load Limit

- For typical load sensitive mho directional distance relay elements, the relay element load pickup level is an MVA limit that depends on the direction of power flow and the line loading angle.
- It is typical to assume a worst-case line loading angle of 30° (current lags voltage by 30° or apparent load impedance angle is 30°), and this angle is typically used to set the relay load limit.
- It is important to note that the relay element load pickup level will be higher for lower line loading angles since the apparent load impedance required to pickup the distance relay element is smaller.
- Directional relays are most sensitive when the apparent load impedance has an angle between 0° and 90°, which means Real and Reactive power flow is into the line (first quadrant of the R-X plane).

Distance Relay Loadability
Two-terminal Transmission Line - Illustration

Load Pickup Apparent Impedance Magnitude = Impedance Setting * $\cos(\tau-\theta)$



Relay Load Pickup Limit
Often based on
30 Degree
Worst Case
Loading Angle
But
A Loading Angle
below 30 Degrees
Results in a
Higher
Relay Load Pickup Limit

Mho Characteristic

Relay Location

Relay Trip MVA = $kV_{\phi\phi}^2 \,/\, [|Z_R|(VTR/CTR)\cos(\tau-\theta)]$

where
- $kV_{\phi\phi}$ = Nominal phase-to-phase kV
- Z_R = Impedance setting of relay
- CTR = CT Ratio
- VTR = VT Ratio
- τ = Maximum torque angle setting of relay
- θ = Loading angle

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Determining a Relay Trip Limit - Challenges

Just as there were challenges in calculating maximum power transfer limits, there are also challenges in calculating relay trip limits.

Most relay trip limits are directional, so applying the limit to both power flow directions is overly conservative

Most relay trip limits are a function of line loading angle, thus the true relay trip limit changes with line loading angle.

The "So What" of Relay Trip Limits in a World of Ambient Adjusted Ratings (AARs) and Dynamic Line Ratings (DLRs)

- While AARs and DLRs allow for reductions in production cost and increases in operating flexibility, they will tend to drive lower safety margins between thermal limits and relay trip limits.
- Attempting to load a line near or beyond a relay trip limit could result in a line trip and a risk of further cascading.
- It may be prudent to consider capping AARs and DLRs at some value to ensure operation never approaches relay trip limits.
- One such idea would be to use a margin of 15% to 30% of the relay trip limit to account for instrument transformer error, relay setting error and drift and potential imbalances in line flow.*
- Such a cap would be more restrictive for longer lines than shorter lines, which is appropriate since longer lines typically require more sensitive relay settings than shorter lines.

* NERC PRC 23 implies a minimum margin of 13% (i.e., 1 / 1.15)

Part 3
THERMAL RATINGS

All Load-Carrying Components Have Thermal Limits

- Conductors and Connectors
  - Overhead Conductors
  - Underground Cable
  - Rigid Bus Conductors
  - Strain Bus Conductors
  - Jumpers
  - Risers
  - Leads
  - Splices
  - Terminals
  - Tees
  - Etc.
- Switchgear
  - Circuit Breakers
  - Breaker Disconnect Switches
  - Station Sectionalizing Switches
  - Field Sectionalizing Switches
  - Etc.
- Transformers
  - Power Transformers
  - Autotransformers
  - Phase Angle Regulators
  - Voltage Regulators / LTCs
  - Etc.
- Other Terminal Equipment
  - Wave Traps
  - Current Transformers
  - Current Transformer Secondaries
    - Relays
    - Meters
    - Transducers
    - Etc.
  - Series Reactors
  - Series Capacitors
  - Etc.

The Limiting Element Controls the Thermal Limit

Most Transmission Branches contain many individual load carrying components in series.

Each of these load carrying components has its own thermal limit.

The overall thermal limit of the transmission branch is the thermal limit of the most limiting series component, which is often referred to as the “limiting element”.

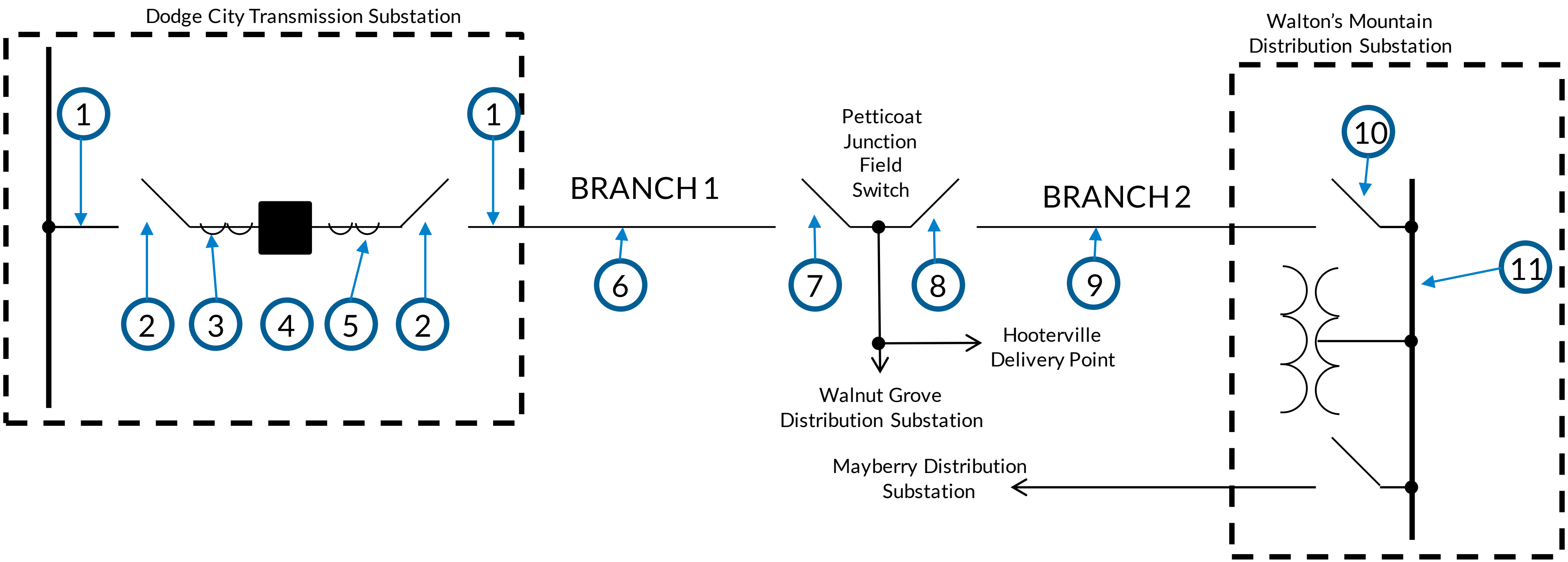
Transmission Branches Have Many Limiting Elements - Example

