Discussion of Legacy, 765 kV and HVDC Bulk Transmission

Iowa State University
Electric Power Forum 2025
HVDC Short Course

May 22, 2025

Purpose & Key Takeaways

- Purpose: This presentation discusses the 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.

Introduction

Key Comparisons: 345 kV, 765 kV and HVDC

	345 kV	765 kV	HVDC
Incremental Need	Pro		
Cost per MW-Mile – Less than 250 Miles		Pro	
Cost per MW-Mile – 250 to 400 Miles		Pro	Pro
Cost per MW-Mile – Greater than 400 Miles			Pro
Land Use per MW-Mile		Pro	Pro
Flow Control when Desired			Pro
Natural Response when Desired	Pro	Pro	
Transmission Losses		Pro	Pro

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

Power Transfer Level \ Power 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**

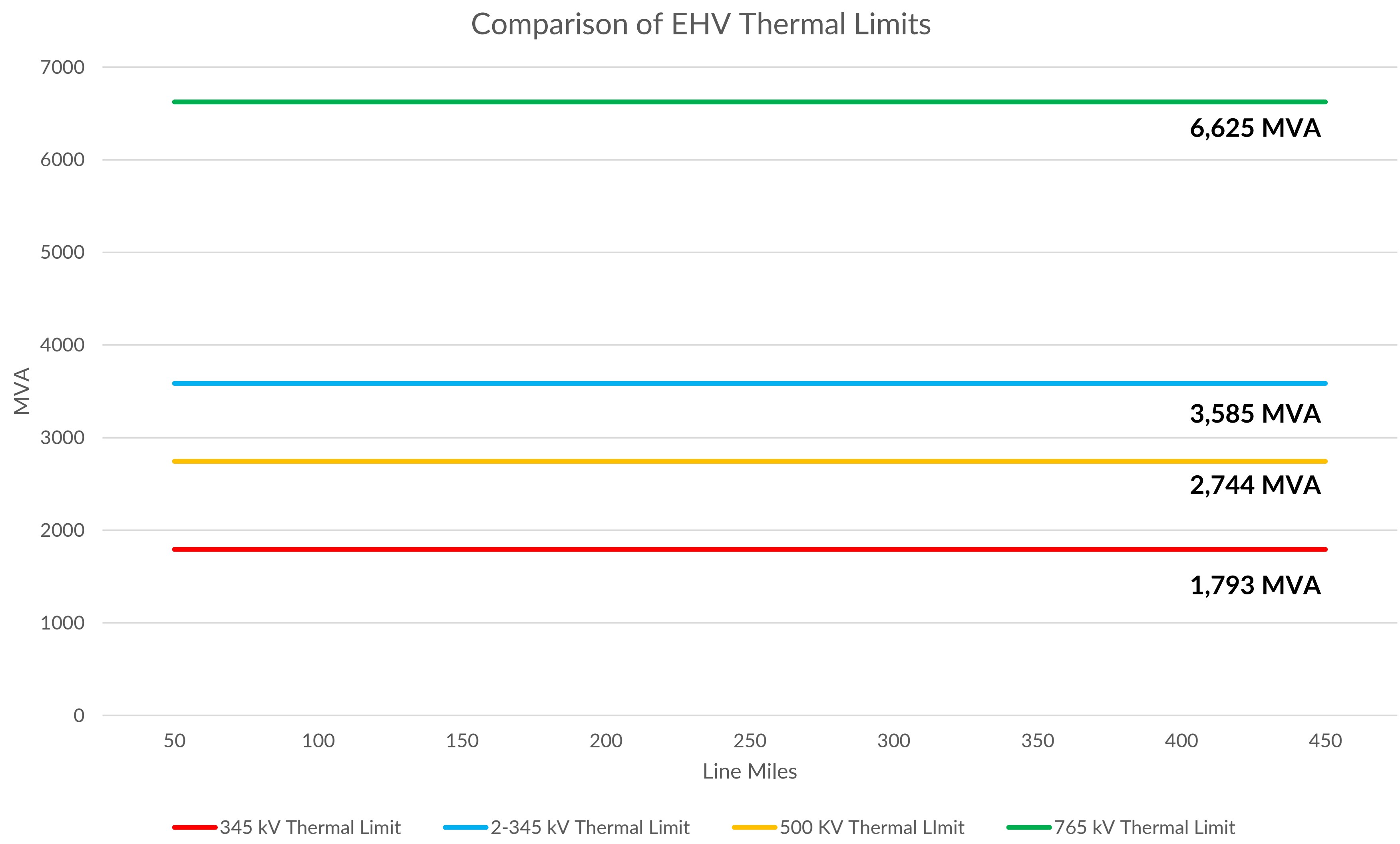
