Discussion of Legacy, 765 kV, and HVDC Bulk Transmission

ERCOT EHV and HVDC Workshop
June 26, 2023

Purpose & Key Takeaways

- Purpose: This presentation discusses the various pros and cons of various transmission voltage levels and characteristics.

Key takeaways:

- When new bulk transmission facilities are required, there are pros and cons to each of the transmission solution choices: 345 kV, 765 kV, HVDC
- An "All Things Considered" strategy where a diverse set of new transmission strategies is considered will result in the best overall transmission system.

Key Comparisons: 345 kV, 765 kV, and HVDC

	345 kV	765 kV	HVDC
Incremental Need	Pro		
Cost per MW-Mile[1]		Pro	
Land Use per MW-Mile		Pro	Pro
Flow Control[2]			Pro
Long Distance Transmission Capabiliy[3]	Good	Better	Best
Contingency Impact	Pro		
Transmission Losses		Pro	Pro

Notes:
1) Pro for HVDC on very long lines
2) Flow control not needed everywhere and sometimes may be undesirable
3) Long distance transmission capability is best on HVDC and proportional to voltage on AC

Comparison of **Typical** 345 kV, 765 KV and HVDC Preferred Applications - There are Exceptions

Transfer Level \ Transfer Distance	Short	Intermediate	Long
High	765 kV	HVDC 765 kV	HVDC
Intermediate	345 kV 765 kV	765 kV	HVDC 765 kV
Low	345 kV	345 kV 765 kV	765 kV

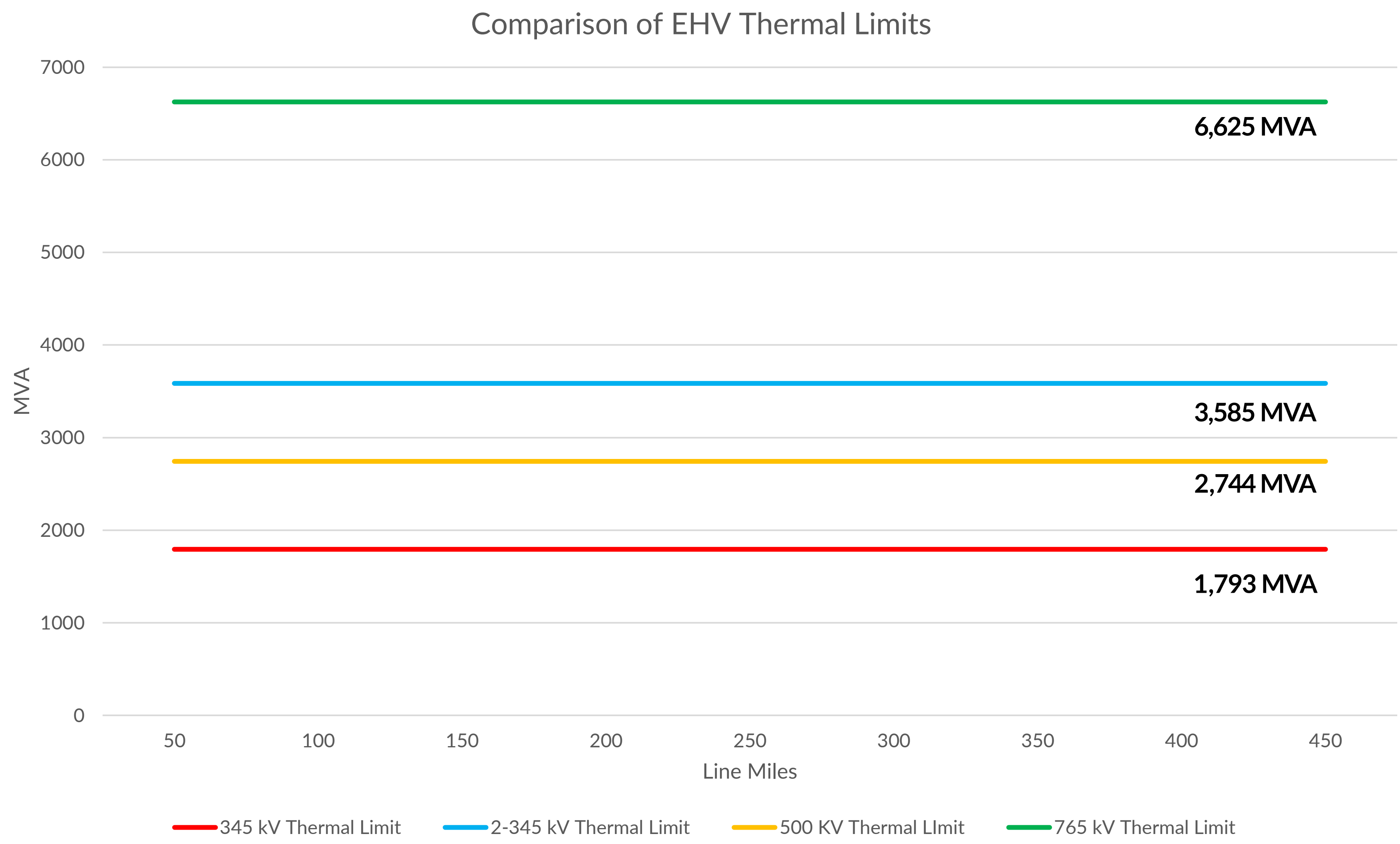
Transmission Limits

Types of Transmission Line Limits

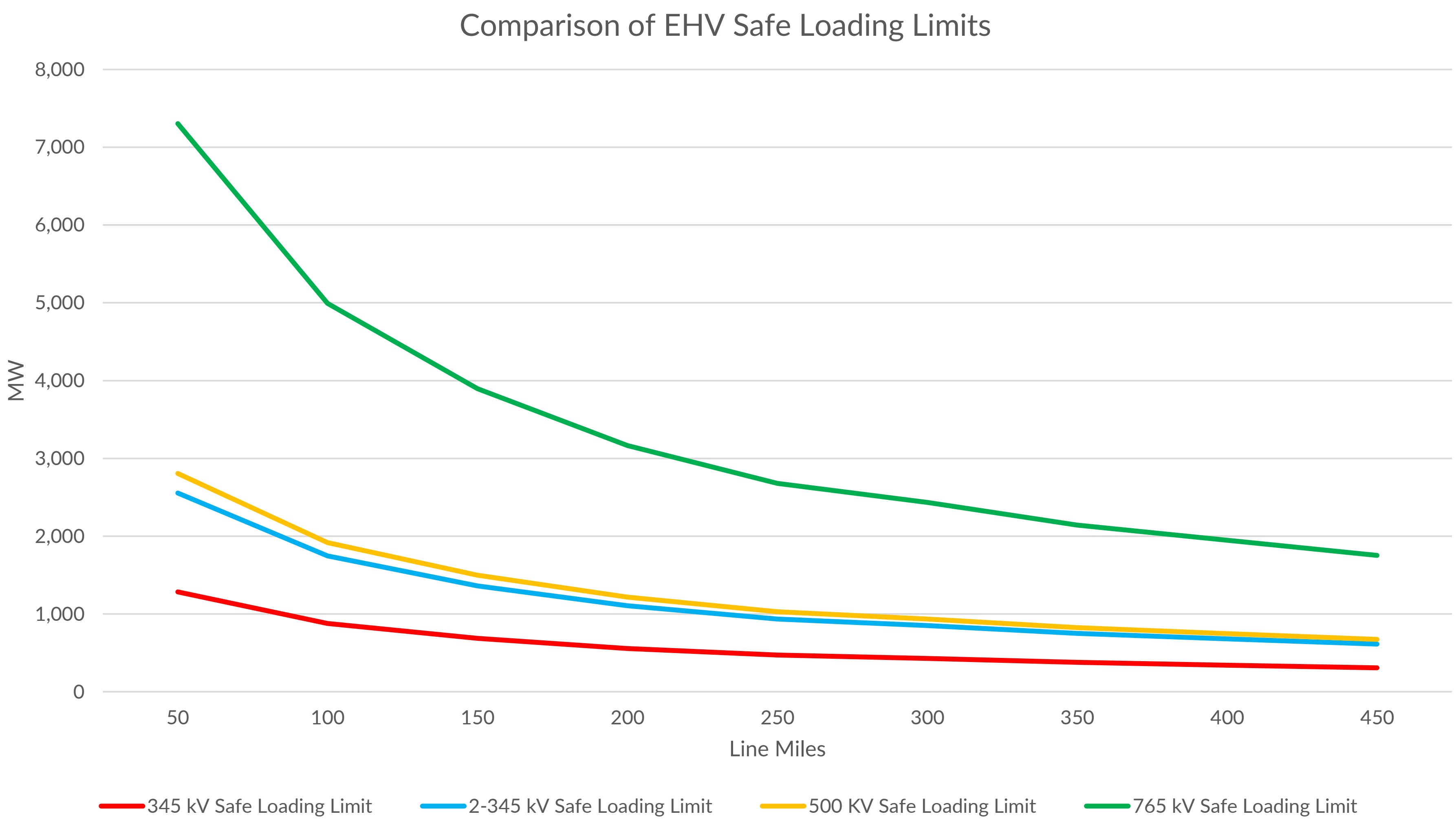
Thermal Limits	Safe Loading Limits	Absolute Limits

• Applies to both AC and HVDC transmission lines
• Driven by facility temperature limits
• Independent of line length.
• Compliance and/or risk mitigation limit.
	• Applies only to AC transmission lines
	• Driven by operational risk management targets
	• Safe loading limits decrease as line length increases.
	• Risk mitigation limit.
	• Based on St. Clair Curve developed by AEP – See Appendix 3
		• Applies to both AC and HVDC transmission lines
		• The lesser of:
		    • Maximum Power Transfer Limit
		    • Relay Trip Limit
		• Based on maximum angular displacement (AC) or maximum allowable voltage drop (HVDC) – See Appendix 2
		• Absolute limits decrease as line length increases.
		• Physical limit – Cannot be exceeded for any duration.

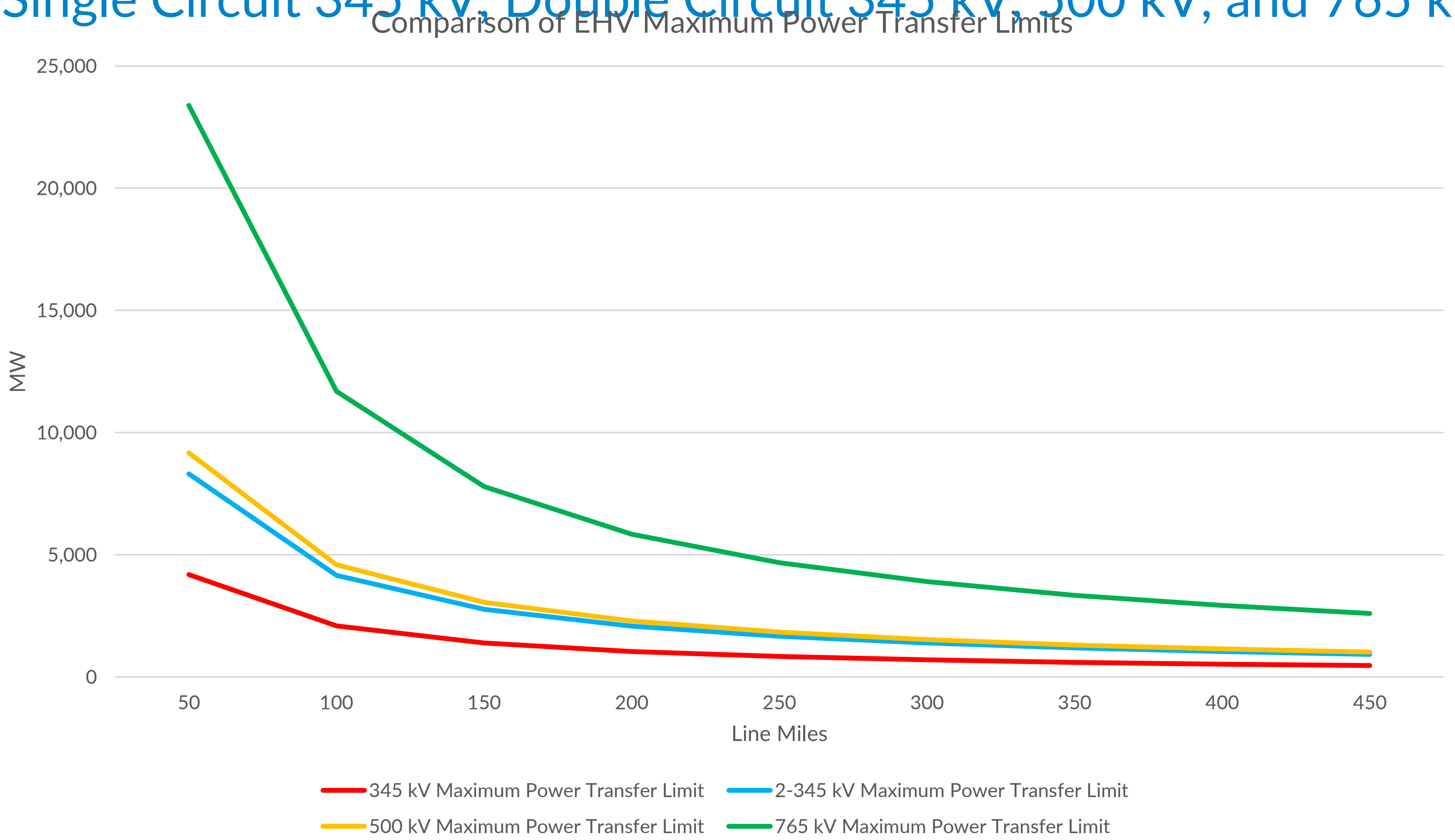
Comparison of **Typical** EHV Line Thermal Limits: Single Circuit 345 kV, Double Circuit 345 kV, 500 kV, and 765 kV