Branch 1 Limiting Elements:

1) Rigid Bus Conductor and Connectors:	1543 A
2) Breaker Disconnect Switch:	2000 A
3) **Bus-side Breaker CT (2000/5 set @ 1100/5):	1100 A
4) Circuit Breaker including Leads and Bushings:	2000 A
5) **Line-side Breaker CT (2000/5 set @ 2000/5):	2000 A
6) *Overhead Conductor and Connectors:	1629 A
7) Field Mounted Transmission Switch:	1200 A
Overall Thermal Limit:	**1100 A**

Branch 2 Limiting Elements:

8) Field Mounted Transmission Switch:	1200 A
9) *Overhead Conductors and Connectors:	1742 A
10) Substation Line Sectionalizing Switch:	1200 A
11) Rigid Bus Conductor:	1937 A
Overall Thermal Limit:	**1200 A**



*Note 1: Includes jumpers and substation risers
**Note 2: Includes CT secondary Burden thermal limits (also 5A or above)

NERC FAC – 008-3
Provisions for Establishing Thermal Limits

- The NERC standard that governs facility ratings is NERC FAC-008-3.
- This standard assigns the responsibility of developing transmission ratings to the Transmission Owner.
- This standard provides for three general methods that can be used to establish a thermal rating based on the most limiting element:
  - "Ratings provided by equipment manufacturers or obtained from equipment manufacturer specifications such as a nameplate rating."
  - "One or more industry standards developed through an open process such as the Institute of Electrical and Electronics Engineers (IEEE) or the International Council on Large Electric Systems (CIGRE)."
  - "A practice that has been verified by testing, performance history or engineering analysis."

Typical Methods Used to Establish Transmission Load Ratings

- For overhead line conductors, the typical practice is to use the IEEE 738 standard, or something equivalent, to calculate the line conductor ratings in accordance with the input assumptions, facility design parameters and risk strategy of the transmission owner.
- For transformers, the typical practice is to use the applicable nameplate ratings.
  - In some situations, some transmission owners may determine that the condition and typical loading cycle of a specific transformer can justify developing a higher transformer rating based on ANSI/IEEE C57.91, although such higher rating will result in an accelerated loss of life and higher failure risks as articulated in the standard.
- For terminal equipment, the typical practice is to use the applicable nameplate ratings (continuous ratings) unless the manufacturer specifically authorizes a higher rating based on specific testing and/or engineering analysis.

THERMAL RATINGS

Part A

Overhead Conductors

Overhead Conductors - Steady-state Thermal Loading Mechanism

- At a high level, the steady-state thermal loading mechanism of an overhead conductor is driven by the following heat balance:

$$Q_{CondLoss} + Q_{Solar} = Q_{Convection} + Q_{Radiation}$$

Where

$Q_{CondLoss}$ = Conductor heat loss rate due to current flow (W or W/ft)

Q_{Solar} = Conductor solar heat absorption rate (W or W/ft)

$Q_{Convection}$ = Convective heat transfer rate away from conductor (W or W/ft)

$Q_{Radiation}$ = Radiated heat transfer rate away from conductor (W or W/ft)

- The heat generated by current flow for a specific conductor is a quadratic function of loading (where loading is proportional to current flow) and is given as follows:

$$Q_{CondLoss} = I_C^2 R_C$$

Where

I_C = RMS Magnitude of the AC current flowing in the conductor (A)

R_C = Resistance of the conductor (Ω or Ω/ft)

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Overhead Conductors Steady-state Thermal Loading Mechanism - Continued

$$Q_{CondLoss} + Q_{Solar} = Q_{Convection} + Q_{Radiation}$$

Based on the heat balance above, heat is added to the conductor by:

- Electrical current flow via resistive conductor losses ($Q_{CondLoss}$)
- Solar radiation (Q_{Solar})

Based on the heat balance above, heat is removed from the conductor by:

- Convection ($Q_{Convection}$) (Due to wind blowing against conductor and/or natural convection)
- Radiation ($Q_{Radiation}$)

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Overhead Conductors Steady-state Thermal Loading Mechanism - Continued

$$Q_{CondLoss} + Q_{Solar} = Q_{Convection} + Q_{Radiation}$$

- The level of heat removal by convection and radiation is proportional to the difference between the conductor temperature and ambient temperature.
- Therefore, in steady state conditions, where steady state applies not only to loading, but to ambient conditions as well, the steady state heat balance will drive the conductor temperature to a unique value that balances conductor heat addition with conductor heat removal.
- IEEE 738 uses the heat balance above to determine, based on input assumptions, the load level that drives the conductor temperature to the maximum allowable conductor temperature.