Transmission Limits

Types of Transmission Line Limits

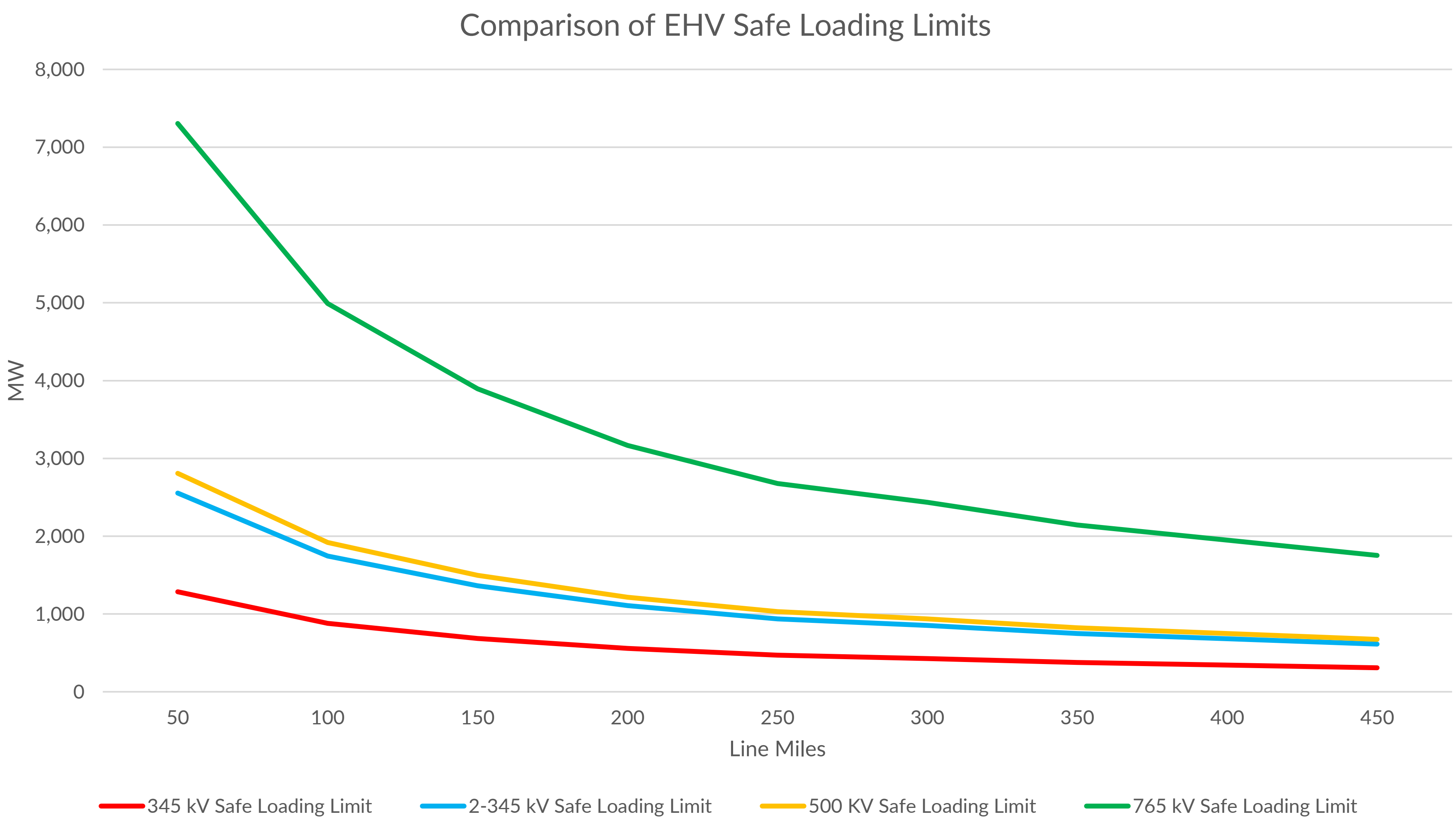
Thermal Limits	Safe Loading Limits (SLLs)	Absolute Limits

• Applies to both AC and HVDC transmission lines
• Driven by facility temperature limits
• Independent of line length
• Compliance, safety and/or facility risk mitigation limit
	• Applies only to AC transmission lines
	• Driven by operational risk inflection points
	• Safe loading limits decrease as line length increases
	• Operational 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 (MPTL)
		  ◦ Relay Trip Limit
		• MPTL is 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

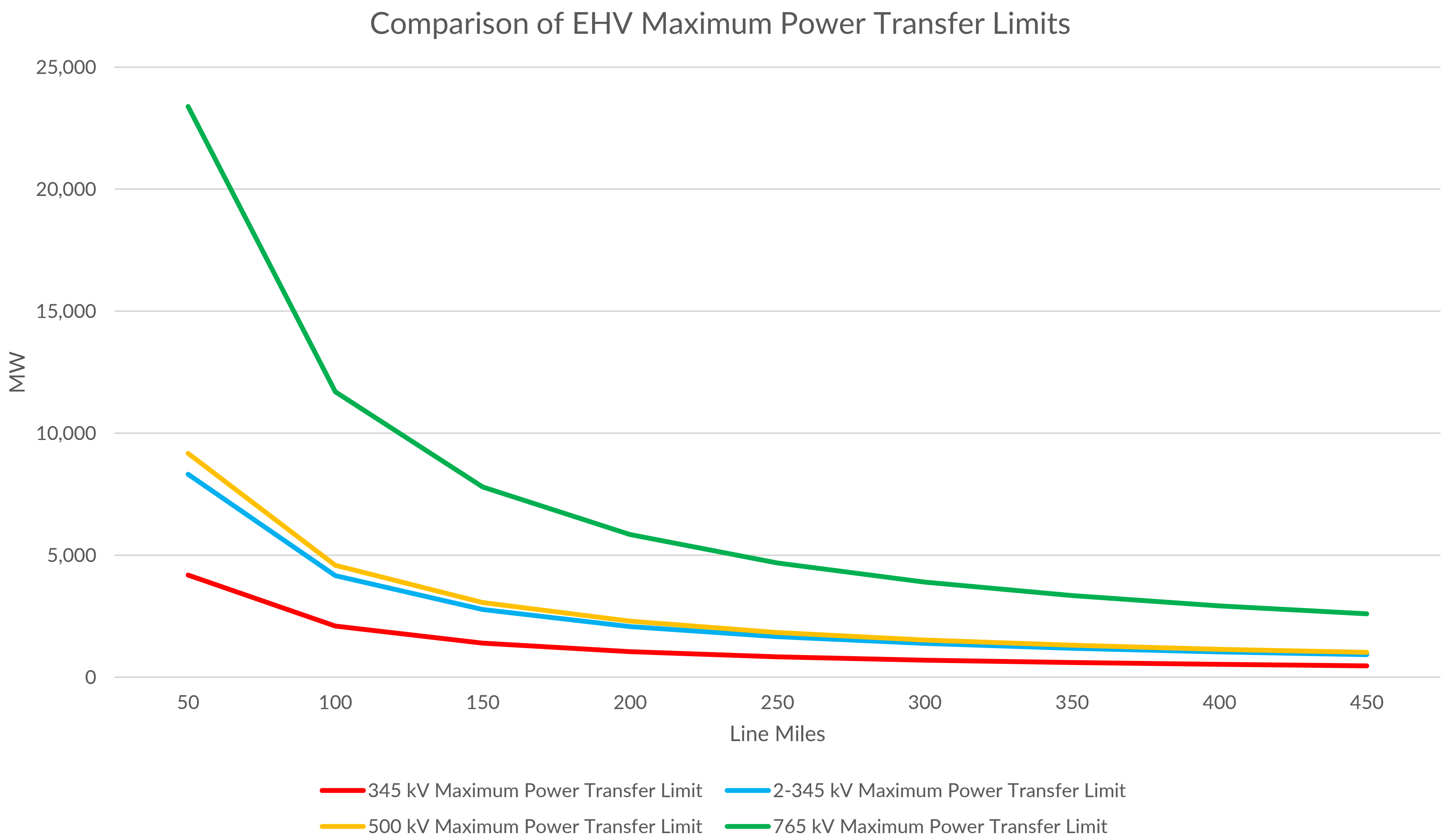


Comparison of **Typical** EHV Line Safe Loading Limits: Single-circuit 345 kV, Double-circuit 345 kV, 500 kV and 765 kV