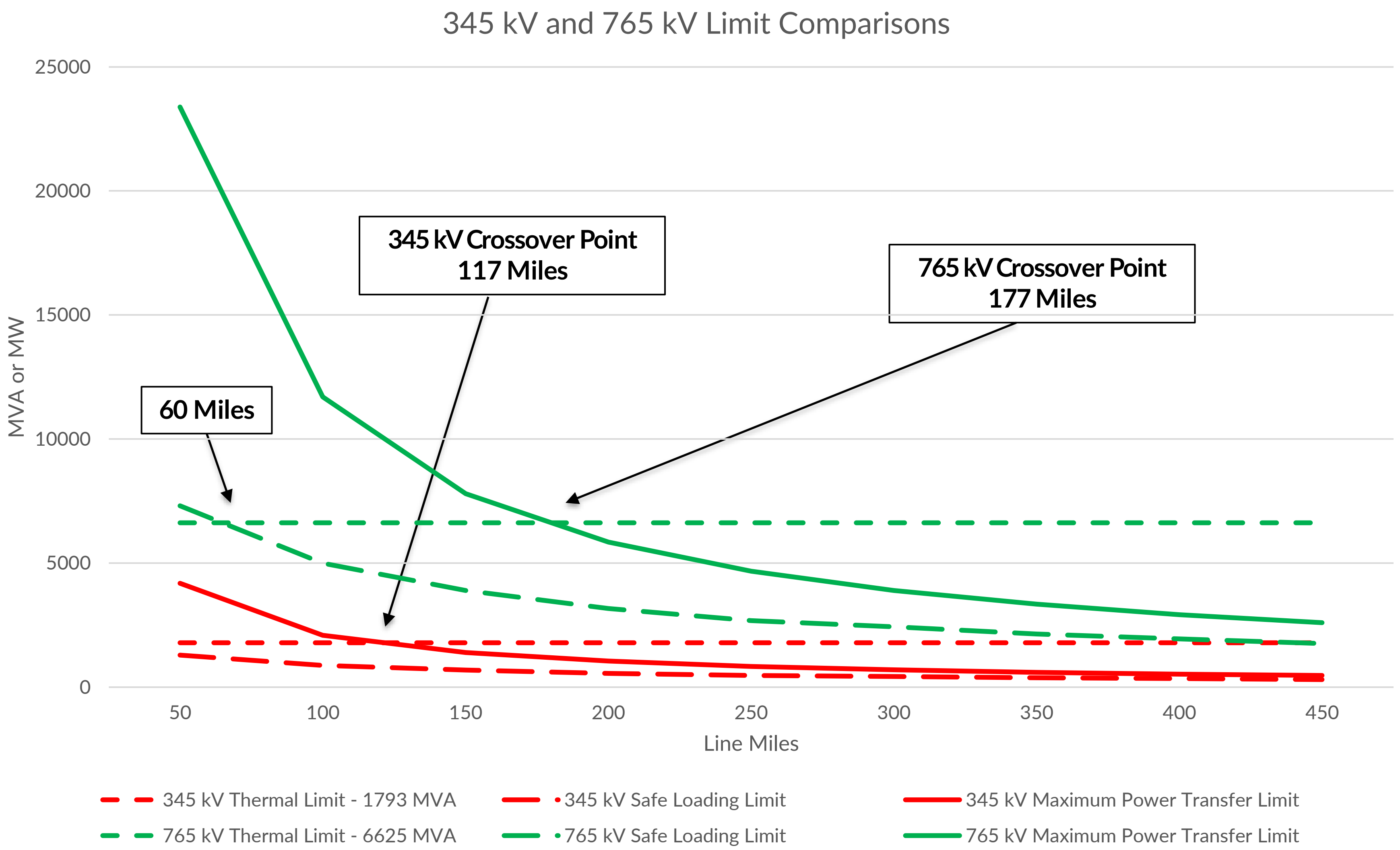
Comparison of **Typical** EHV Line Safe Loading Limits: Single Circuit 345 kV, Double Circuit 345 kV, 500 kV, and 765 kV



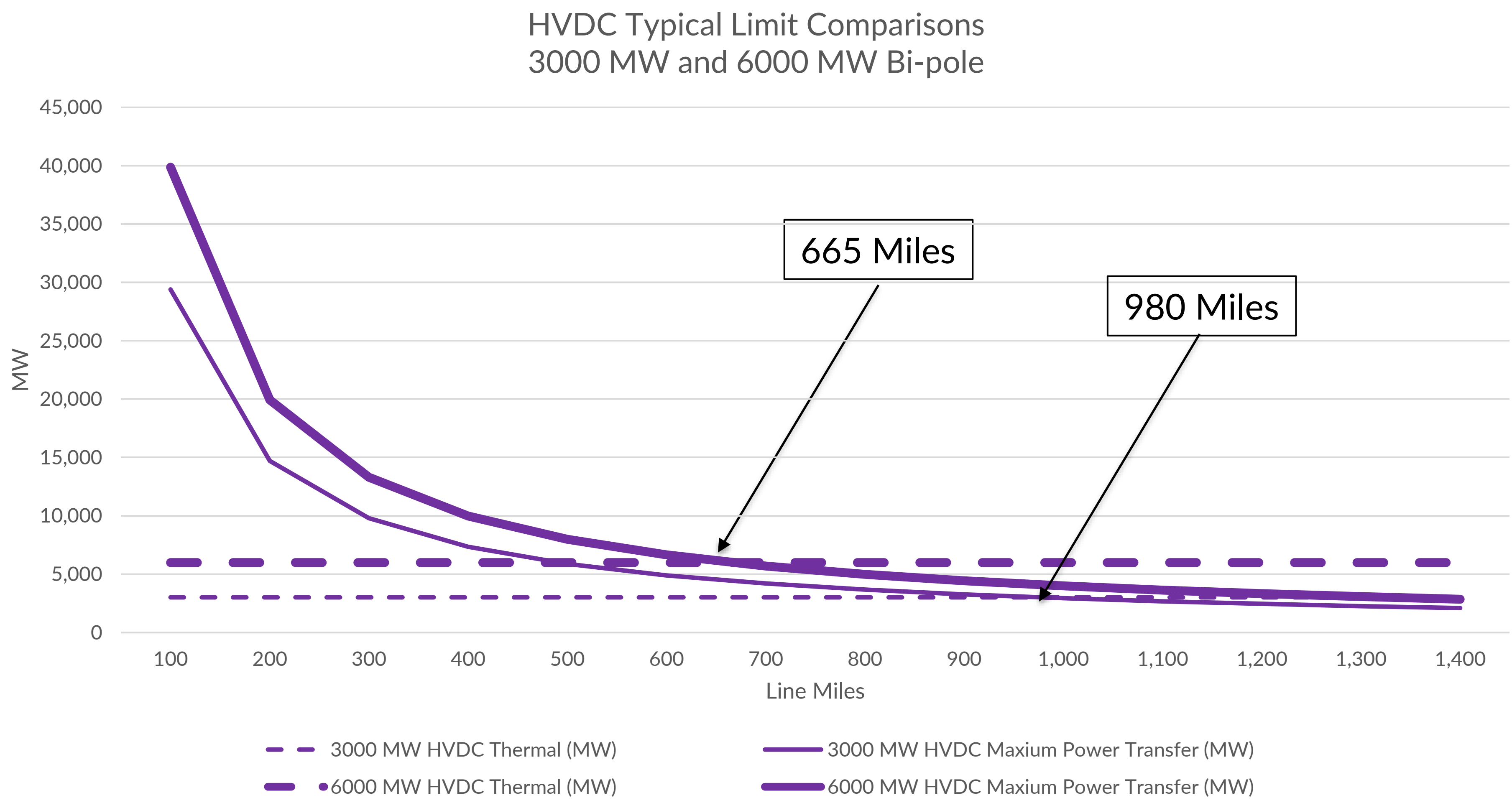
Comparison of **Typical** EHV Line Maximum Power Transfer Limits: Single Circuit 345 kV, Double Circuit 345 kV, 500 kV, and 765 kV



Comparison of **Typical** EHV Line Limit Curves: Single Circuit 345 kV and 765 kV



Comparison of <u>**Typical**</u> +/- 640 kV HVDC Limits 3000 MW and 6000 MW Bi-pole

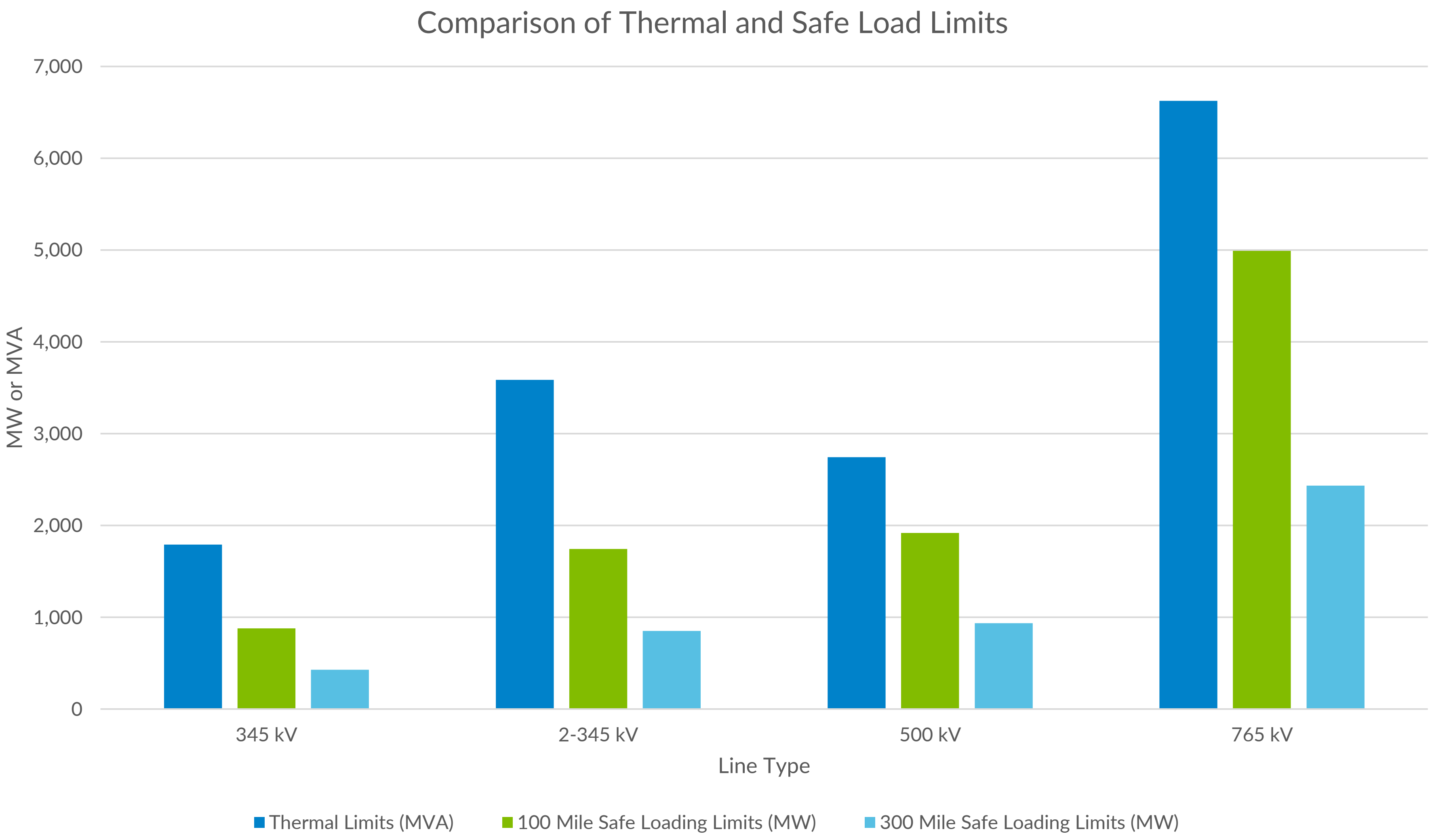


Comparison of Legacy Bulk Transmission with 765 kV

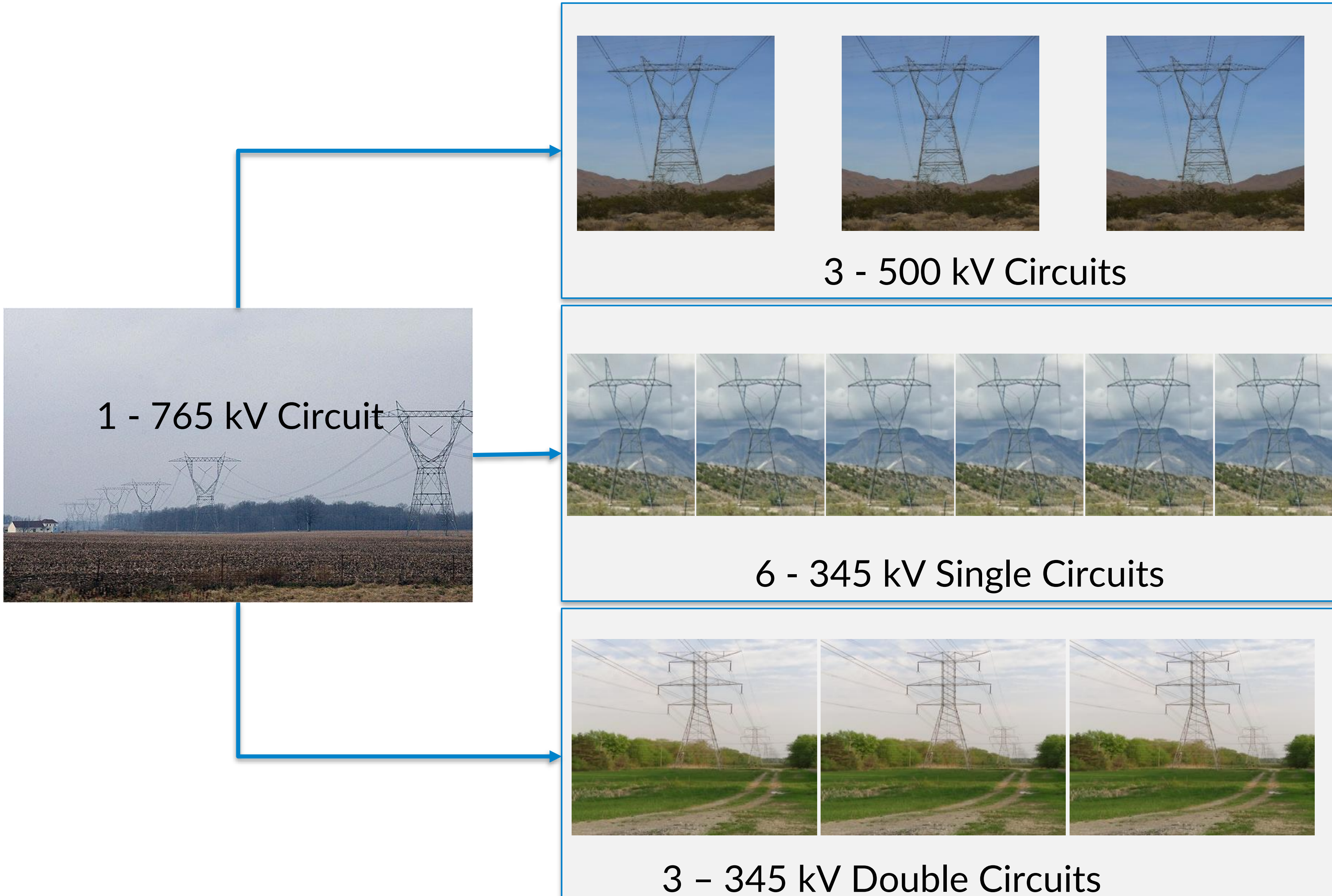
Key Takeaways for Comparison of Legacy Bulk Transmission with 765 kV