Maximum Allowable Conductor Temperature Drives Conductor Thermal Rating

Given an assumed ambient temperature, solar radiation level, wind speed, wind direction and other parameters, the thermal rating of a conductor is a direct function of the maximum allowable conductor temperature.

The maximum allowable conductor temperature in turn is based on three considerations:

- Conductor Sag Limits based on the National Electrical Safety Code (NESC) (Instantaneous Requirement)
- Maximum Allowable Loss of Tensile Strength over Time (Cumulative Requirement)
- Potential Long-term Creep Elongation (Cumulative Requirement)

Continued…

Maximum Allowable Conductor Temperature Drives Conductor Thermal Rating, continued

- If the conductor sag limits drive the maximum allowable conductor temperature:
  - The sag limit is instantaneous and not cumulative.
  - There will be no difference between the normal and emergency maximum allowable conductor temperature
  - Thus, there will be no difference between the normal and emergency rating of the conductor.
  - CAVEAT: There could be a difference between the normal and emergency thermal rating of the conductor if the assumed ambient conditions differ for normal vs. emergency ratings (not a typical practice).
- If loss of tensile strength or long-term creep elongation drives the maximum allowable conductor temperature and the conductor sag limit does not:
  - The loss of strength or creep elongation limits are cumulative and not instantaneous.
  - Therefore, there can be a difference between the normal and emergency maximum allowable conductor temperature based on risk assessment.
  - Thus, there can a difference between the normal and emergency thermal rating of the conductor as well.

Conductor Sag Limits - Description

For safety reasons, the National Electrical Safety Code requires a minimum distance be maintained between an energized conductor and the ground at all times. This is known as a **vertical clearance requirement.**

- The specific clearance requirement is a function of i) voltage level and ii) the nature of what is located beneath the conductor (e.g., farmland vs. railroad vs. highway, etc.).
- To account for construction tolerances and changes to the ground topology, most transmission owners will introduce a safety margin, often referred to as a clearance buffer, of two to five feet to ensure clearance, thus the clearance requirement is set at the NESC minimum clearance plus the clearance buffer.
- The actual clearance between an overhead conductor and the ground is a function of i) the ground topology, ii) the heights of the conductor attachment points at structures, iii) the length of the span and iv) the length of the conductor.
- Assuming ground topology, attachment point height and span length are fixed, the clearance varies with changes in the length of the conductor.

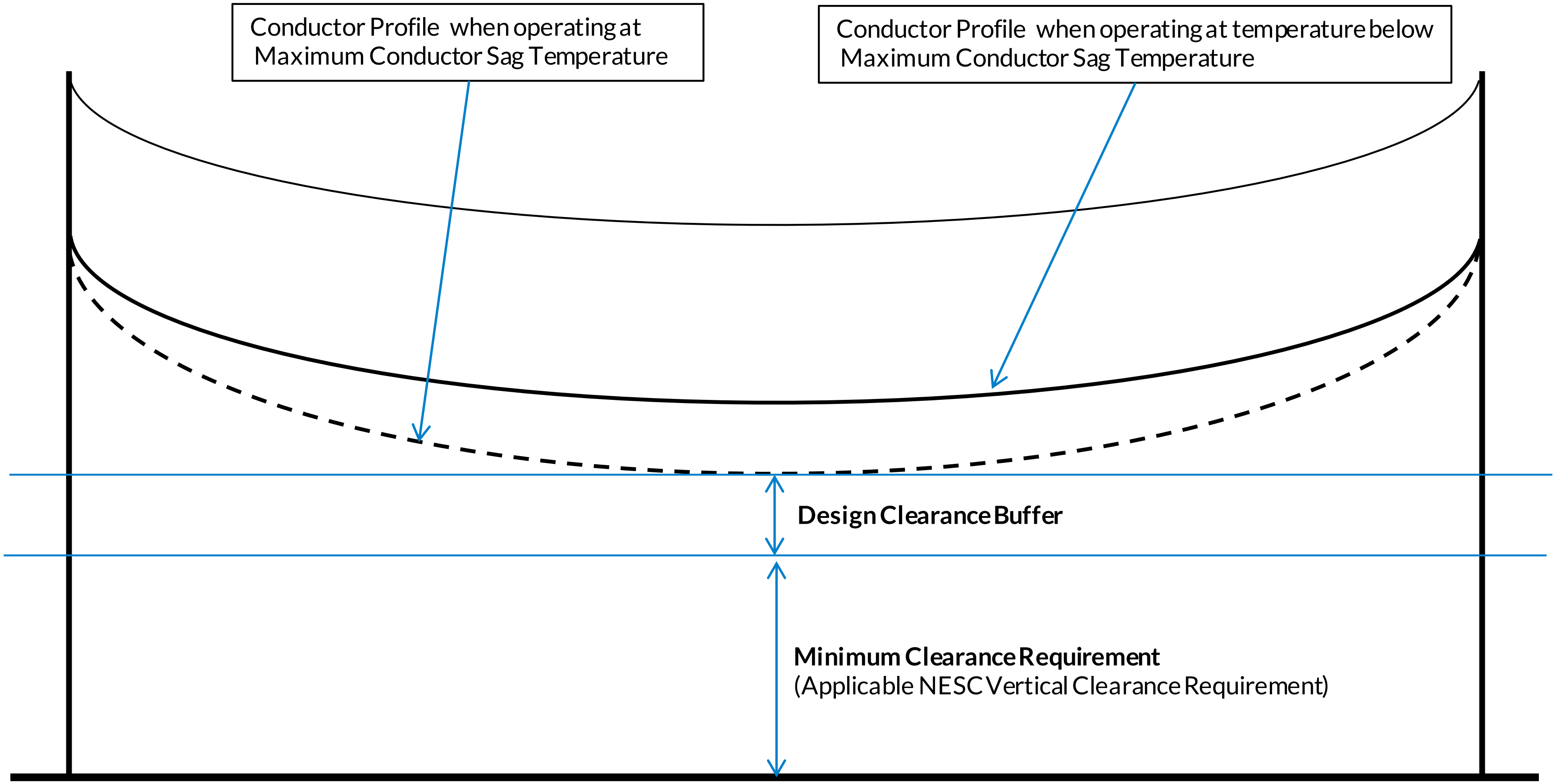
Conductor Sag Limits Description - Continued