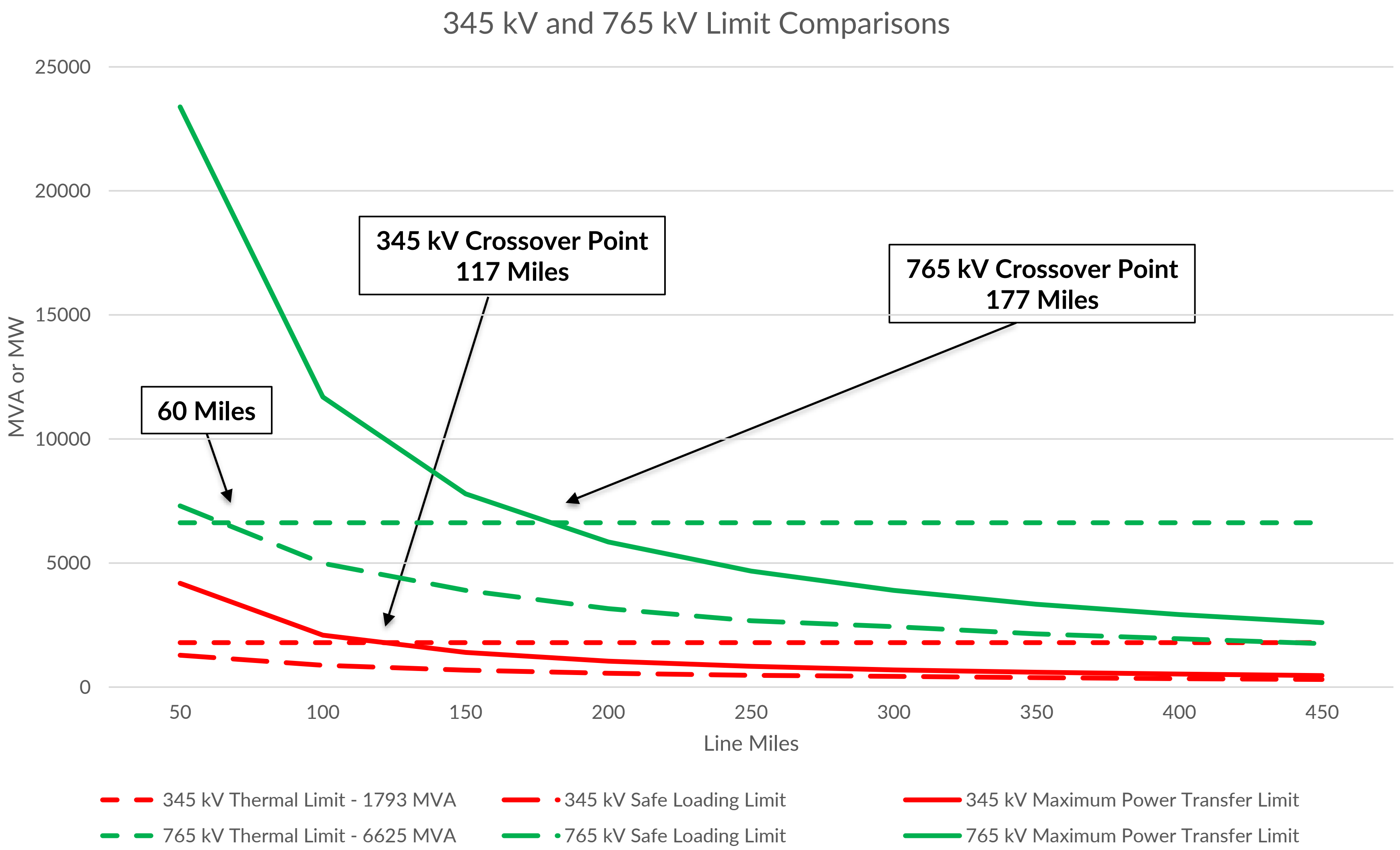
NOTE: Assumes strong terminals (50 kA fault duty)

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



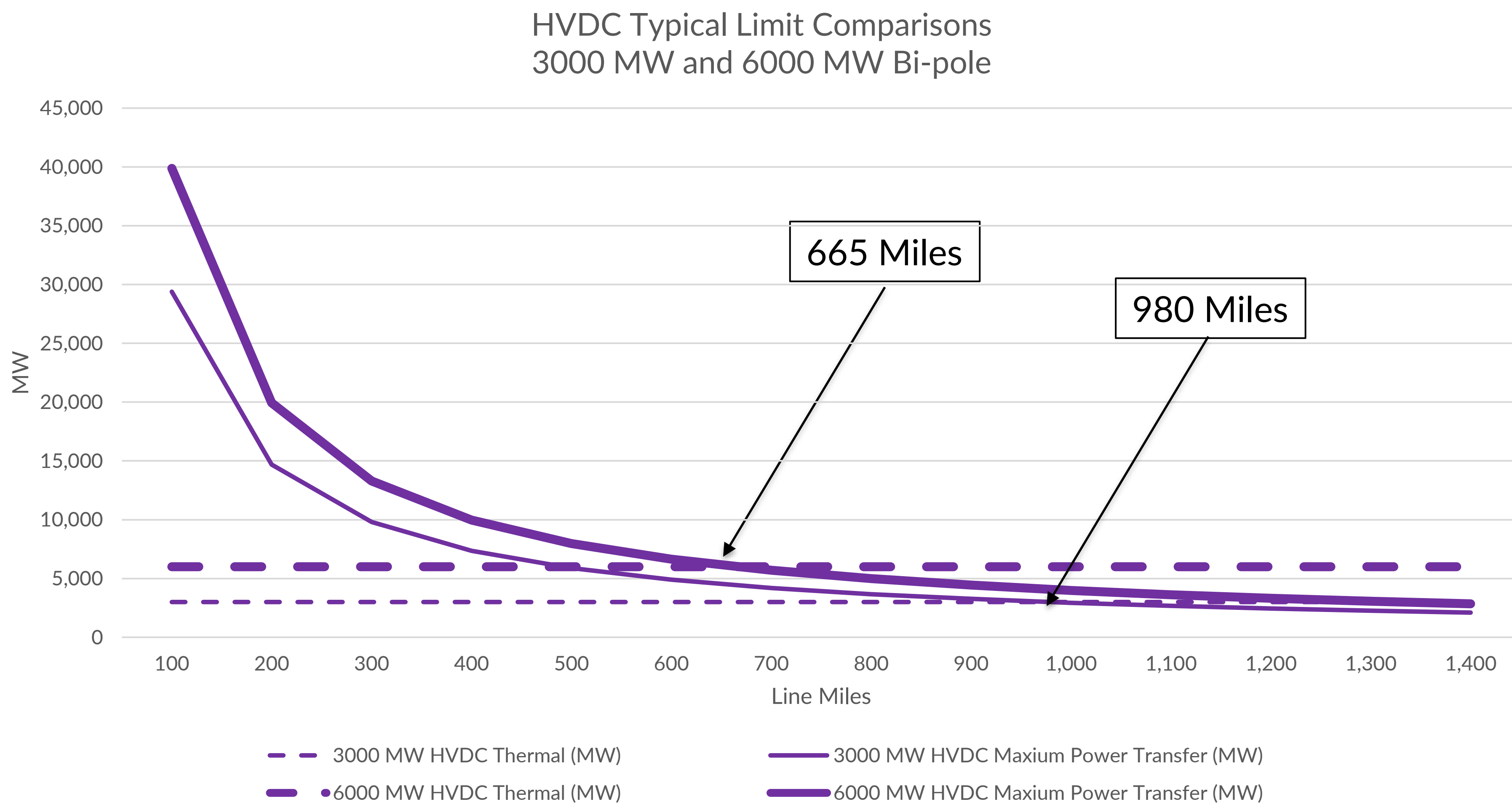
NOTE: Assumes terminals are infinite buses.