- The benefits of 765 kV transmission over 345 kV transmission options include the following:
  - Lower capital cost per MW-mile
  - Lower land usage per MW-mile
  - Fewer circuit miles required
  - Lower energy and capacity losses
- The benefits of 345 kV transmission over 765 kV include the following:
  - Lower impact of contingencies
  - Better suited to serve incremental needs when system change is not great

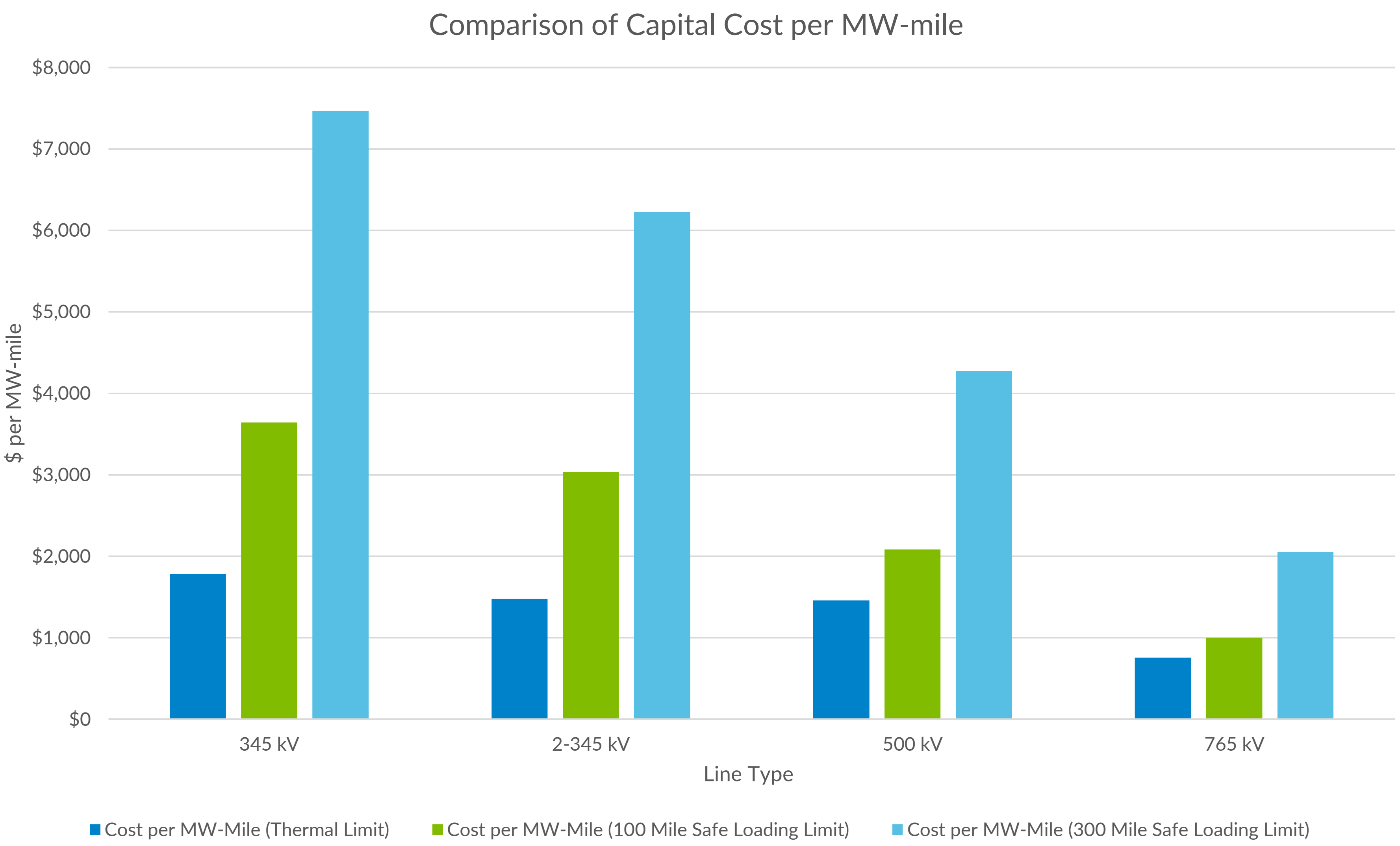
Comparison of Thermal and Safe Loading Limits
765 kV, 500 kV, Single-circuit 345 kV, Double-circuit 345 kV



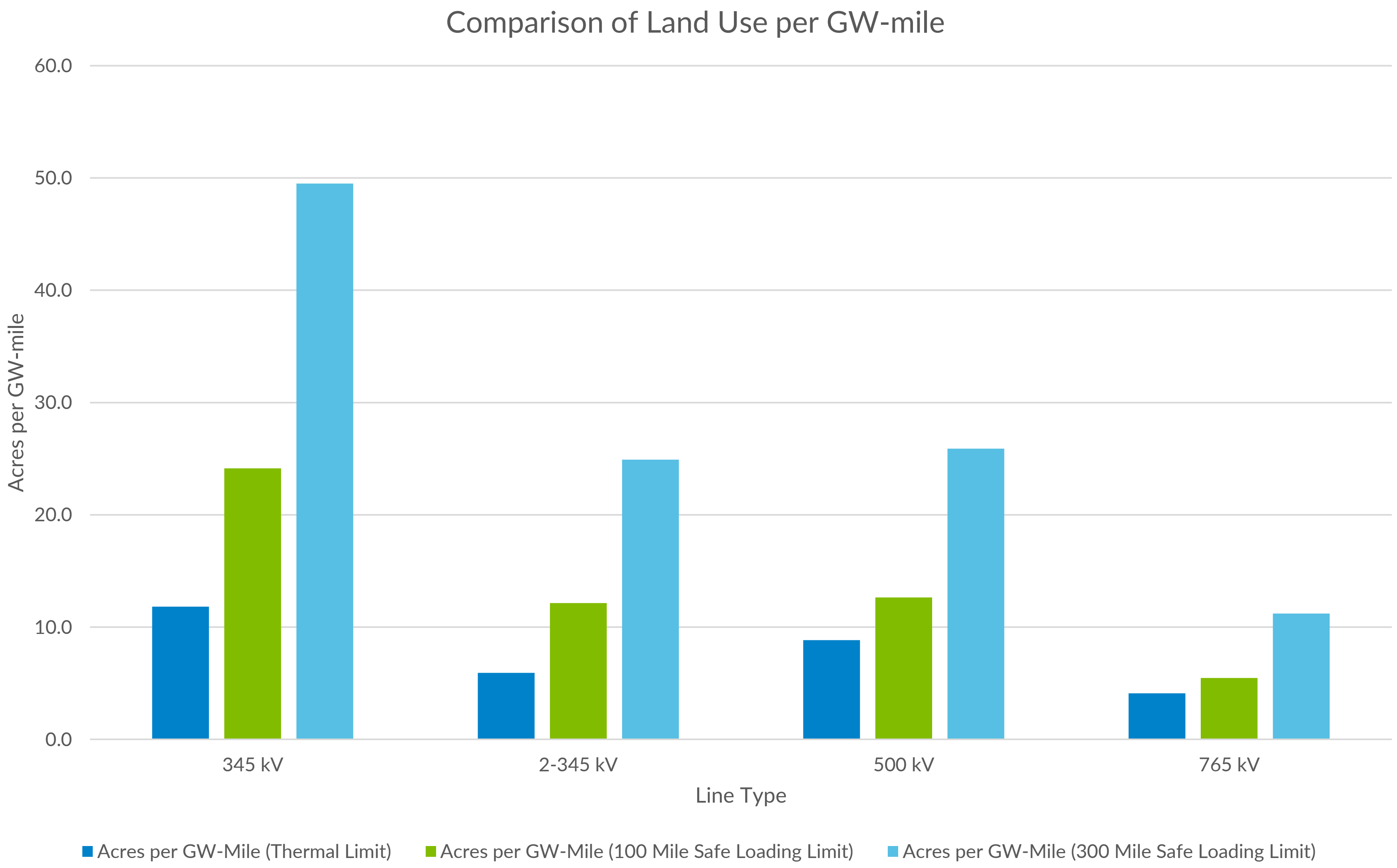
Based on the Previous Slide, from a Safe Loading Limit standpoint:



Comparison of Capital Cost Per MW-Mile ($ per MW-Mile)



Comparison of Land Use Per GW-Mile (Acres per GW-Mile)



Contingency Impacts

- The impact to the system of the loss of a 765 kV transmission line can be greater than the impact to the system of a loss of a legacy EHV line (345 kV, 500 kV, etc.).

- Therefore, using 765 kV for just one or two lines may not bet the best choice since the system must be planned to operate with the loss of up to two EHV AC lines (i.e., NERC TPL P6 contingency).

- However, if a commitment is made to establish a regional backbone at the 765 kV level and such a backbone can be justified, then the contingency impacts of 765 kV are typically fully mitigated.

Transmission Losses

- Transferring a fixed amount of power via higher voltage reduces current proportionally, and since most transmission losses are load losses proportional to the square of current, use of higher voltage transmission has a significant advantage in terms of energy and capacity loss reduction.

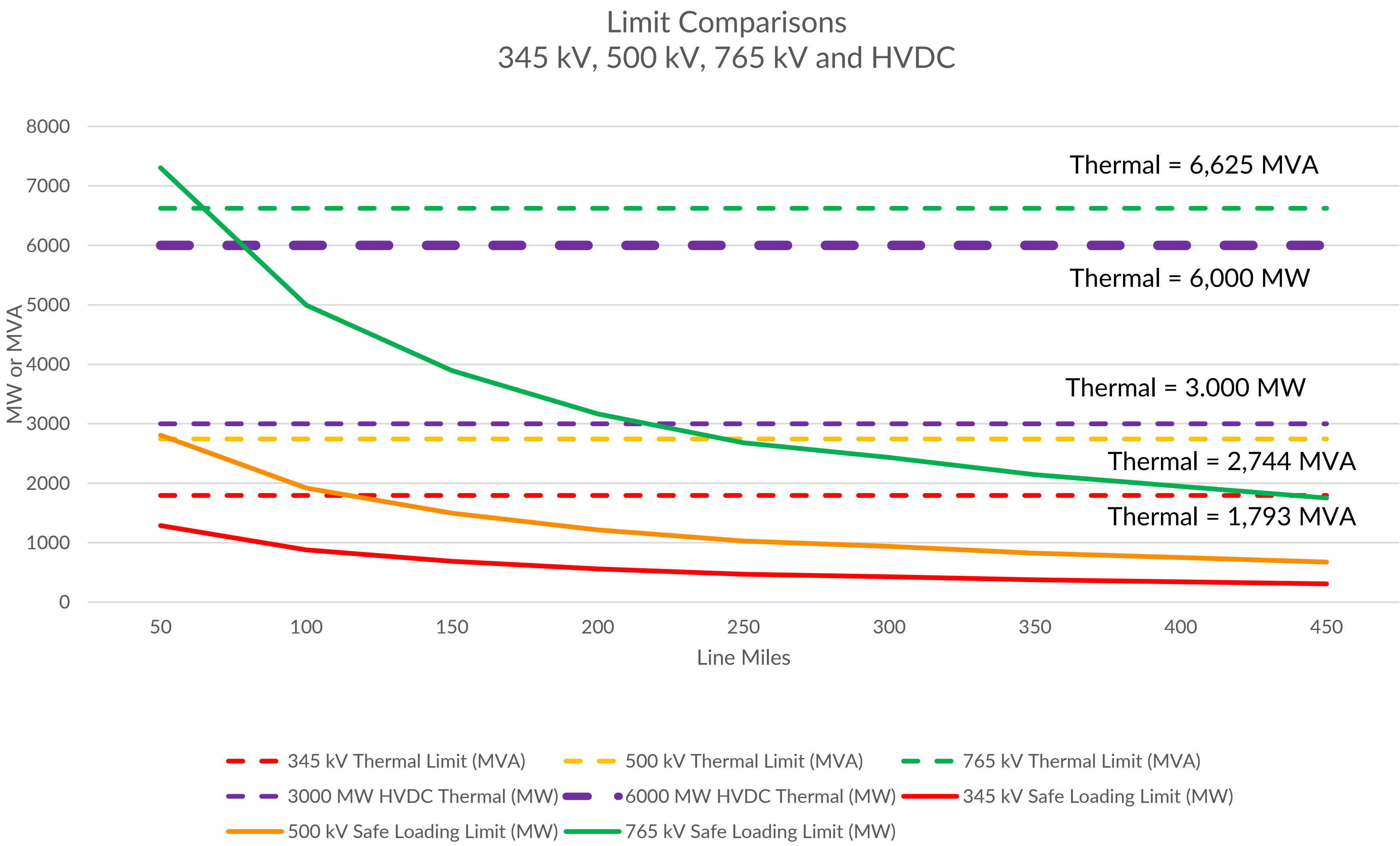
	345 kV	765 kV
Number Circuits	12	2
Circuit Length (Miles)	100	100
Thermal Capacity (MVA)	21,504	13,250
Assumed Flow (MW)	5,000	5,000
Phase Current per Circuit (A)	697	1,889
$R_{Conductor}$ (Ohms)	4.63	2.16
Capacity Losses (MW)	81	46
Annual Energy Losses (MWh)	710,374	403,628