Conductor length in an overhead conductor span is a function of:

- Forces applied to the conductor
- Conductor temperature
- Conductor creep (conductor elongation over time due to tension)

- As previously discussed, everything else equal, as the current flow in a conductor increases, the conductor temperature will increase to ensure heat balance
- The higher conductor temperature will elongate the conductor via thermal expansion, which will increase the conductor sag and reduce the conductor vertical clearance.
- Horizontal clearance requirements can also come into play since increased conductor length means higher potential conductor blowout.
- Therefore, the maximum conductor temperature is the temperature that results in a conductor sag that provides a vertical clearance equal to the NESC requirement plus the clearance buffer.
- Therefore, the conductor sag limit could drive the maximum allowable conductor temperature, and thus the maximum rating on the line.

Conductor Sag Limits: Illustration of Conductor Sag Limits



Conductor Sag Limits: Summary

The NESC sag limit on a transmission line conductor applies at all times and is the same for both normal and emergency conditions.

Therefore, the normal and emergency sag loading limits will be the same except in rare cases where a transmission owner's specific facility rating methodology calls for different ambient assumptions for normal vs. emergency ratings (e.g., different wind speed assumptions, etc.).

If the conductor sag is the limiting element for a transmission line, which it often is, the normal and emergency rating will be based on the sag limit and will generally be the same.

Forcing the normal and emergency rating to be different would create an artificial constraint that results in a lower normal rating than would otherwise be permitted, and this could cause unnecessary congestion.

Conductor Loss of Tensile Strength Limits - Description

The NESC requires that the maximum conductor tensions to be as follows:

Initial Sag: No more than 35% of Conductor Rated Breaking Strength

Final Sag: No more than 25% of Conductor Rated Breaking Strength

Heavy Wind and Ice Loading: No more than 60% of Conductor Rated Breaking Strength

- The rated breaking strength of a conductor will decrease over time if the conductor is exposed to elevated temperatures due to partial annealing of conductor strands.

- The decrease in rated breaking strength is a function of both the elevated temperature magnitude and the duration of exposure.

- Typical practice is to limit the loss of rated breaking strength to no more than 10% of the initial rated breaking strength of the conductor over the useful life of the line.

- To minimize loss of rated breaking strength, a transmission owner will limit maximum allowable conductor temperatures over the life of the line, and these limits could be different for normal vs. emergency conditions based on risk considerations.

Long-term Creep Elongation

Conductor length will increase over time due to the following three impacts:

- Continuous tension on the conductor
- Abnormal loads due to heavy wind and ice loading which, when removed, will not allow the conductor to go all the way back to its pre-abnormal loading length (i.e., plastic deformation)
- Operation at high temperature for extended periods of time.

To ensure vertical clearance requirements continue to be met over the life of a transmission line conductor, there may be an upper limit on maximum conductor operating temperature, under both normal and emergency conditions, to limit long-term creep elongation.

THERMAL RATINGS

Part B

Transmission Lines

Thermal Ratings of a Transmission Line

- As stated earlier, the thermal ratings of an overhead transmission line are based on the thermal ratings of the most limiting element, where limiting elements could be either:
  - Overhead conductors
  - Terminal equipment
- To the extent the limiting element is terminal equipment, the normal and emergency rating will generally be the same.
- To the extent the limiting element is a conductor sag limit, the normal and emergency rating will generally be the same.
- To the extent the limiting element is loss-of-tensile strength and not conductor sag, the normal and emergency ratings will generally be different.
- There are exceptions to the above depending on the specific facility rating methodology in use.

How Conservative are Thermal Rating Assumptions?

For summer ratings, loading is positively correlated with temperature, so the selection of ambient temperatures are not overly conservative given ambient temperature assumptions represent typical maximum temperature levels in the area.

For winter ratings, loading is often negatively correlated with temperature, so the selection of ambient temperatures may consider the negative correlation between loading and ambient temperature, which could vary from system to system, based in part on how much potential electric heating load is on the system

- However, IEEE 738 recommends using maximum temperatures for the season in question.