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



NOTE: Reducing the 765 kV thermal limit from 6625 MVA (5000 A) to 5300 MVA (4000 A) would extend the SLL crossover point to about 90 miles and the MPTL crossover point to about 225 miles.

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

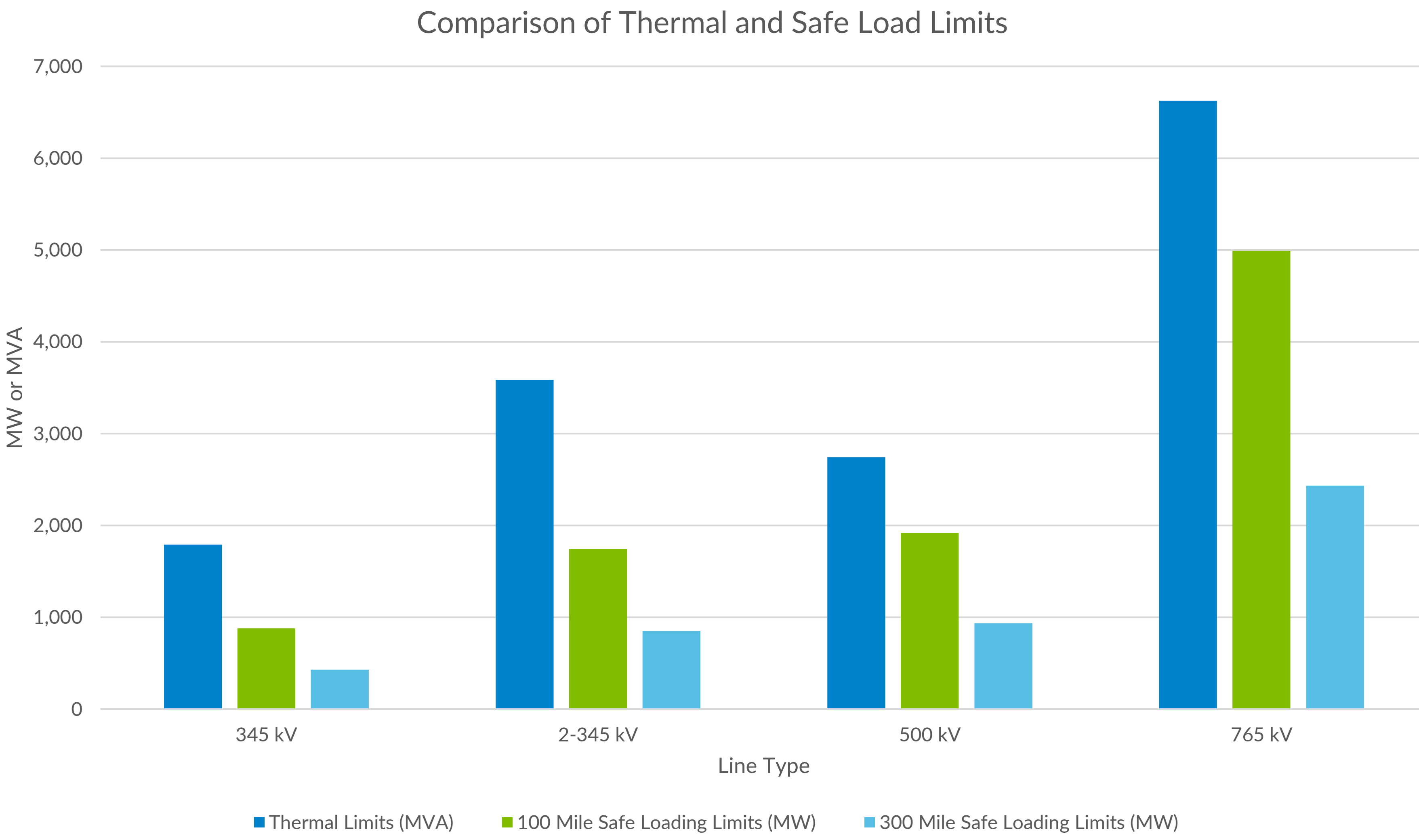


Comparison of Legacy Bulk Transmission with 765 kV

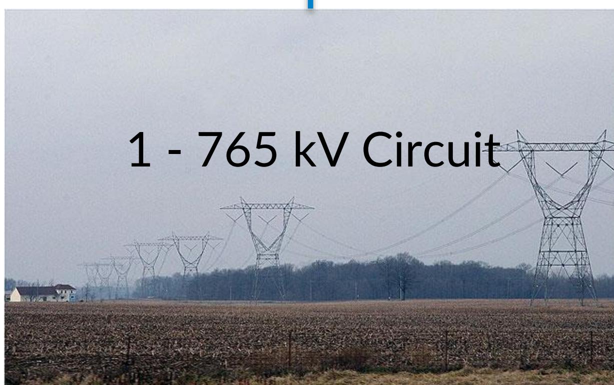
Key Takeaways for Comparison of Legacy Bulk Transmission with 765 kV

- The benefits of 765 kV transmission over 345 kV or 500 kV transmission options include the following:
  - Lower capital cost per MW-mile
  - Lower land usage per MW-mile
  - Lower energy and capacity losses per MW-mile
- The benefits of 345 kV transmission over 765 kV include the following:
  - 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:



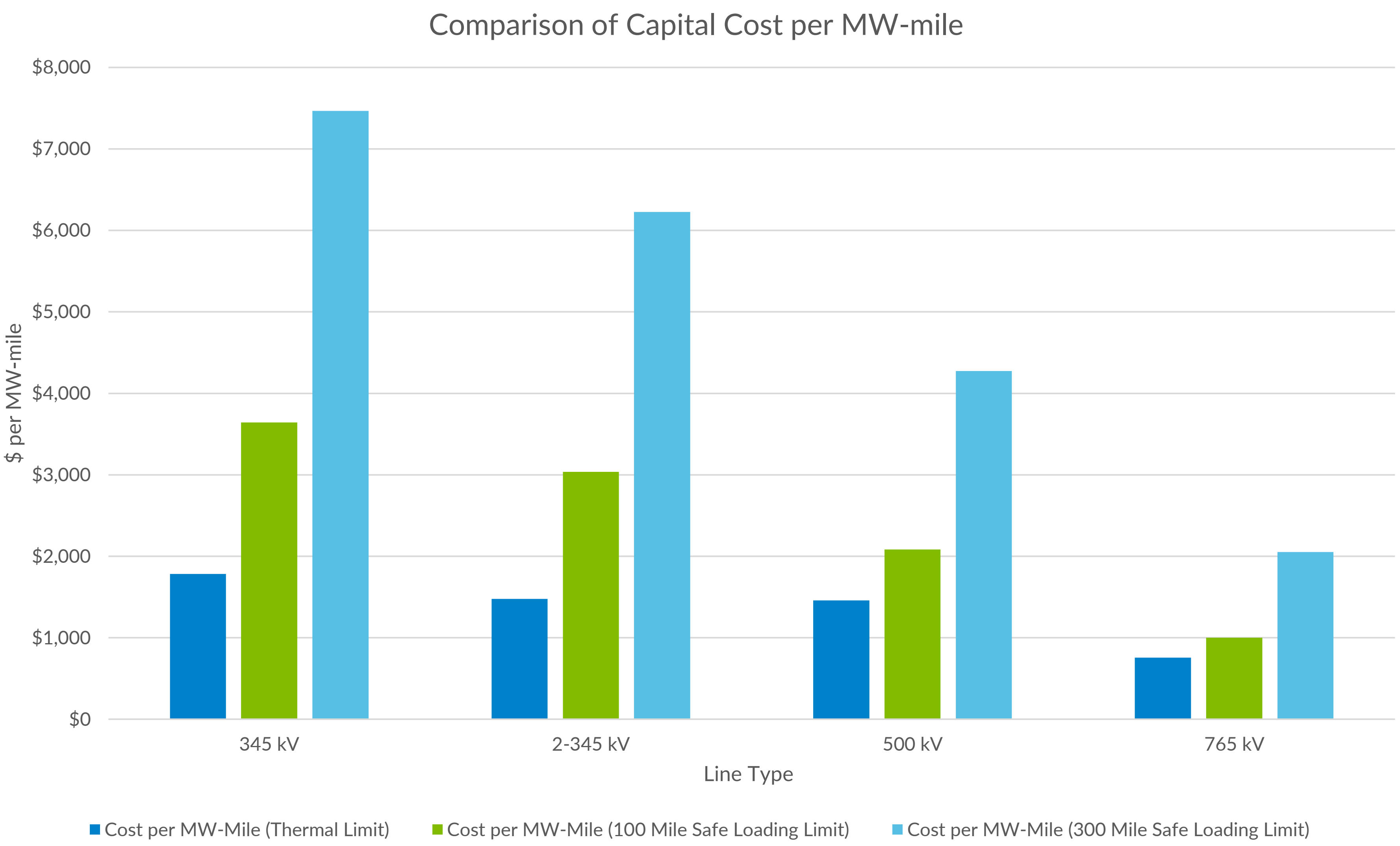
1 - 765 kV Circuit

3 - 500 kV Circuits

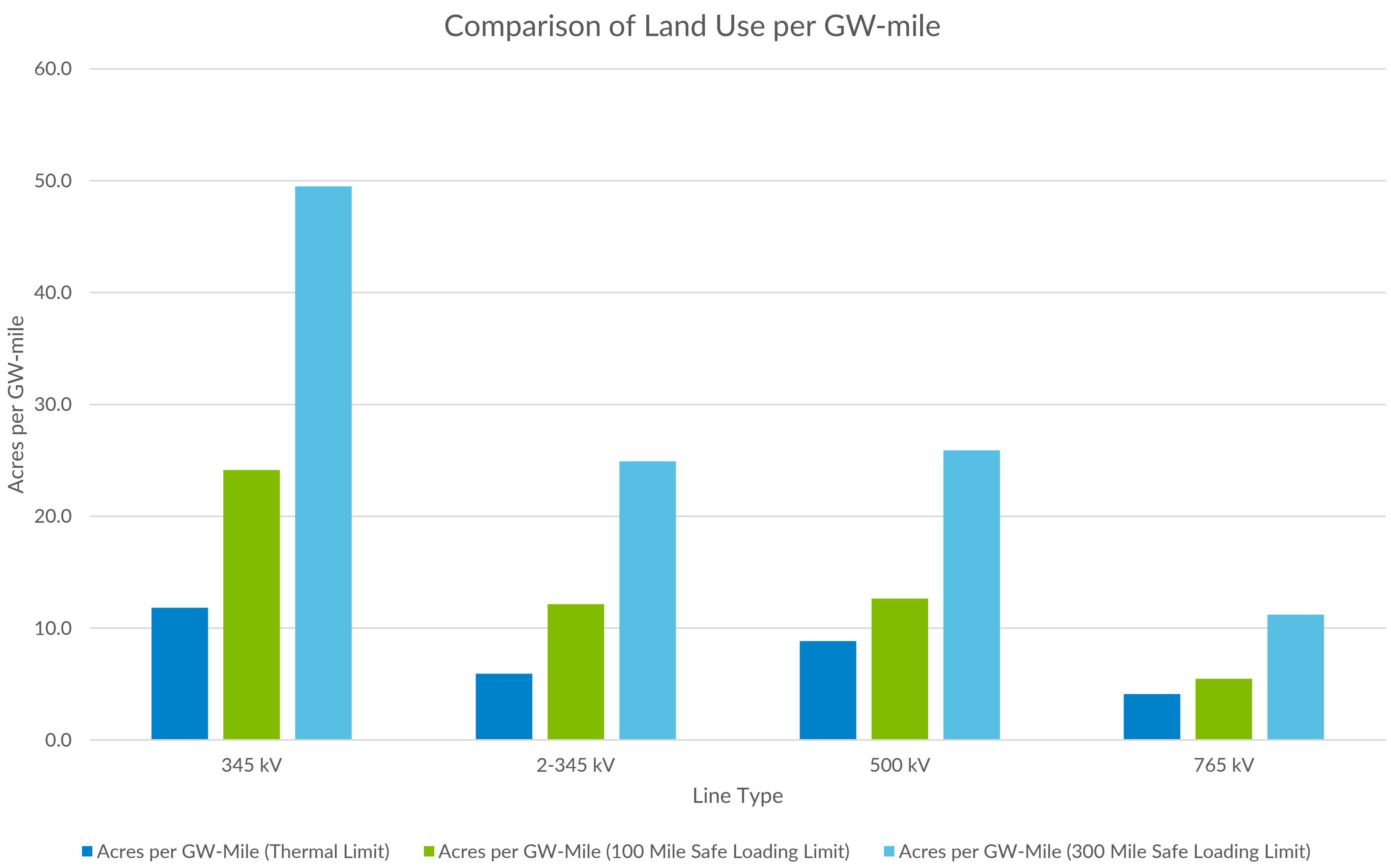
6 - 345 kV Single Circuits

3 – 345 kV Double Circuits

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



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



Transmission Energy Losses Example

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 of 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
Maximum Annual Energy Losses (MWh)	710,374	403,628

NOTE: Conductor I^2R loss reductions could be partially offset by higher Corona losses.

345 kV vs. 765 kV Contingency Impacts

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

- However, a more robust 765 kV design can result in the elimination of many of the higher order contingency types for 765 kV facilities, including:

    - NERC TPL-001 P7 Double-circuit line contingencies
    - NERC TPL-001 P5 Protection system failure contingencies
    - NERC TPL-001 P4 Stuck breaker contingencies
    - NERC TPL-001 P2.3 and P2.4 Internal breaker fault contingencies
    - NERC TPL-001 P2.2 Straight bus contingencies

- Furthermore, if a commitment is made to establish a regional backbone at the 765 kV level and such a backbone can be justified, this can reduce the impact of 765 kV contingencies since there are other 765 kV facilities available to support the loss of one or two 765 kV facilities.

345 kV vs. 765 kV Line Contingency Frequencies

- Everything else equal, the forced outage rate of a transmission line is proportional to line length or line exposure.

- Based on the above, one would expect a 200-mile 765 kV line to have more forced outages over time than a 5-mile 345 kV line, and that is a valid expectation.

- However, given the same line length, historic operating data suggests that the higher the voltage class, the lower the annual faults-per-mile (AFPM) rate.

    - Distribution AFPM Rate > Sub-transmission AFPM Rate
    - Sub-transmission AFPM Rate > HV Transmission AFPM Rate
    - HV transmission AFPM Rate > EHV transmission AFPM Rate

- And limited data also suggests that 345 kV lines tend to have higher faults-per-mile-per-year rates than 765 kV lines.

    - 345 kV AFPM Rate > 765 kV AFPM Rate

HVDC Transmission Applications