Comparison of 765 kV with HVDC

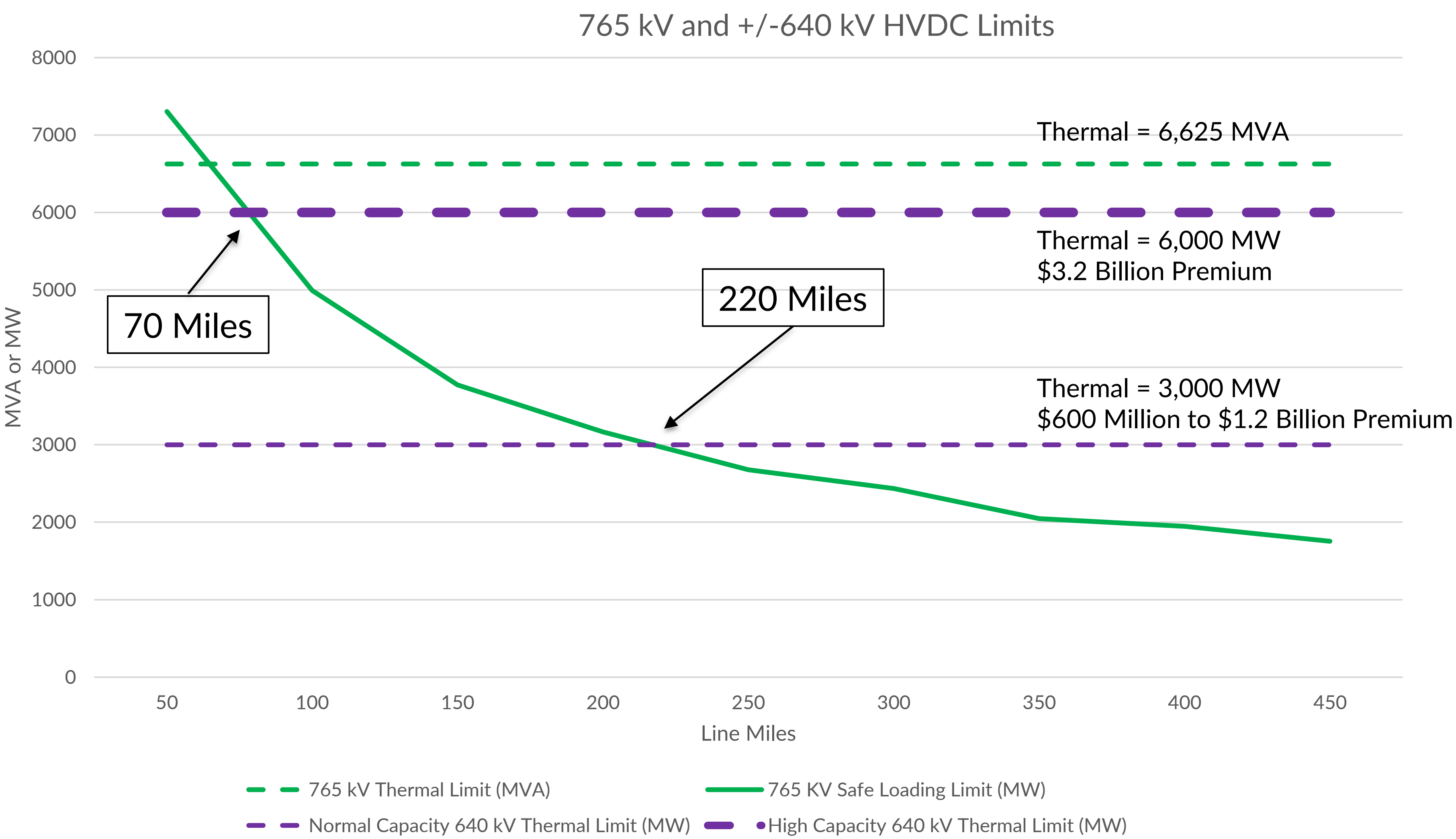
Key Takeaways for Comparison of 765 kV with +/-640 kV HVDC

- The benefits of 765 kV transmission over HVDC include the following:
  - Lower capital cost per MW-mile for line lengths below the "250 to 400 mile" range due to HVDC converter requirements.
  - Higher capability over shorter and intermediate distances due to higher thermal rating.
  - Natural flow response when desired
- The benefits of HVDC transmission over 765 kV include the following:
  - Flow control capabilities when desired or needed
  - Lower capital cost per MW-mile for line lengths above the "250 to 400 mile" range.
  - Higher capability over longer distances due to much higher maximum power transfer capabilities
  - Flexible reactive power support with no net reactive power consumption (VSC)

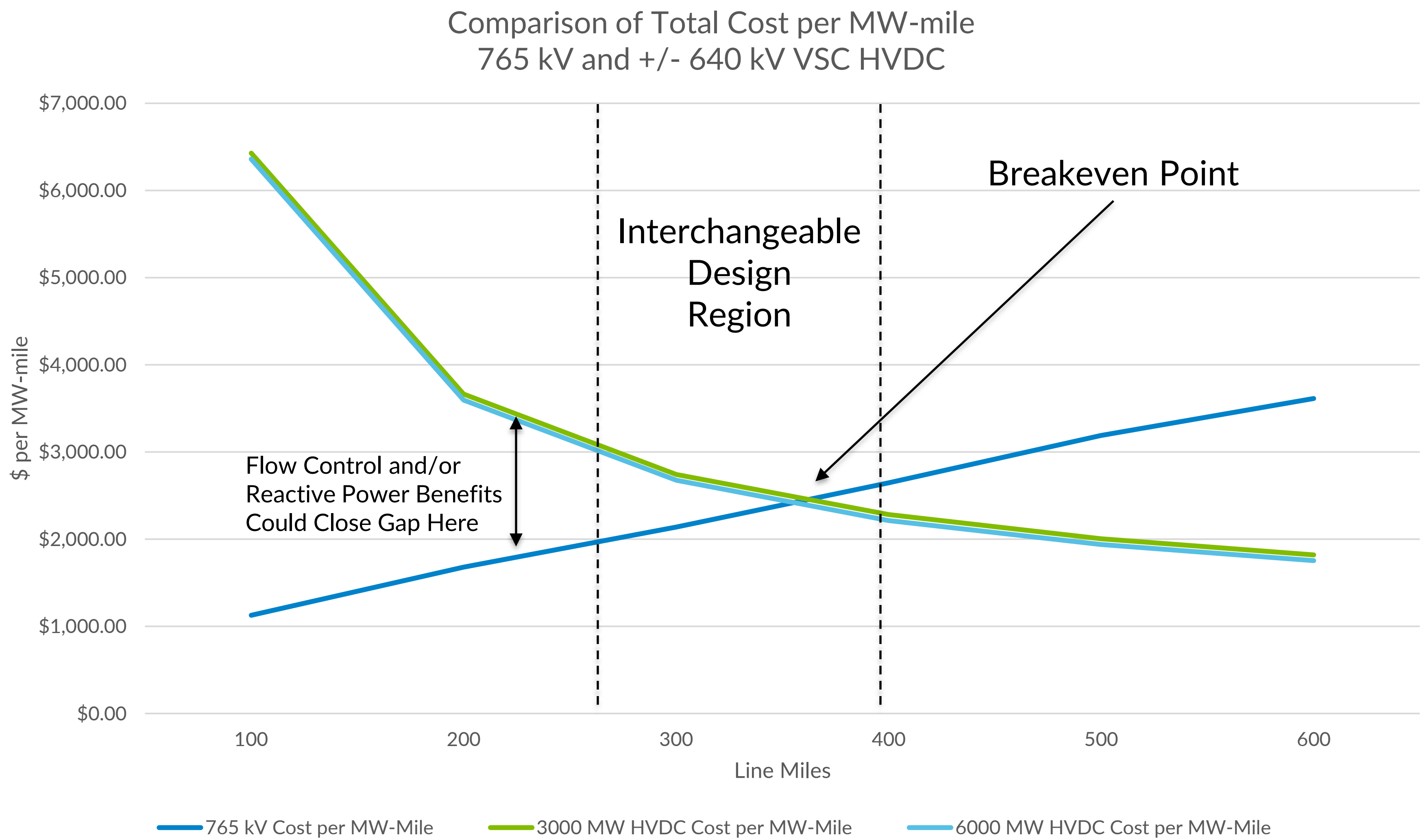
Comparison of **Typical** 345 kV, 500 kV, 765 kV and HVDC Limits



Focus in on Comparison of **Typical** 765 kV and HVDC Limits



Comparison of Typical Total Cost per MW-mile for Various Line Lengths - 765 kV vs. +/- 640 kV VSC HVDC



Flow Control Benefits of HVDC

- HVDC has the potential to provide substantial flow control benefits when dispatched automatically and co-optimized with resource dispatch.
- Challenges may persist and undermine potential flow control benefits when multiple HVDC bi-poles exist and schedules must be manually coordinated to follow potential volatile dispatch of renewable resources.
- Flow control is most desirable when HVDC is built in parallel with underlying AC lines and the HVDC bi-pole can be controlled as necessary to remove congestion from the AC parallel lines up to the maximum flow limit of the HVDC bi-pole.
- Flow control is less beneficial when there are shifts in resource output from one region to the next (e.g., from south of the load to north of the load. from east of the load to west of the load, etc.).
  - AC flows will adjust naturally as resource output shifts.
  - HVDC schedules have to be changed, either manually, via automatic dispatch by SCED (which is still a 10-minute delay in a five-minute market or dispatch cycle) or by following phase angles at the AC terminals of the HVDC bi-pole.

HVDC Reactive Power Benefits

- Under steady state conditions, an HVDC bi-pole transmission line (not including converters) does not consume nor generate reactive power.

- Heavily loaded long AC lines and conventional Line Commutated Converter (LCC) HVDC bi-poles require substantial amounts of reactive power.
  - CAVEAT: AC lines longer than 300 miles with loading restricted to the safe load limit will be loaded below the Surge Impedance Loading level and thus the line will produce net reactive power.

- The newer Voltage Source Converter (VSC) HVDC technology eliminates reactive power consumption issues associated with heavily loaded long AC lines and LCC HVDC technologies

- Furthermore, the newer VSC HVDC technology adds reactive power control as an additional benefit at the AC terminals of the bi-pole to manage reactive power on the interconnected AC systems at each terminal.

HVDC Contingency Impacts

- HVDC contingency impacts would be comparable to those of 765 kV lines when the MW capabilities are comparable.

- It is important to note that a complete loss of an HVDC bi-pole is actually an N-2 contingency. A plus for HVDC

- It is also important to note that an HVDC bi-pole has only two conductors, thus the conductor exposure is two-thirds that of 765 kV on a per circuit mile basis. A plus for HVDC

- On the other hand, unlike EHV AC facilities, it is important to note that HVDC bi-pole contingencies can also be driven by forced converter outages. A plus for 765 kV.

Conclusions

Key Conclusions and Takeaways

- The best transmission system is one that is planned with an “all things considered” strategy.
- When legacy voltages are preferable, such voltage levels should align with those that already exist in the area.

	Legacy Voltage Levels Compared to 765 kV and VSC HVDC	765 kV Compared to Legacy Voltage Levels	765 kV Compared to VSC HVDC	VSC HVDC Compared to EHV AC Voltages
Pros	• Contingency impact • Better suited for incremental needs	• Lower capital cost • Lower land usage • Fewer circuit miles • Lower losses	• Lower capital costs except for very long lines. • Higher capabilities on shorter lines • Natural flow adjustments	• Flow control capabilities • Lower capital costs on very long lines • Higher capabilities on longer lines • Reactive power mitigation
Cons	• Higher capital cost • Higher land usage • More circuit miles • Higher losses	• Contingency impact • Not suited for incremental needs	• No Flow control capabilities if needed • Higher capital costs on very long lines • Potential reactive power issues	• Higher capital costs except for very long lines. • Not suited for incremental needs • No natural flow adjustments

Questions

Appendix 1
Transmission Limit Considerations

Historic Role of Limits

- Legacy transmission lines were constructed primarily for local purposes, thus:
  - The shorter length of most legacy transmission lines were such that thermal limits were well below absolute limits in most cases.
  - The gap between thermal limits and absolute limits provided a natural safety margin that:
    - prohibited operation too close to the absolute limit;
    - enhanced system stability and voltage, and;
    - eliminated the need for safe loading limits in operations and planning.
- Therefore, while safe loading limits and absolute limits are not new to the industry, in most cases, they have not been relevant in the operation and planning of transmission systems in the past.

Future Role of Limits

- In the future, the gap between thermal limits and absolute limits could narrow or disappear altogether:
  - Technologies such as ambient adjusted ratings, dynamic line ratings, and composite core conductors could increase thermal limits but will have no impact on absolute limits.
  - As operations becomes more regional and less local, the average distance power must travel from resource to load could increase substantially, thus increasing the relevance of safe loading limits and absolute limits.
  - Displacement of conventional generation with inverter-based generation reduces system strength and thus could further complicate the ability to transfer vast amounts of power long distances across the system.
- In the future, safe loading limits and absolute limits will become more relevant in the operation and planning of the transmission system.

Maximum Power Transfer Limits

- The maximum power transfer limit of a transmission line is a physical limit that cannot be exceeded.
- The maximum power transfer limit for an AC transmission line is inversely related to line length given by the following formula:

Maximum Power Flow (MW) = $|V_S||V_R|/ |X_L|$

where V_S = Voltage at Sending Terminal in $kV_{\phi\phi}$
V_R = Voltage at Receiving Terminal in $kV_{\phi\phi}$
X_L = Series reactance of line in Ohms

- The maximum power transfer limit for an HVDC bi-pole is also inversely related to line length and given by the following formula:

Maximum Power Flow (MW) = $2[1.05V_N][1.05V_N - 0.95V_N] / R_L = 0.21V_N^2 / R_L$

where V_N = Nominal HVDC Voltage in kV_{LN}
R_L = Series resistance of line in Ohms

- See Section 2 for more details on establishing maximum power transfer limits.