Continued…

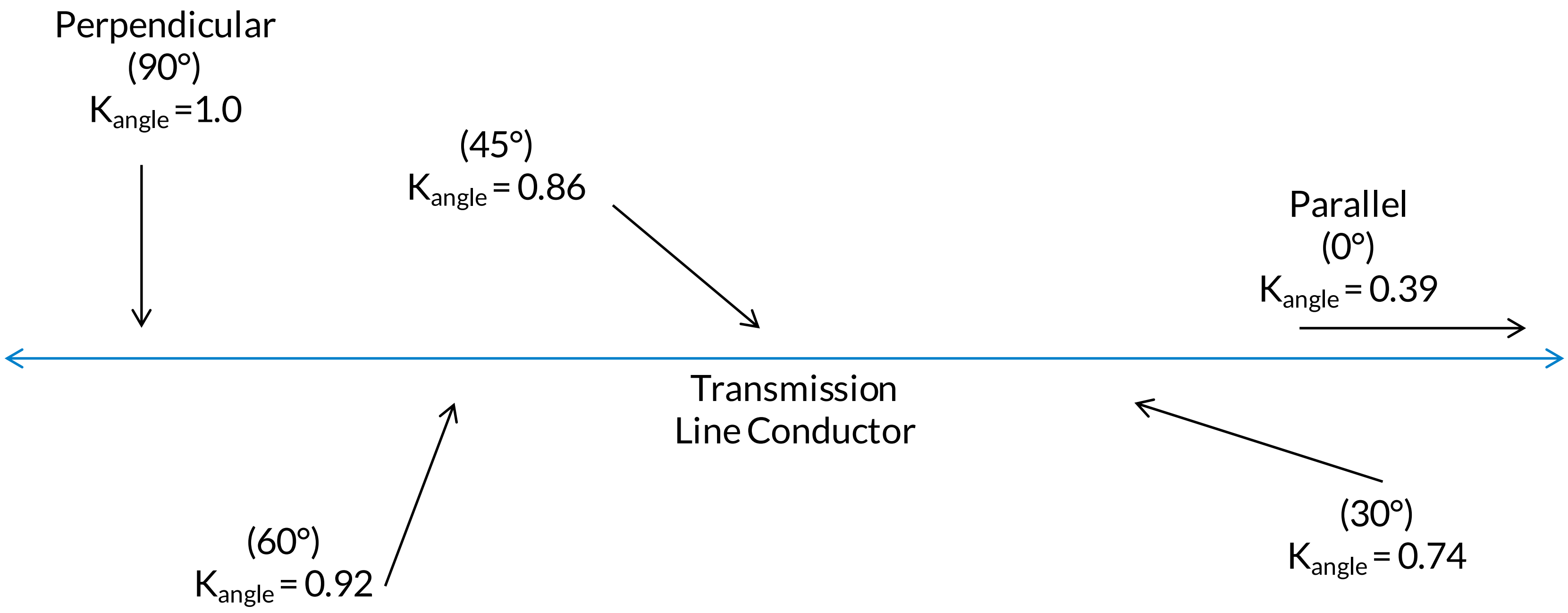
How Conservative are Thermal Rating Assumptions?, continued

- For wind speed, a conservative approach would be to assume zero wind speed and natural convection, and some entities have done that as a worst-case approximation.
- Most transmission owners use 2.0 Ft / sec or higher (some transmission owners in certain regions use 4.0 Ft / sec or even higher wind speeds).
- A 2.0 ft / sec wind speed may not be considered conservative in the summer, where wind speeds are often lowest during the highest temperatures (still air), which is also the time when loading is the highest.
- Wind direction assumptions are often <u>not worst case</u>, but instead represent the <u>best-case scenario</u>, and this practice justifies the use of lower wind speeds in most cases.

Impact of Wind Direction Relative to Conductor Direction on Convective Heat Removal

- In the IEEE 738 standard, the convective heat removal from a conductor due to wind is a function of the angle between the wind direction and the conductor direction.
- Highest convective heat removal due to wind occurs when the wind direction is perpendicular to the line.
- Lowest convective heat removal due to wind occurs when the wind direction is parallel to the line and is about 38.8% of the convective heat removal due to wind when the wind direction is perpendicular to the line.
- For other wind direction angles relative to the line, the convective heat removal is at an intermediate value depending on the angle between the wind direction and line.
- Many facility rating methodologies assume perpendicular wind direction, which is a best-case assumption, but such an assumption is OK if wind speed assumption are conservative (e.g., 2.0 Ft / sec).