There are at least five applications for HVDC Transmission

- **Traditional 1:** HVDC used as a long lead line for remote generating plants:
  - Sometimes referred to as "coal-by-wire", long distance HVDC lead lines were installed to facilitate remote mine-mouth coal-fired generation since long HVDC lines were more economical than long distance fuel transportation.
  - The "high" capacity factor operation of the coal-fired plant and associated HVDC lead line (sized just above the capacity of the coal-fired plant) allowed for HVDC converter costs to be spread across many MWh.
- **Traditional 2:** HVDC used as a back-to-back tie between two asynchronous systems to allow for power transfer between two asynchronous systems.
- **Traditional 3:** HVDC used as a long-distance interregional power transfer mechanism. More common in the Western Interconnection.
- **Merchant:** HVDC used to facilitate long distance energy transfers for "paying customers" (generators and loads) via a subscription service. The line is funded and scheduled by the owner and subject to interconnection service.
- **Dispatchable:** An emerging concept where HVDC is planned by the RTO and funded by the RTO load, placed under the functional control of the RTO, and schedules are co-optimized with the RTO's resources every five minutes via a common real-time Security Constrained Economic Dispatch algorithm.

Comparison of 765 kV with HVDC
Key Takeaways

Key Takeaways for Comparison of 765 kV with 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 the high capital cost of HVDC converters.
  - Provides natural flow response when desired to follow potentially volatile generation dispatch (and load) patterns.
- The benefits of HVDC transmission over 765 kV include the following:
  - Lower capital cost per MW-mile for line lengths above the "250-to-400 mile" range due to the same or lower capital cost per mile for the HVDC line and diminishing 765 kV safe load capacity over longer distances.
  - Provides flow control capabilities when desired to minimize flow on lower capacity parallel AC facilities and to manage congestion on the AC system in general.
  - May provide additional ancillary benefits when not available from other sources.