Safe Loading Limits

- The Safe Loading Limit (or SLL) represents an inflection point between an operating state of lower risk and stress versus an operating state of higher risk and stress.
- Historically, Safe Loading Limits have mainly been used just to inform what voltage levels and line characteristics might be appropriate for new AC transmission line facilities.
- Operating HVDC lines at or near maximum power transfer limits does not introduce substantial reliability risk since HVDC flows are precisely controlled, so safe loading limits are not typically used for HVDC facilities.
- For AC lines, Safe Loading Limits can also be used as:
  - A metric for assessing overall operational risks for the current or planned transmission system.
  - A metric to inform where focus should be placed on more detailed voltage stability and angular stability studies and analysis.
  - The basis for a line rating when the thermal limit is higher than the absolute limit (e.g., a longer line) and a safety margin is needed between the actual line rating and the absolute limit to ensure reliability.

Establishing Safe Loading Limits

- A well-known methodology for establishing safe loading limits is to base them on the surge impedance loading and length of an AC transmission line, as proposed in the IEEE paper referenced below:
  - 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.
- The methodology described in the referenced paper above is sometimes referred to at the St. Clair curve methodology and establishes a safe loading limit for an AC transmission line based on the lesser of:
  - the load level where the voltage drop across the line exceeds 5%
  - the load level where the angular displacement across the line reaches 44.5° (i.e., a 30% margin between the maximum power transfer limit and the safe loading limit)
- In practice, for shorter lines, the voltage drop criteria (≤ 5.0%) tends to drive the safe loading limit and for longer lines the angular displacement criteria (≤44.5°) tends to drive the safe loading limit.
- The St. Clair curve methodology establishes the safe loading limit of an AC transmission line based solely on the length of the line in miles and the surge impedance loading calculated for the line.
- See Section 3 for more details on establishing safe loading limits for AC lines.

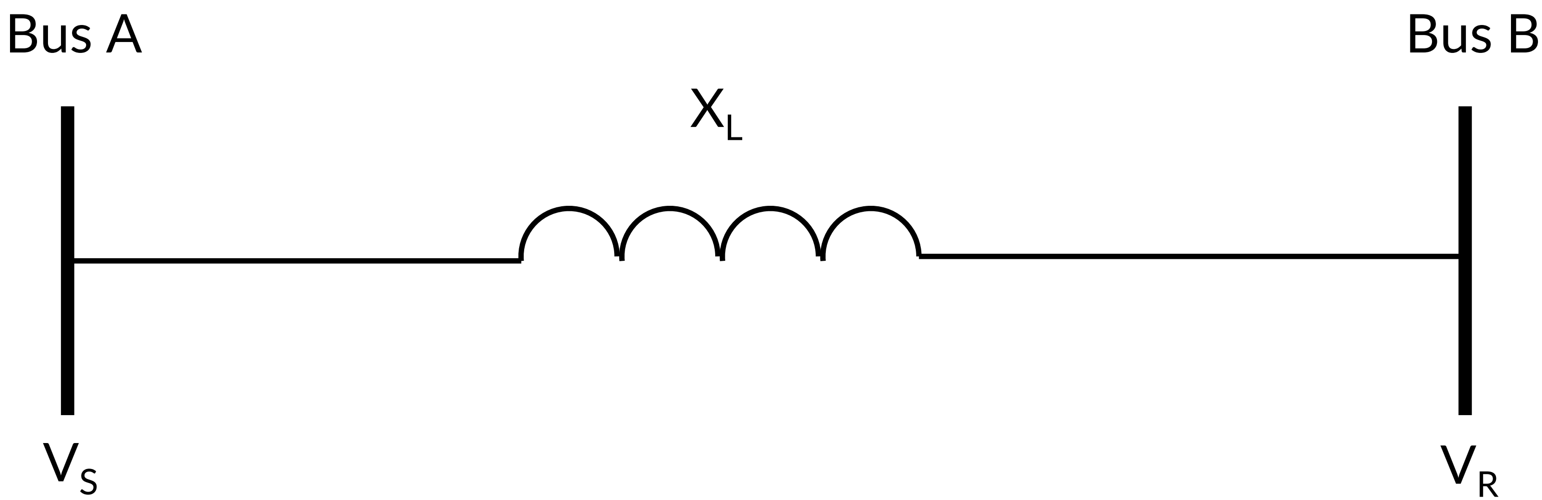
Appendix 2 – Maximum Power Transfer Limits

Power Transfer through an AC Transmission Line

The power flow through an AC transmission line connected to Bus A at the source terminal and Bus B at the receiving terminal can be approximated by the following formula:

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

where
- V_S = Voltage at Bus A in per unit or $kV_{\phi\phi}$
- V_R = Voltage at Bus B in per unit or $kV_{\phi\phi}$
- X_L = Series reactance of line in per unit or Ohms
- δ = Angle by which V_S leads V_R in radians or degree

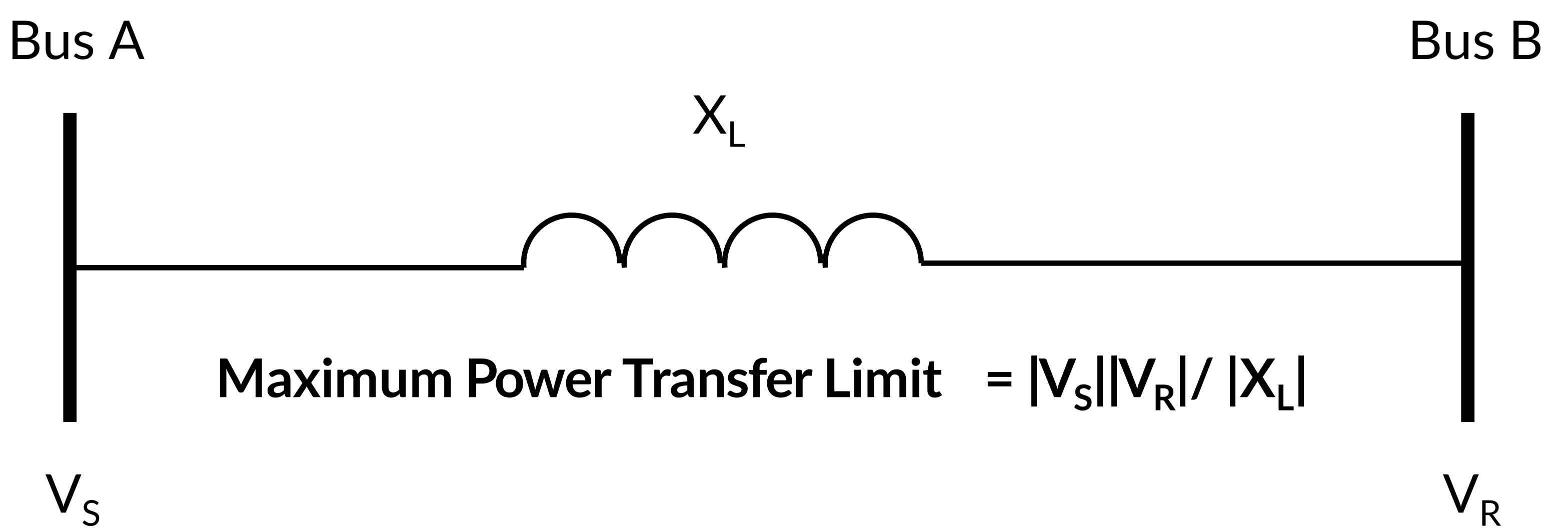


Maximum Power Transfer Limit - AC Transmission Line

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

Maximum Power Flow (Per Unit or MW) = $|V_S||V_R|/ |X_L|$

where
- V_S = Voltage at Bus A in per unit or $kV_{\phi\phi}$
- V_R = Voltage at Bus B in per unit or $kV_{\phi\phi}$
- X_L = Series reactance of line in per unit or Ohms

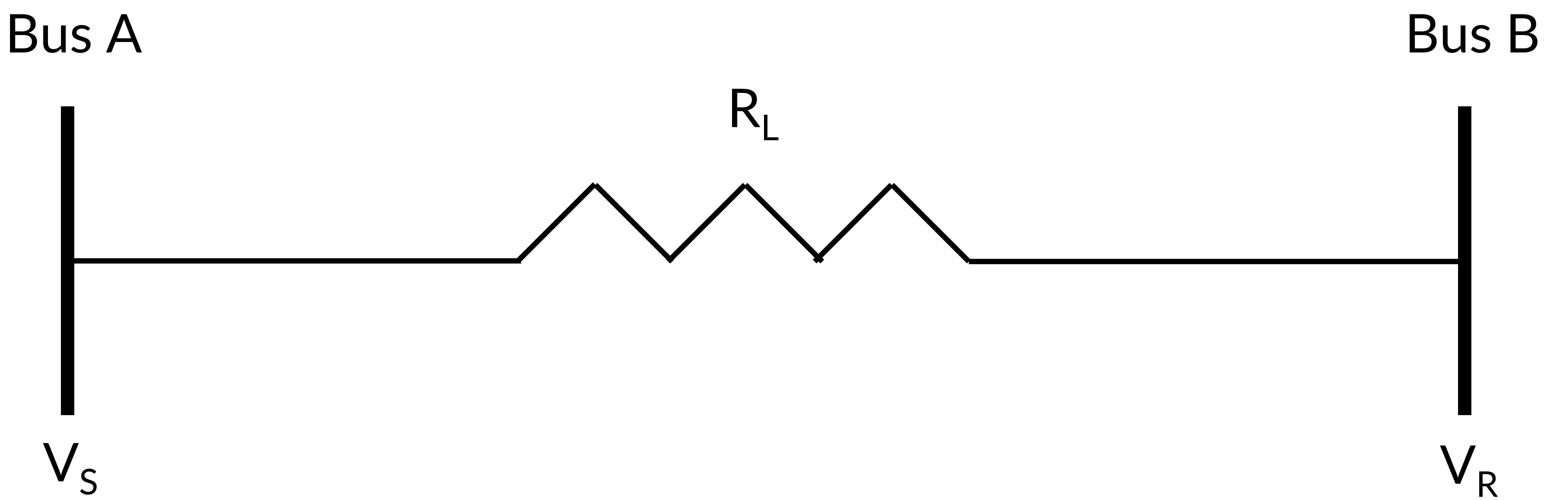


Power Transfer through an HVDC Bi-pole

The power flow through an HVDC bi-pole connected to Bus A at the source terminal and Bus B at the receiving terminal can be approximated by the following formula:

Power Flow (Per Unit or MW) = $2*[V_S][V_S - V_R] / R_L$

where
- V_S = Voltage at Bus A in per unit or kV_{LG}
- V_R = Voltage at Bus B in per unit or kV_{LG}
- R_L = Series resistance of line in per unit or Ohms



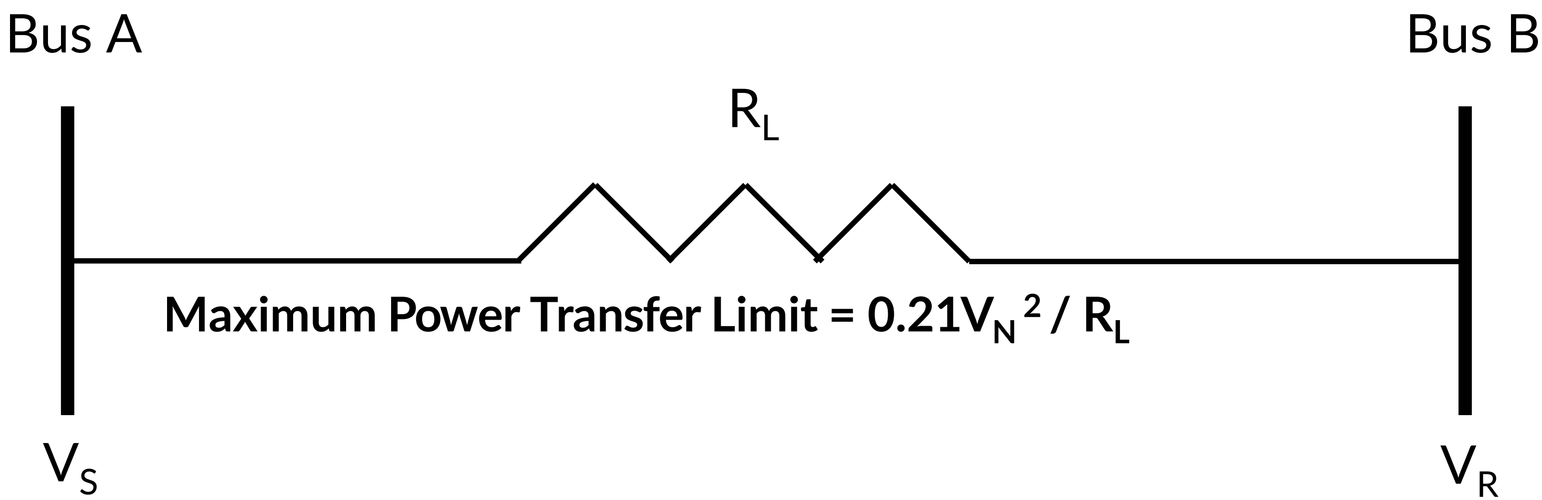
Maximum Power Transfer Limit - HVDC Bi-pole

The maximum power flow through an HVDC bi-pole occurs when the difference between the sending-end and receiving-end voltage is a maximum, which is typically about 10% of nominal voltage

Maximum Power Flow = $2*[1.05V_N][1.05V_N - 0.95V_N] / R_L = 0.21V_N^2 / R_L$

where V_N = Nominal HVDC Voltage in per unit or kV_{LG}

R_L = Series resistance of line in per unit or Ohms



Appendix 3– Safe Loading Limits

Establishing Safe Loading Limits

- A well-known methodology for establishing safe loading limits is to base them on the surge impedance loading and length of an AC transmission line, as proposed in the IEEE paper referenced below:
  - 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.
- The methodology described in the referenced paper above is often referred to as the St. Clair curve methodology and establishes a safe loading limit for an AC transmission line based on the lesser of:
  - the load level where the voltage drop across the line exceeds 5%
  - the angular displacement across the line reaches 44.5° (i.e., a 30% margin between the maximum power transfer limit and the safe loading limit)
- In practice, for shorter lines (below 200 miles), the voltage drop criteria (≤ 5.0%) tends to drive the safe loading limit and for longer lines (above 200 miles) the angular displacement criteria (≤44.5°) tends to drive the safe loading limit.
- The St. Clair curve methodology establishes the safe loading limit of an AC transmission line based solely on the length of the line in miles and the surge impedance loading calculated for the line.