Impact of Wind Direction on Convective Heat Rejection



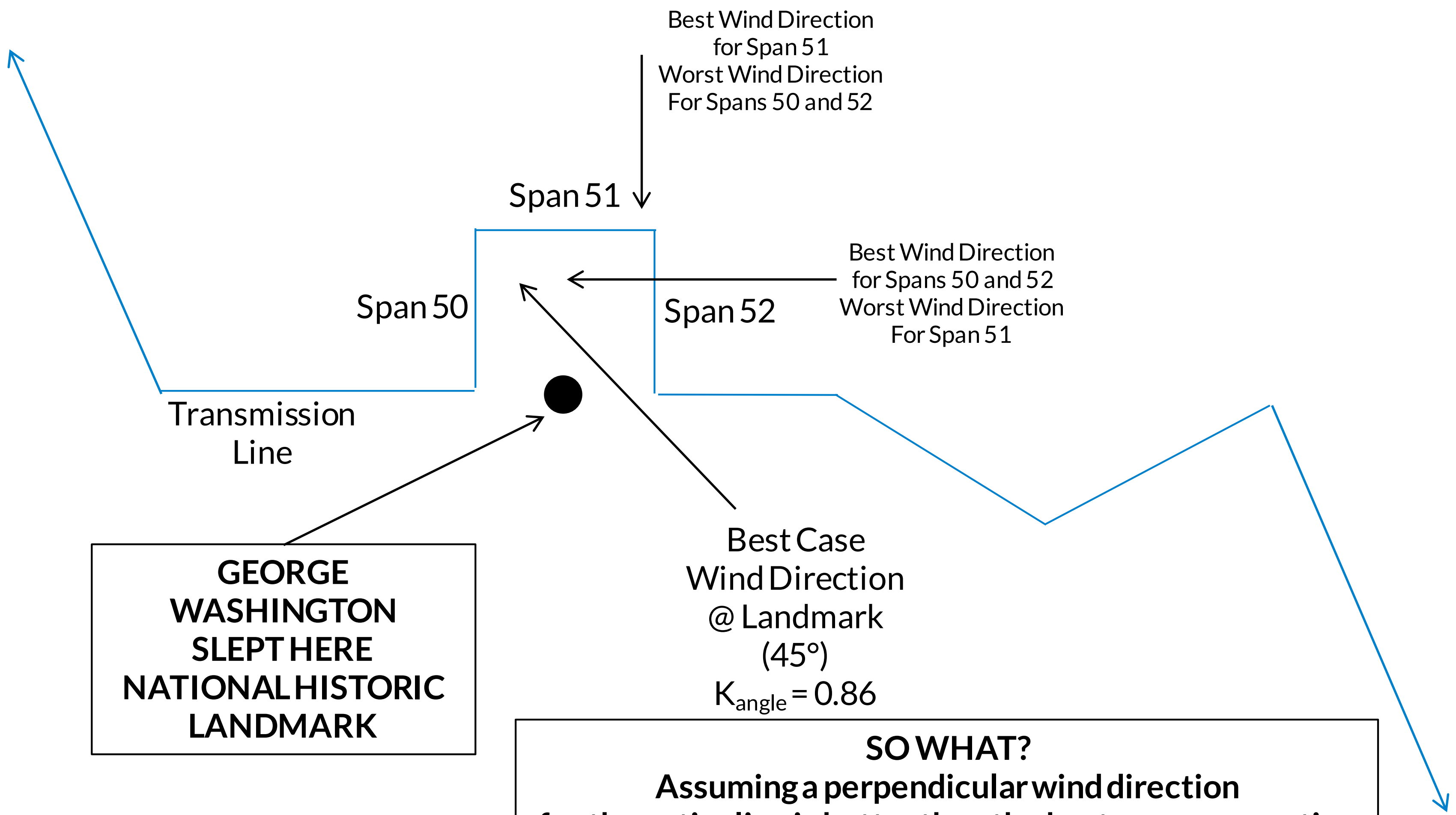
IEEE 738-2012 Wind Direction Factor = $K_{angle} = 1.194 - \cos(\phi) + 0.194\cos(2\phi) + 0.368\text{Sin}\,(2\phi)$

where ϕ = Angle between wind direction and conductor direction

Be Cautious with Wind Speed and Wind Direction Assumptions

- As indicated, a typical industry practice (although not universal) is to assume best-case wind direction (perpendicular) and conservative wind speeds (2.0 Ft / Sec or lower).
- It is important to note that both wind speed and wind direction vary both with time and location
- It is important to also note that at low wind speeds, turbulence will likely ensure wind direction is not completely parallel to the conductor.
- It is also important to note that conductor direction also varies. That is, most lines are not straight, but often change direction.
- Therefore, it is rare that the wind direction will be perpendicular to the conductor, but also rare that it will be parallel.
- Given a chain is only as strong as a its weakest link, some caution should be exercised in making wind speed and wind direction assumptions.
  - CAVEAT. Wind speeds vary along the conductor, and average wind speed between two dead-end structures is the driver for sag limited lines, not lowest wind speed.

Typical Transmission Line Example



SO WHAT?
Assuming a perpendicular wind direction for the entire line is better than the best-case assumption (basically impossible), so such assumptions should be coupled with conservative wind speed assumptions.

Part 4
VOLTAGE AND STABILITY RATINGS

Voltage and Stability Ratings

Related to the maximum power transfer limits, sometimes there are voltage and stability ratings applied, either to transmission branches or to transmission interfaces, to ensure operation of the transmission system in a manner that mitigates the risk of a voltage or angular stability issue.

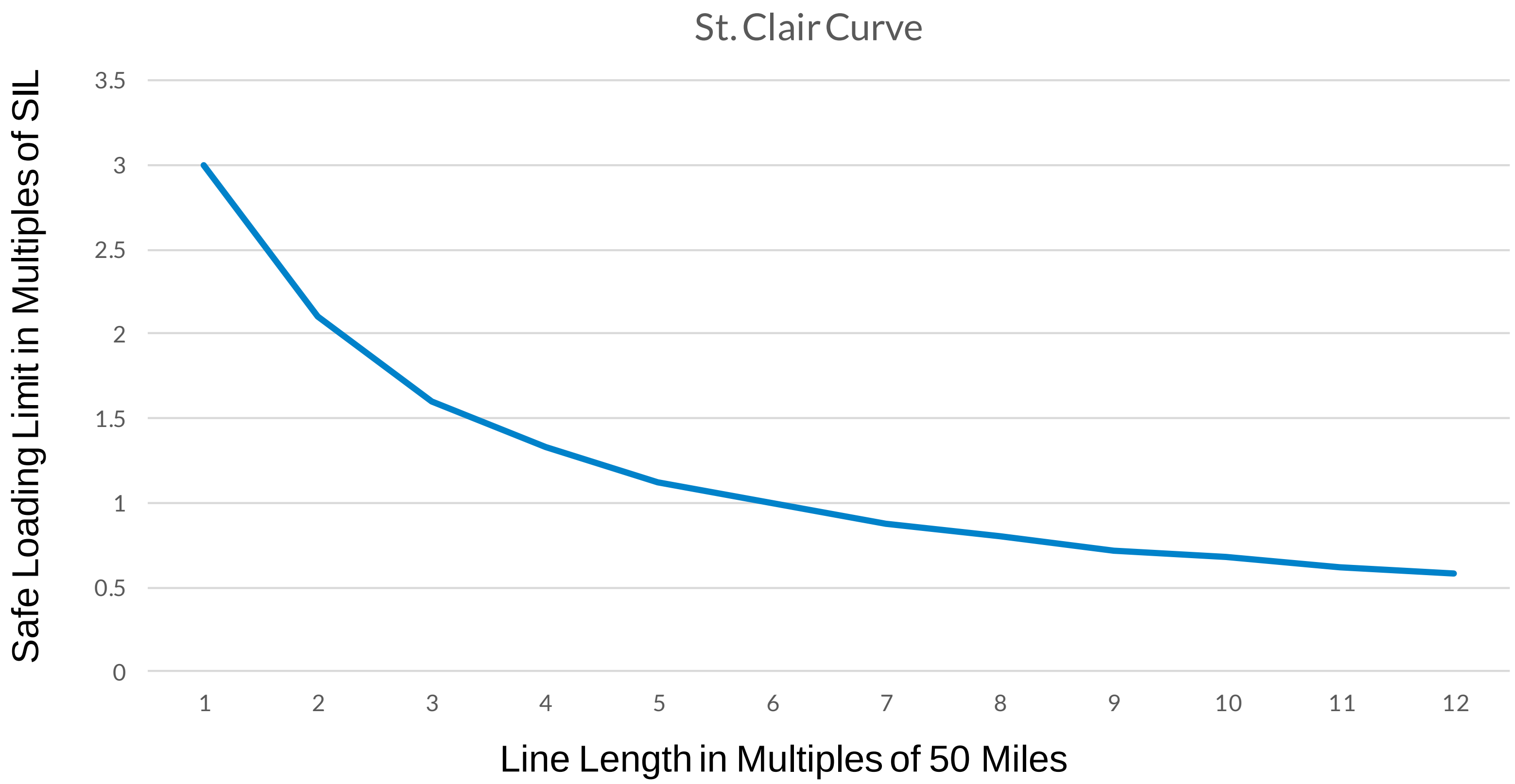
Unlike maximum power transfer limits, voltage and stability limits are soft limits.