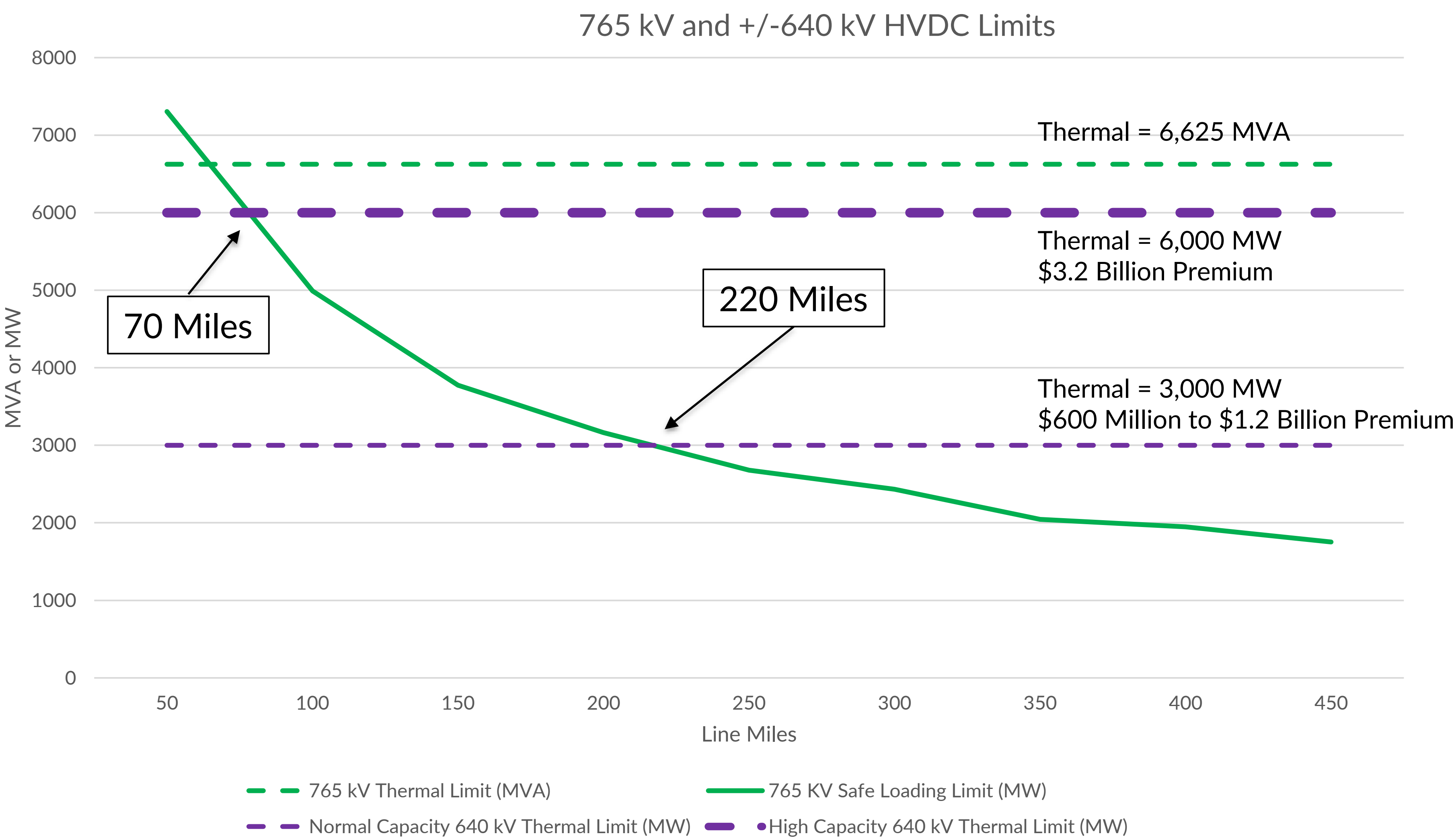
Comparison of 765 kV with HVDC Capital Cost per MW-mile

765 kV vs. HVDC – Incremental Capital cost per MW
2023 Dollars

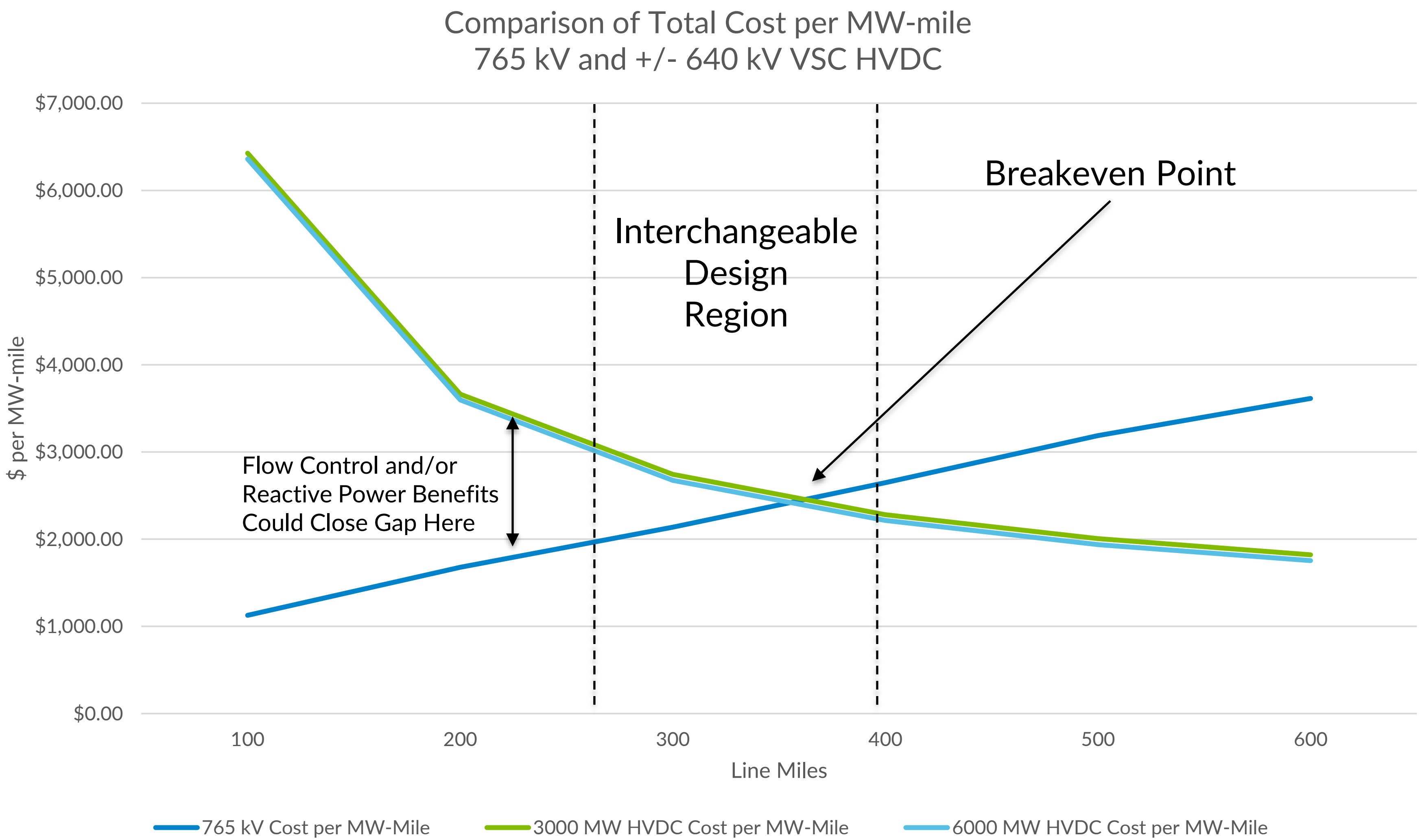
Line Type	Zero-Mileage Cost (Terminal Costs) Million $	Line Cost per Mile Million $ per Mile
765 kV AC Overhead Line (6-795 ACSR Conductor Bundle)	$ 62.6	$5.0
+/- 640 kV, 3000 MW HVDC Bi-pole (2-1590 ACSR Conductor Bundle)	$1,658.0	$2.7
+/- 640 kV, 6000 MW HVDC Bi-pole (6-795 ACSR Conductor Bundle)	$3,316,0	$5.0

- Zero-mileage cost for 765 kV much less than HVDC alternative.
- Line cost per mile for HVDC is either less than or the same as 765kV.
- The 765 kV capacity diminishes with line length whereas the HVDC capacity does not.
- **CONCLUSION:** This implies a mileage break-even point when comparing 765 kV to HVDC.