Surge Impedance Loading (SIL) of a Transmission Line

- The Surge Impedance Loading (SIL) of an AC transmission line represents the MW flow on the line where the reactive power consumed by the distributed inductance of the line exactly balances the reactive power injected by the distributed capacitance of the line.
- The SIL for a given line is a function of the line voltage, distributed line inductance per mile and distributed line capacitance per mile, but not the length of the line.
- The SIL of a line can be a good indicator of the Safe Loading Limit of the line.
- $SIL = (V_{\phi\phi})^2 / (L/C)^{1/2}$

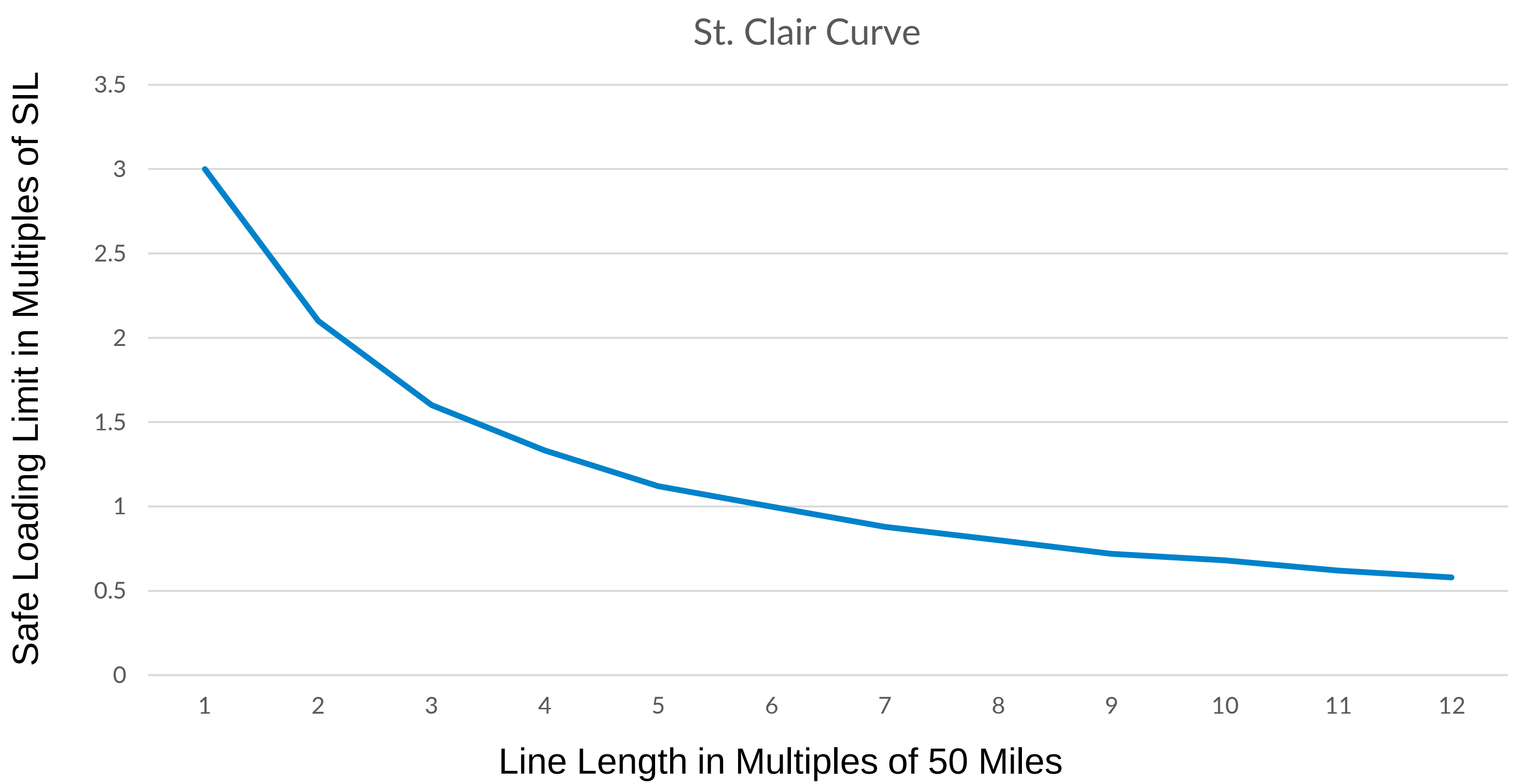
  where

  - SIL = Surge Impedance Loading of Line expressed in MW
  - $V_{\phi\phi}$ = Phase-to-phase Nominal Voltage of Line expressed in kV
  - L = Inductance per Mile of Line Expressed in Henrys
  - C = Capacitance per Mile of Line Expressed in Farads
  - $(L/C)^{1/2}$ = Surge Impedance of Lossless Transmission Line in Ohms

Developing Safe Loading Limits based on the St. Clair Curve

- The St. Clair Curve was developed by AEP in the 1950s and updated in 1979.
- The St. Clair Curve expresses the maximum safe loading limit for a transmission line as a function of line length.
- The Safe Loading Limit for a line is expressed in percent of the line's Surge Impedance Loading, thus the same curve can be used for various line voltages and design characteristics.
- For a given line length, the St. Clair curve provides a multiplier to be applied to the line's Surge Impedance Loading to determine the Safe Loading Limit in MW.
- The St. Clair Safe Loading Limit is the limit where the voltage drop of the line exceeds 5.0% **and/or** the loading on the line exceeds 70% of the maximum power transfer limit (about 44.5° angular displacement).
- Voltage drop dominates for shorter lines and angular displacement dominates for longer lines.
- **Example:**
  - For a line length of 200 miles, the St. Clair SIL Multiplier is 1.3.
  - Therefore, if a specific 345 kV line design has a SIL of 390 MW, the SLL would be calculated as SLL = 1.3 * 390 MW = 507 MW

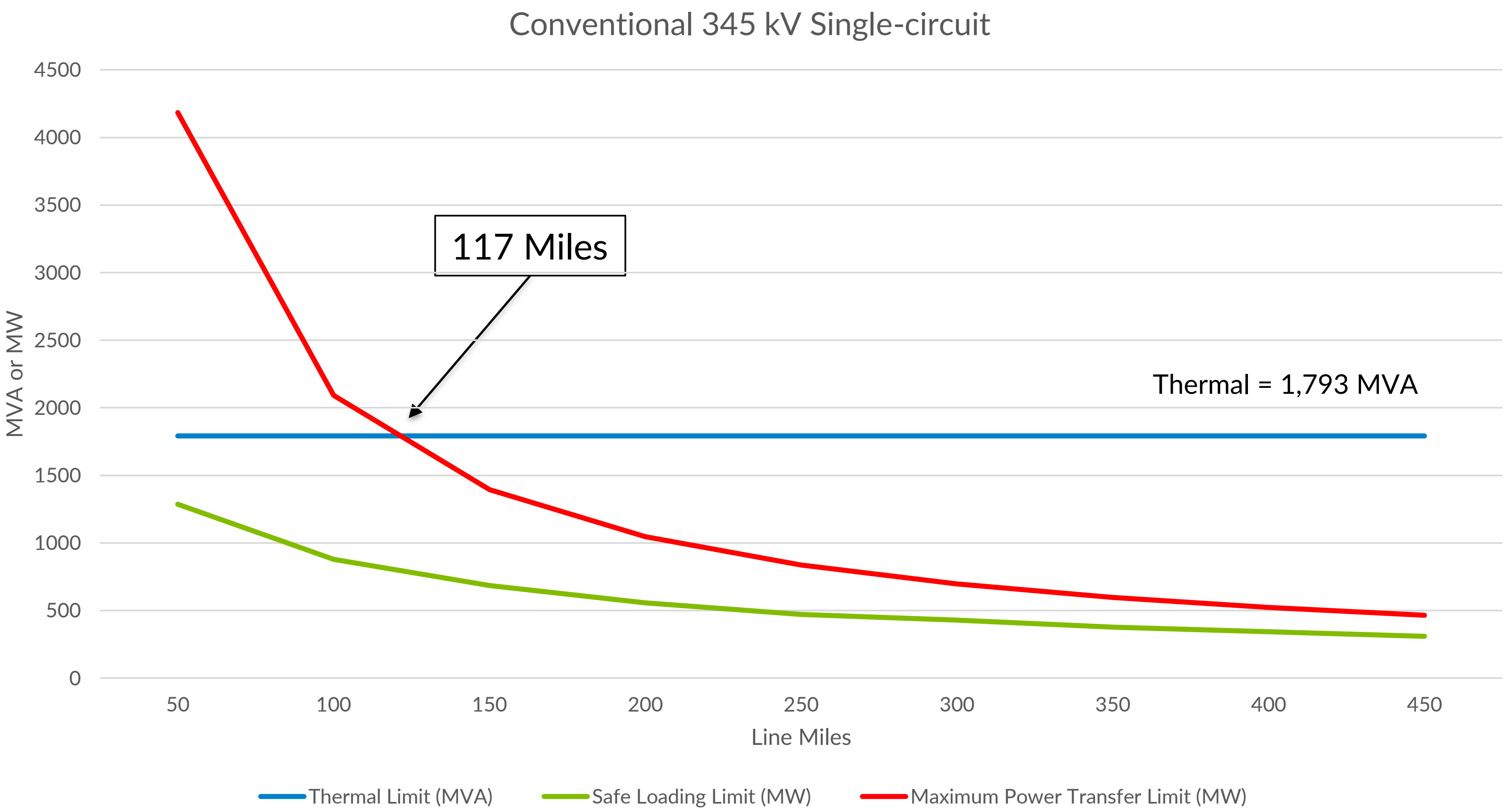
St. Clair Curve**



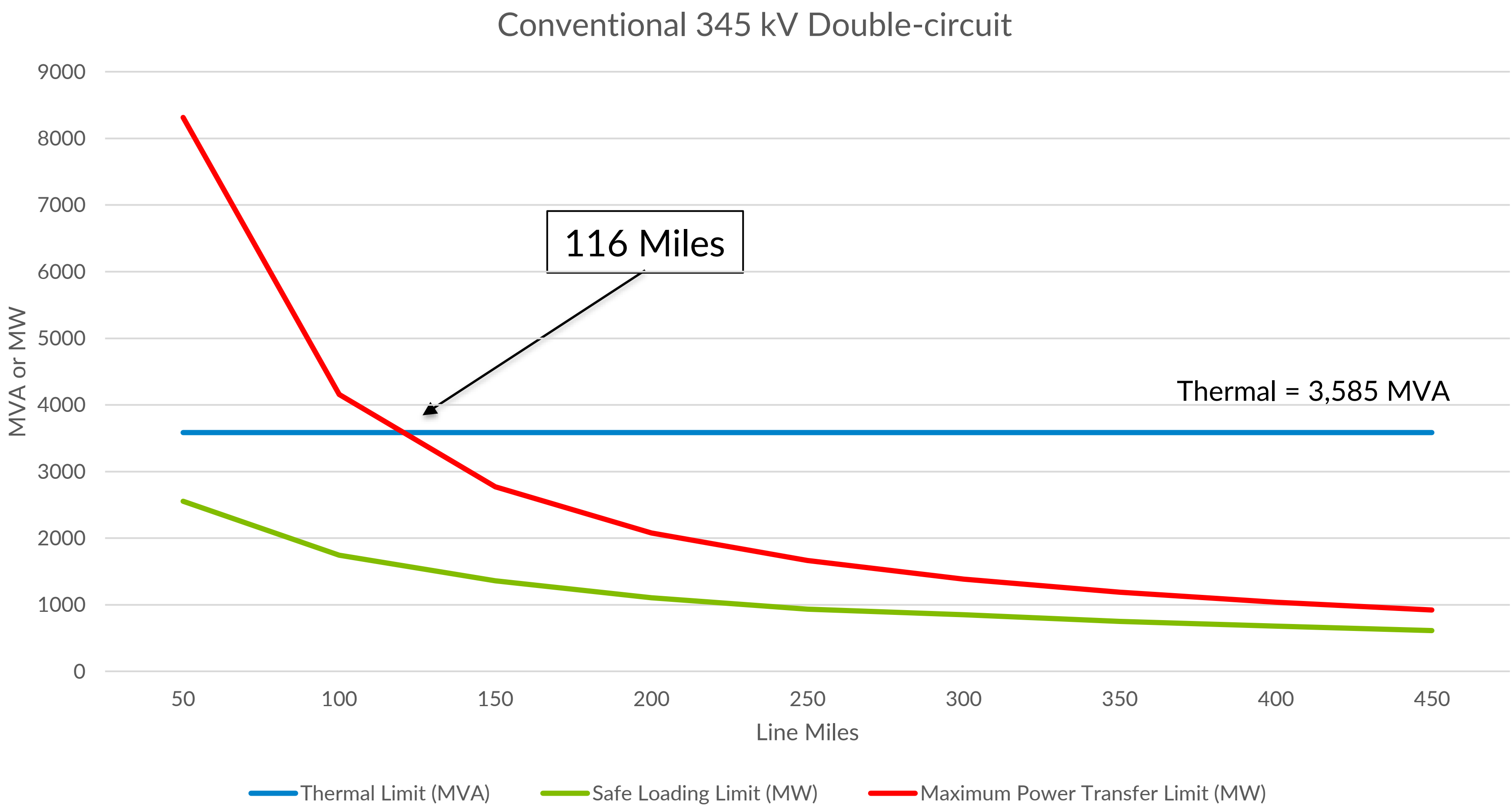
**Dunlop, R.D., Gutman, R., Marchenko, P.P., *Analytical Development of Loadability Characteristics for EHV and UHV Transmission Lines*, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 2, March/April 1979.