Most transmission branches and/or transmission interfaces have no such ratings, but some do.

Often these ratings are informed by voltage stability analysis and/or angular stability analysis that suggests a safe operating limit.

Another option for voltage and stability ratings are ratings interpolated from the St. Clair Curve which suggests a safe loading limit based on the length and SIL of a line. This could serve as a screening limit to trigger additional investigation.

St. Clair Curve**



**Dunlop, R.D., Gutman, R., Marchenko, P.P., *Analytical Development of Loadability Characteristics for EHV and UHV Transmission Lines*, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 2, March/April 1979.

Example – Voltage and Stability Safe Loading Limit From St. Clair Curve

Consider a hypothetical 345 kV Line:

• Length:	150 Miles
• Thermal Rating:	1792 MVA
• Surge Impedance Loading:	430 MW

- From the St. Clair Curve, maximum safe loading for a 150 Mile line is at 1.6 x SIL.
- Since the SIL is 430 MW, the voltage and stability safe loading limit would be:
  - 1.6 x 430 MW = 688 MW (about 38.4% of thermal limit)
- The voltage and stability limit is a soft limit that simply suggests loading above 688 MW could incur some additional risks related to voltage and/or stability.
- The St. Clair curve uses a 5% voltage drop and 30% steady state stability margin (which is 70% of $MPTL_{Branch}$). Alternative parameters could be used.

Example – Voltage and Stability Safe Loading Limit From St. Clair Curve

Consider a hypothetical 765 kV Line:

• Length:	150 Miles
• Thermal Rating:	6625 MVA (Roughly 3.7 x 345 kV)
• Surge Impedance Loading:	2390 MW (Roughly 5.6 x 345 kV)

- From the St. Clair Curve, maximum safe loading for a 150 Mile line is at 1.6 x SIL.
- Since the SIL is 2390 MW, voltage and stability safe loading limit would be:
  - 1.6 x 2390 MW = 3824 MW (about 57.8% of thermal limit)
- For longer lines, 765 kV can be loaded at a higher percentage of the thermal limit than 345 kV under the St. Clair Curve loadability guide.
- So while a 765 kV thermal rating is 3.7 times the 345 kV thermal rating, a 765 kV voltage and stability rating (based on St. Clair Curve) is 5.6 times the 345 kV voltage and stability rating for any line length.

MISO

Summary of St. Clair Curve Voltage and Stability Ratings

- Voltage and stability ratings from the St. Clair Curve are soft ratings and loading above such limits is not prohibited.
- However, such limits are indicative of a loading risk inflection point and would be a good check against thermal ratings established for long lines.
- Such ratings would be particularly useful for long lines where AARs and DLRs are being utilized or when winter seasonal ratings are being utilized.

Part 5
RATING SPECIFICATION VS. RATING SCOPING

Rating Specification

- It is important to distinguish between rating specification and rating scoping.
- Rating specification is the calculation, specification and/or determination of the rating magnitude and supporting facility rating methodology.
- Rating specification is delegated to the asset owner by NERC FAC 008
- The asset owner is in a unique position to perform rating specification due to:
  - Knowledge of asset design and capabilities
  - Knowledge of facility and equipment condition
  - Knowledge of ambient conditions in the vicinity of the facility
  - Asset owners assume the risks of asset operation, and thus are the entities that determine how best to manage risk. Rating specification is an important part of risk management.

MISO

Rating Scoping

- Rating scoping is the determination of overall rating structure.

- Examples of rating scoping activities include:
  - Determining the number of seasonal rating sets to be used per year
  - Determining standard rating durations for emergency ratings
  - Determining if and how many emergency ratings are needed per branch
  - Determining how normal vs. emergency ratings are applied.
  - Determining if time-of-day ratings are needed based on dispatch patterns

- Rating scoping could be a joint responsibility between the asset owners, the system planners and the system operators.

- For example, operations and planning personnel could have a say in:
  - How many seasonal ratings sets are developed
  - How many emergency ratings are required per facility
  - The required emergency rating durations to facilitate system adjustments

- However, once the ratings are scoped, the asset owner is the entity that determines the rating magnitude.

Part 6

RATING DURATIONS

Thermal Rating Durations

Normal ratings are continuous ratings and should have no duration limits.

Emergency ratings are applicable to emergency conditions and often have duration limits.

The loss-of-life impacts that excessive thermal loading will have on a facility are cumulative, but a duration limit is per occurrence.

However, if a standardized duration limit is set based on the time required to make system adjustments, then the asset owner can specify a rating magnitude based on a predetermined duration limit by considering:

- The predicted frequency of events that allow for the use of emergency ratings.
- The probability that ambient conditions and load levels will drive loading above the normal ratings during such events.
- The useful life and current condition of the facility.
- The maximum allowable cumulative impact on facility life over the projected life of the facility.

Thermal Rating Durations Standardization

- A standard emergency rating duration can be developed based on the amount of time required to:
  - Redispatch generation based on typical ramp rates and redispatch magnitudes
  - Start up, synchronize and ramp up quick-start generation including notification times
  - Notification time for topology changes and/or load shed.
  - Implementation time for topology changes and/or load shed.
  - NOTE: Implementation times for topology changes and/or load shed that require field switching should include allowance for crew redirection time, crew travel time and switching time.

- A standard emergency rating duration of four (4) hours is typical, but such duration limits could be longer or shorter.

- If the duration limit is standardized and determined first, the asset owner can then specify the rating magnitude accordingly based on an overall risk assessment.

- When normal and emergency ratings are the same, rating duration limits do not exist for emergency ratings and post contingent system adjustments would not be allowed.

Part 7
SEASONAL, TIME-OF-DAY, AMBIENT ADJUSTED AND DYNAMIC LINE RATINGS

Seasonal Ratings

- Seasonal ratings account for the fact that seasons with lower ambient temperatures can tolerate higher loading for a given maximum allowable conductor temperature than seasons with higher ambient temperatures.

- That is:
  - heat removal due to convection and radiation is a function of the temperature difference between the conductor temperature and the ambient temperature, and
  - lower ambient temperatures will induce higher heat removal rates for a given set of maximum allowable conductor temperatures,
  - which allows for higher electrical loading (higher I^2R heat injection) to maintain the conductor temperature at the maximum allowable conductor temperature.

- Transmission owners have historically used summer and winter ratings sets to account for differences in ambient temperatures between the summer and winter seasons

- Today, four seasonal rating sets are sometimes used, which provides more granularity in considering ambient temperature variations throughout the year.

Time-of-day Ratings

Another potential way to expand rating sets is the use of day-time vs. night-time ratings for each season.

- During night-time hours, temperatures are lower, wind patterns are different, and solar radiation does not cause heat injection into conductors, thus there is the potential for higher ratings at night than during the day for a given season.
- Historically higher ratings at night were only marginally useful, but in the future where much of the energy is supplied by renewable resources, dispatch patterns at night, which may be dominated by wind output, will be very different from dispatch patterns during the day, where solar will play a larger role.
- For example, today wind generation at night may be curtailed based on ratings that were designed around day-time conditions, and this could be mitigated via the use of day-time and night-time rating sets for each season.
- Using time-of-day ratings in lieu of ambient adjusted ratings and dynamic line ratings aligns with the "80/20 rule" where you can get much of the benefit of AARs or DLRs without making the investment in equipment to monitor ambient conditions or transmission line sag.

Ambient Adjusted Ratings & Dynamic Line Ratings

- **Ambient Adjusted Ratings (AARs)** allow for real-time adjustments to ratings based on actual weather conditions, primarily temperature, but possibly wind speed and direction as well as solar radiation levels if there is sufficient equipment to monitor such parameters.
- **Dynamic Line Ratings (DLRs)** allow for real-time adjustment to ratings by monitoring the sag and/or tension of transmission line conductors to estimate ratings.

- These methods are useful in real-time operations where real-time data is available on actual weather conditions or system conditions.
- In planning and forward operational studies, these methods are more problematic because data on ambient and facility conditions is not available and cannot be accurately predicted, particularly for long-term planning.
- The old saying "Plan for the worst and hope for the best" describes the way in which ambient adjusted ratings and dynamic line ratings should be applied.
  - If such ratings provide opportunities to reduce congestion and/or enhance operational flexibility in real-time, that is a good thing,
  - but in the planning horizon, it would be better to use seasonal ratings or seasonal ratings with time-of-day components to ensure reliability, robustness and resilience.

Cautions when using AARs and DLRs

- AARs and DLRs can provide specific cost and reliability benefits in real-time operations, but they can provide false reassurance in forward studies and long-term planning, so their application is generally limited to real-time operations.
- Even when used in real-time operations, weather conditions can change quickly, and some AARs and DLRs could be volatile, making it more challenging to operate the system within constraints.
- As stated earlier, seasonal ratings are not always calculated with worst-case assumptions, so there could be times where AARs and DLRs will be more constraining than seasonal ratings, particularly when wind direction is monitored, although the AAR or DLR may be the more accurate rating.
- On longer lines and areas where system strength is more of an issue, AARs and DLRs could push real-time thermal limits toward absolute limits.
- There is some cost to applying AARs and DLRs on specific facilities (monitoring equipment), so consideration should always be given to using more granular seasonal ratings sets, which include time-of-day components.

Questions?

Contact for more information