Appendix 4
EHV and HVDC Limit Curves

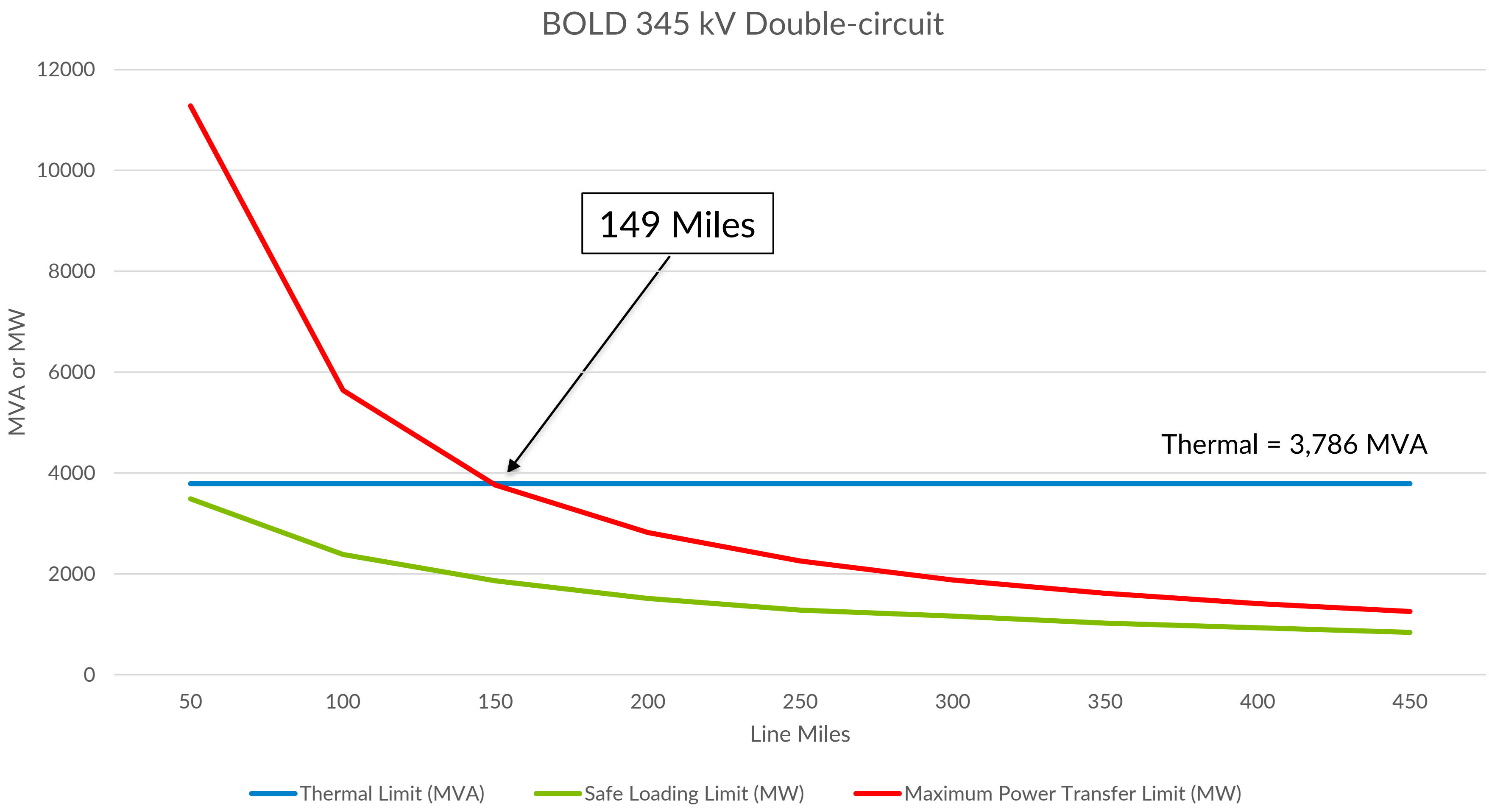
Comparison of Typical 345 kV Limits
Conventional Single-circuit, 2-Conductor Bundle
Surge Impedance Loading = 429 MW



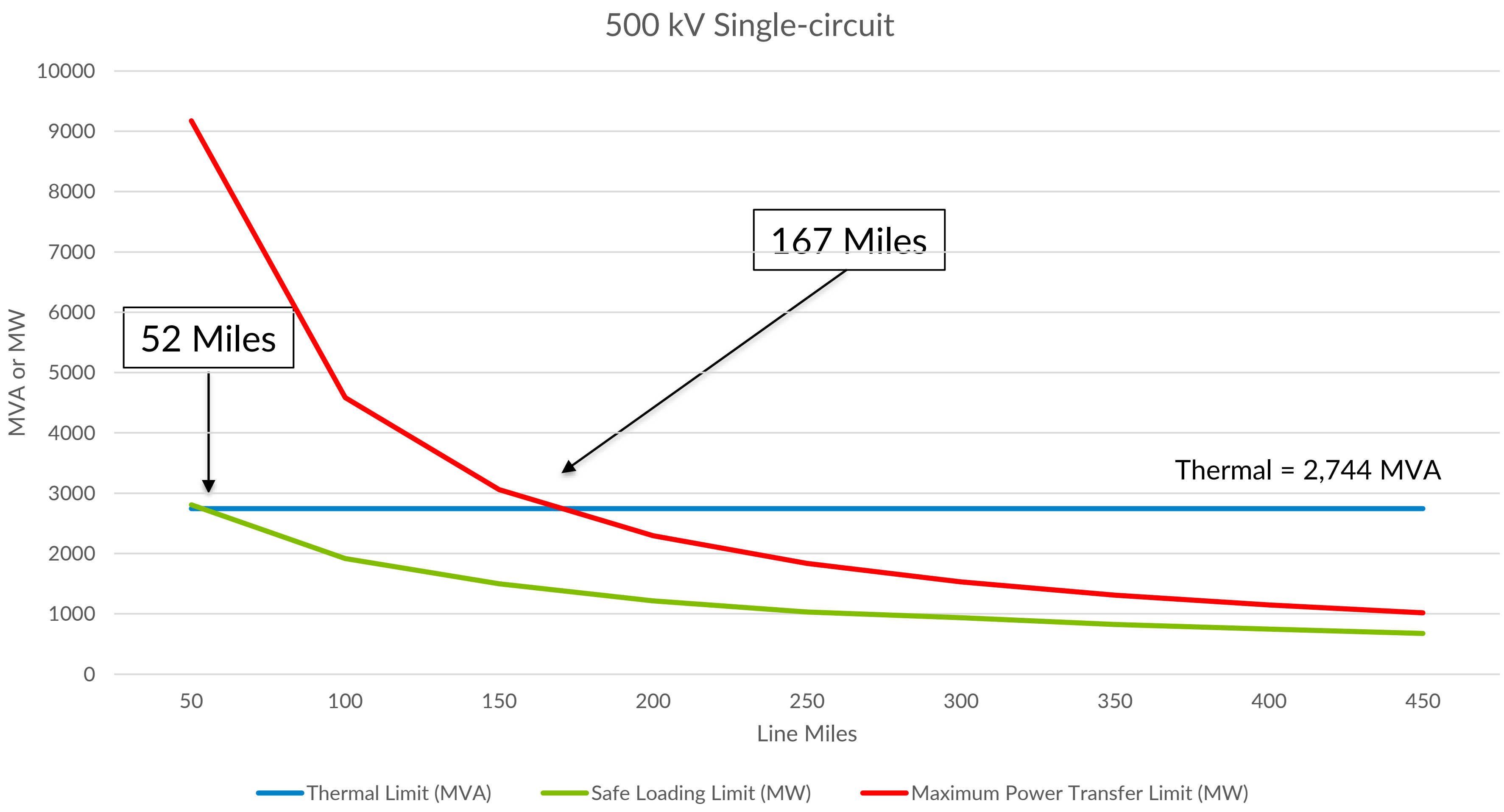
Comparison of Typical 345 kV Limits
Conventional Double-circuit, 2-Conductor Bundle
Surge Impedance Loading = 851 MW



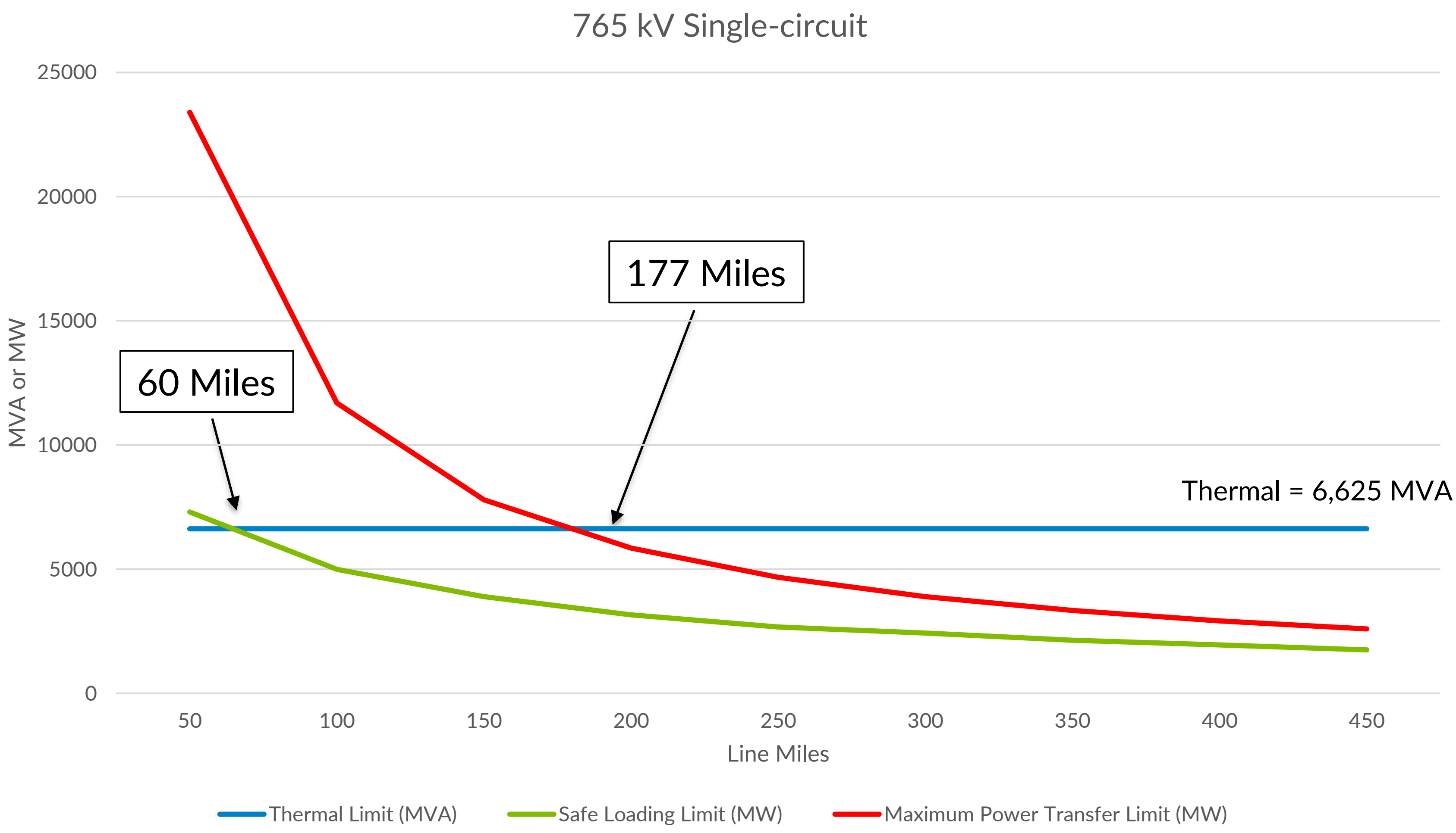
Comparison of Typical 345 kV Limits BOLD Double-circuit, 3-Conductor Bundle Surge Impedance Loading = 1,162 MW



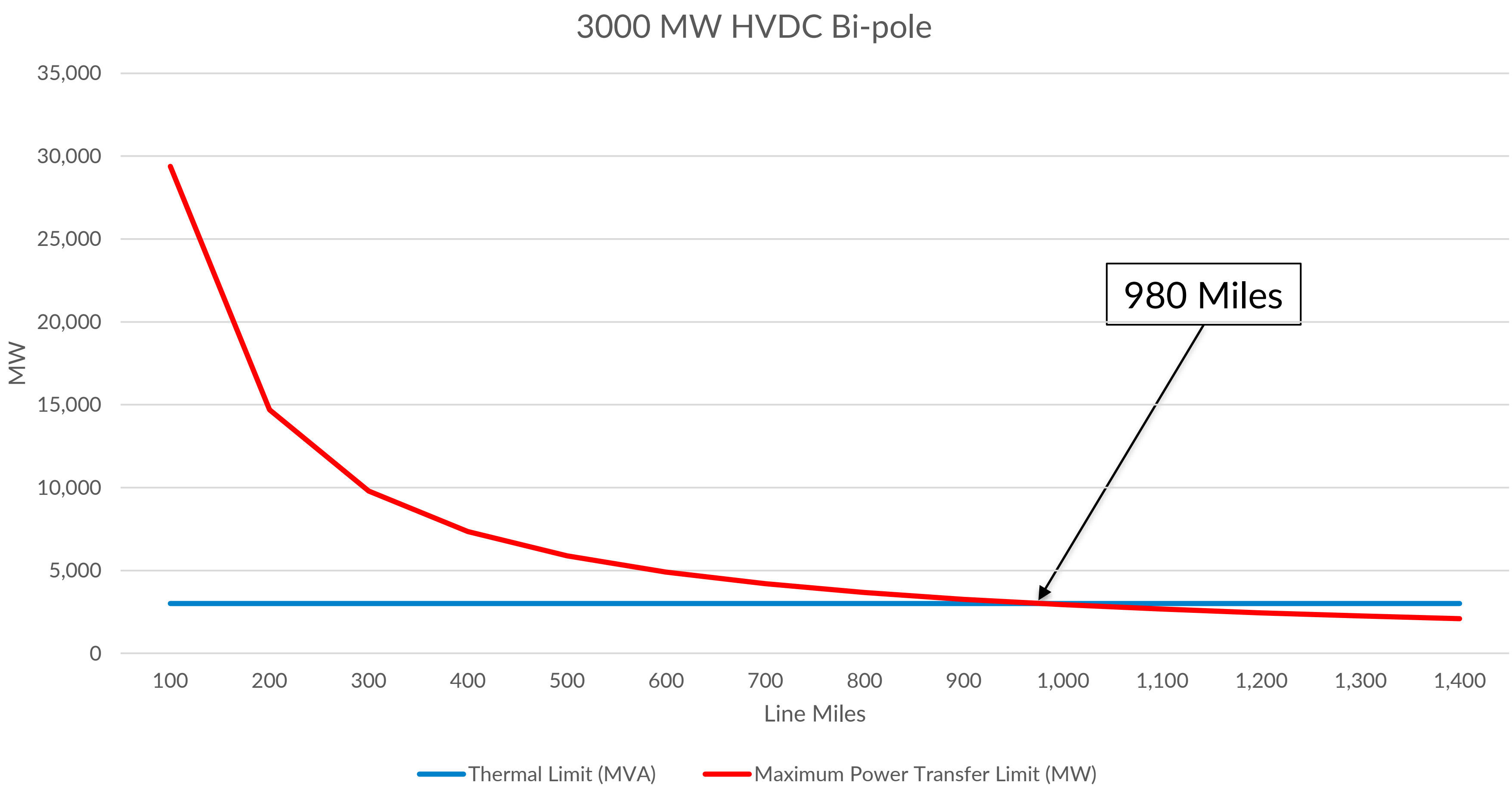
Comparison of Typical 500 kV Limits Single-circuit, 3 - Conductor Bundle Surge Impedance Loading = 936 MW



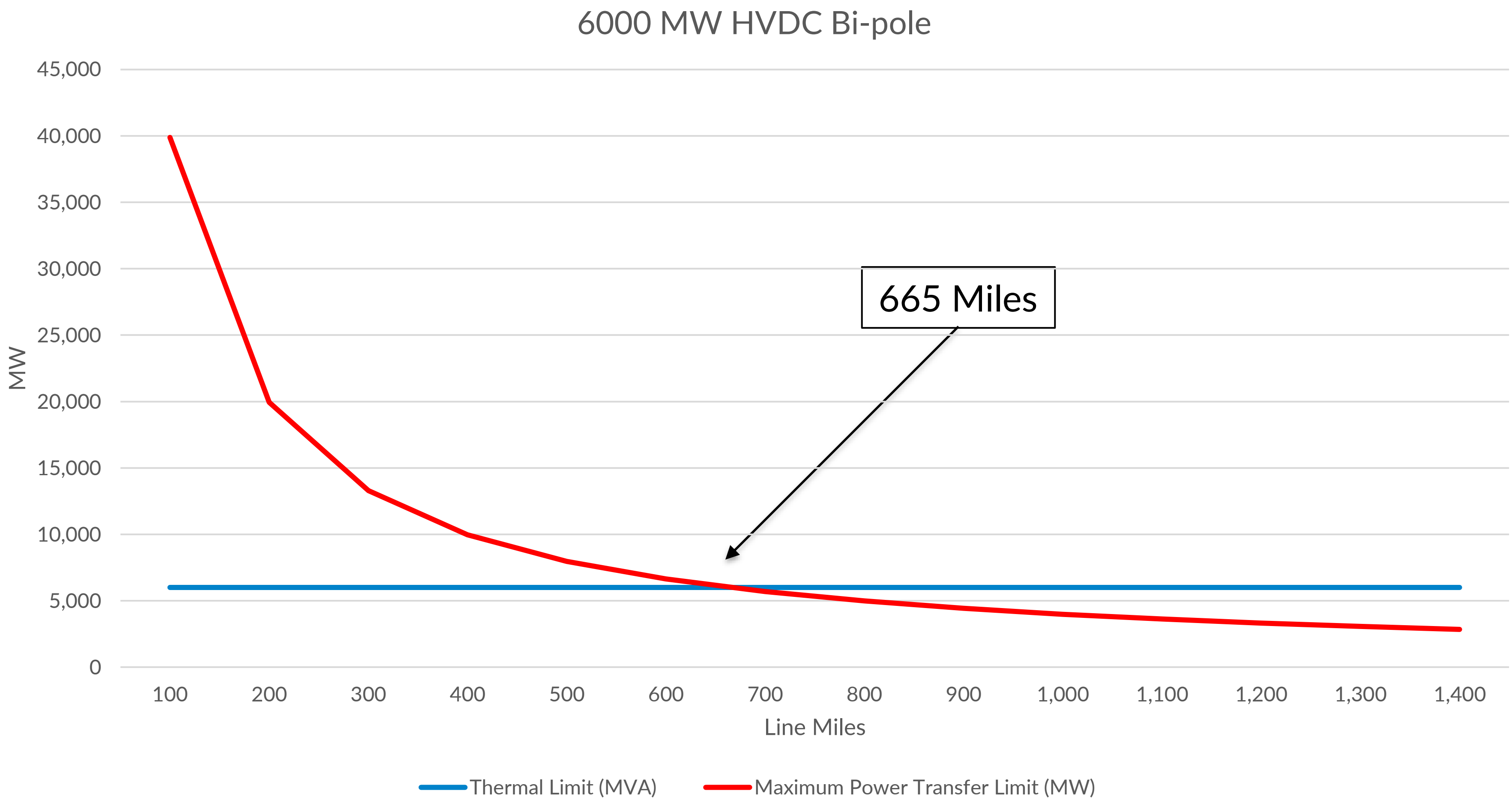
Comparison of Typical 765 kV Limits Single-circuit, 6 - Conductor Bundle Surge Impedance Loading = 2,435 MW



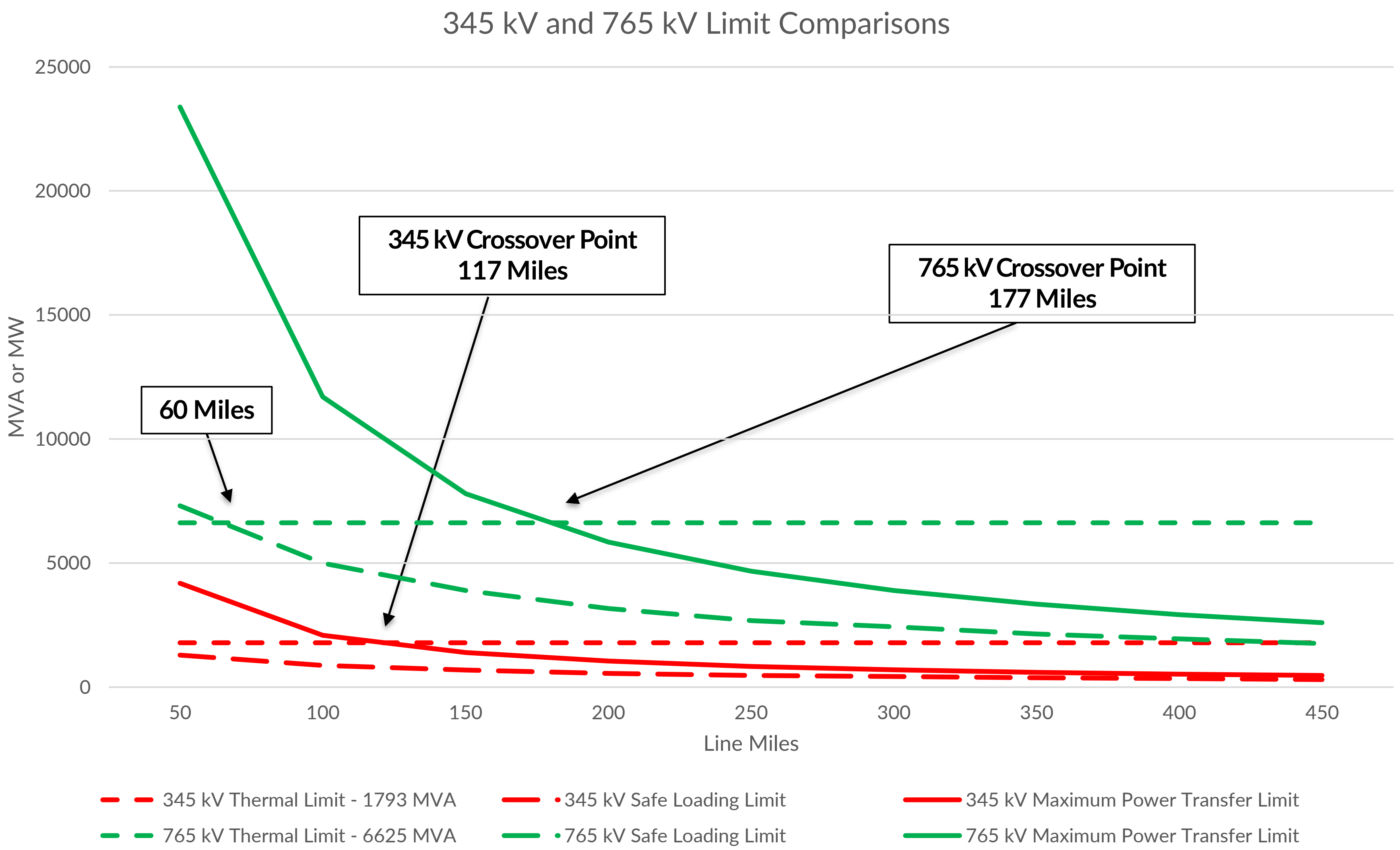
Comparison of Typical +/- 640 kV HVDC Limits
3000 MW Bi-pole
2-Conductor Bundle, 1 Converter per Terminal (2 Total)



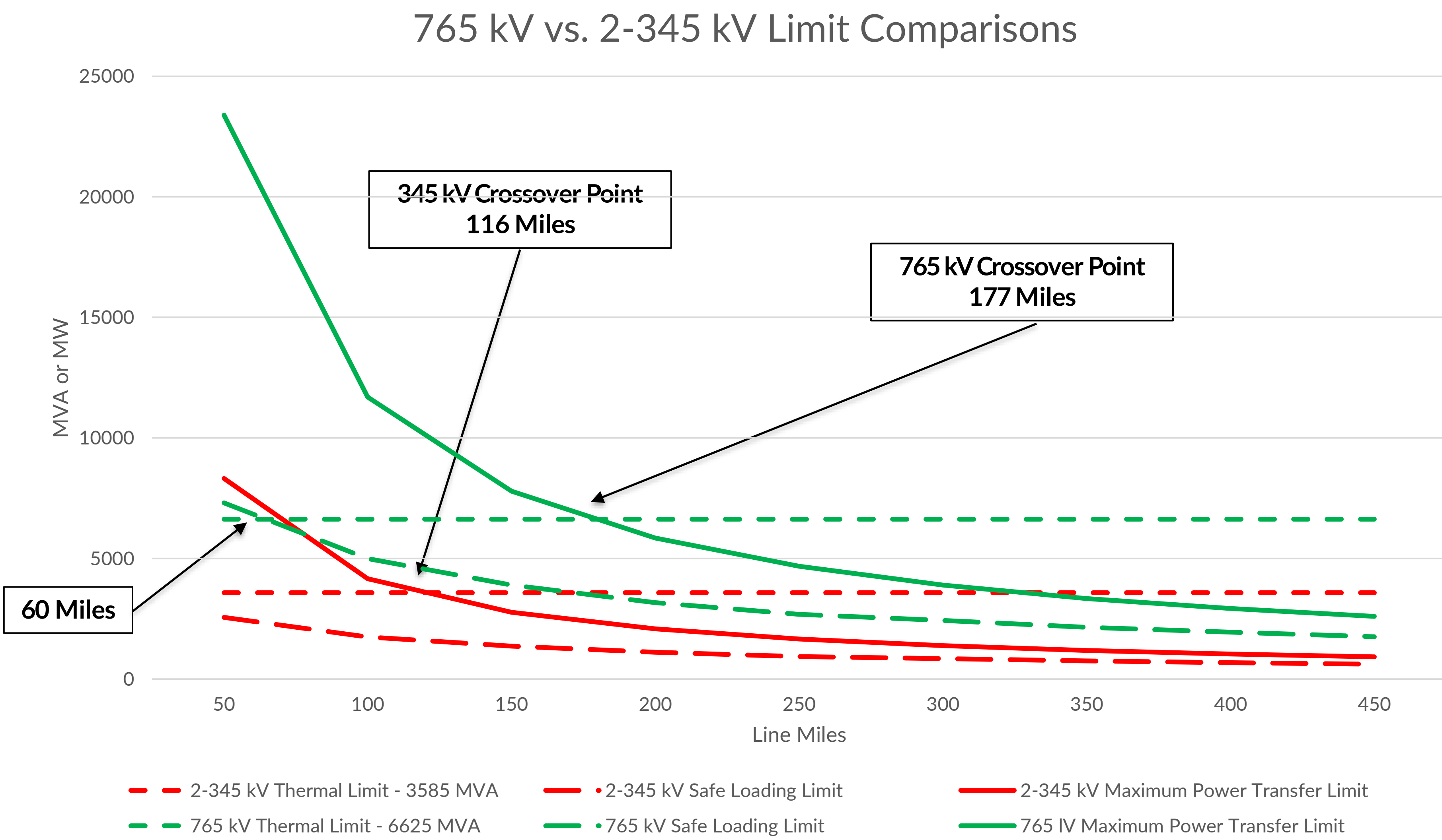
Comparison of Typical +/- 640 kV HVDC Limits 6000 MW Bi-pole 6-Conductor Bundle, 2 Converters per Terminal (4 Total)



Comparison of Typical EHV Line Limit Curves: Single Circuit 345 kV and 765 kV



Comparison of Typical EHV Line Limit Curves: Double Circuit 345 kV and 765 kV



Comparison of Typical EHV Line Limit Curves: 500 kV and 765 kV