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



Comparison of 765 kV with HVDC Flow Control vs. Natural Response

AC vs. HVDC Flows

- As we all know, flows on AC transmission lines are a natural function of:
  - The topology and characteristics (e.g., impedances, etc.) of the transmission system.
  - Location and magnitude of generation and load.
  - Status of transmission facilities (outages, etc.).
- There are technologies that can assist in controlling the flow on AC lines, but these technologies are generally applied only in special circumstances:
  - Switchable series reactors and capacitors (very limited control options – in or out)
  - Phase angle regulating transformers (rough control at best)
  - Static synchronous series compensators (more precise control)
- HVDC flows are precisely scheduled or controlled. Potential options include:
  - Manually entered schedules
  - Automatic controls to follow the output of a source generation resource
  - Automatic controls to emulate an AC transmission Line (based on voltage phase angle difference and a simulated impedance)
  - Potentially dispatching HVDC flows in real-time via Security Constrained Economic Dispatch to co-optimize resource outputs with HVDC schedules.

AC Flows are Natural - HVDC Flows are Controlled

- The flows on AC transmission lines are determined naturally by the topology of the system and location of generation and loads
  - AC flow control simply modifies the characteristics of the AC system.
- The response of AC transmission flows to changes in generation, load and system topology is natural and instantaneous.
- Natural flows and instantaneous response on AC transmission lines can be a good thing or a bad thing.
- The flows on HVDC transmission lines are controlled or scheduled rather than natural.
- The response of HVDC transmission flows to changes in generation, load and system topology requires manual intervention or control action, and while it can be fast, it is not instantaneous.
- The requirement of flows on HVDC transmission lines to be controlled or scheduled can be a good thing or a bad thing.

Pros of HVDC Flow Control

- The ability to control flows on HVDC lines can provide a number of benefits.
- Because HVDC flows are schedules and not dependent on the transmission system topology and characteristics, the entire capacity of an HVDC line can be used whenever needed and there is no risk that a generation or AC transmission contingency will cause the HVDC line to overload on a post contingent basis.
- This allows an HVDC bi-pole line to act like a “vacuum cleaner”, absorbing flow off of heavily loaded parallel AC lines up to the capacity of the HVDC line without a risk that the HVDC bi-pole could become overloaded.
  - NOTE: The underlying AC system must be strong enough to withstand a mono-pole or bi-pole trip of the HVDC facility.
- One or more HVDC bi-pole lines can also be used to manage AC transmission congestion and minimize overall transmission system losses if the HVDC line flows can be co-optimized in real-time with resource outputs via a centralized Security Constrained Economic Dispatch algorithm.

Cons of HVDC Flow Control

- While the ability to control flows on HVDC lines can provide a number of benefits, the lack of natural response on HVDC lines can be problematic under a future where generation dispatch (and possibly load) is much more volatile.
- Fast morning ramp-down of wind in one region coupled with fast morning ramp-up of solar in another region (or vice versa) can cause very fast and significant changes to flow patterns on the AC system.
- If HVDC schedules do not follow these fast and significant changes in resource dispatch, they can create substantial congestion and/or reliability risk on the underlying AC transmission system.
- VSC HVDC equipment is capable of very fast response and bi-directional response, so there are two strategies to mitigate this phenomenon which will be briefly discussed on the next two slides.

Mitigation Strategy 1
Create Natural Flow Response on the HVDC System

- One method to mitigate the requirement for flow control and lack of natural flow response of an HVDC line is to install a control system that emulates the natural response of an AC line.
- Such a control system would simulate a predetermined proxy AC line impedance and then continuously control flows on the HVDC bi-pole based on the phase angle difference between the AC bus voltages at the sending and receiving ends of the line.
- For long distances where the capacity of an AC line is significantly derated, this is a promising strategy.
- For shorter distances where there is sufficient capacity in an AC line, it would likely be best to simply install an AC line and save the cost of the HVDC converter equipment that would otherwise be required.

Mitigation Strategy 2
Co-optimize Resource Output with HVDC Flow via SCED

- A more promising mitigation strategy being pursued by MISO is to allow the Security Constrained Economic Dispatch algorithm that clears the real-time market to co-optimize HVDC schedules with resource output every five (5) minutes.
- This does not provide instantaneous response but does allow for automatic control of HVDC schedules to occur every five (5) minutes based on data that is ten (10) to fifteen (15) minutes old (i.e., real-time SCED dispatch is every five (5) minutes and initiated about ten (10) minutes ahead of the targeted dispatch time point in the real-time market using inputs that are up to five (5) minutes old).
- Co-optimizing HVDC and resource dispatch via SCED mitigates or eliminates potential transmission congestion.
- MISO developed some conceptual formulations for this strategy about five (5) years ago and is now working with NREL to test and enhance these potential formulations.

Co-optimize Resource Output with HVDC Flow via SCED Potential Terms and Conditions

- The MISO proposal to co-optimize HVDC flow would apply only to HVDC bi-poles that are:
  - Completely internal to the MISO footprint
  - Selected by the MISO regional planning process and funded and controlled by MISO
- Dispatchable HVDC would not require market participants nor bids and offers.
- Therefore, co-optimization would **<u>not</u>** apply to:
  - Interregional HVDC bi-poles connecting MISO with another RTO or other external area.
    - **WHY?** In real-time markets, all real-time interchange schedules are determined manually since they must balance and the two different market SCED algorithms will in general specify different dispatches for interregional schedules.
  - Merchant HVDC lines that are funded outside of MISO by subscription service and subject to the MISO generation interconnection process.
    - **WHY?** Externally funded HVDC lines are scheduled by external parties based on the terms and conditions of subscription service and associated interconnection service rights and not funded by or under the functional control of MISO.

Co-optimize Resource Output with HVDC Flow via SCED Successes and Challenges

- Five (5) years ago, MISO developed conceptual formulations (additional primal variables, additional objective function terms and additional constraints) for use in the LP solver that implements the market Security Constrained Economic Dispatch algorithms for the purpose of co-optimizing HVDC schedules with resource outputs.
- These conceptual formulations were capable of modeling HVDC losses using a stepped piece-wise linear approximation of the quadratic HVDC losses curve.
- More recently, MISO partnered with NREL to test these formulations, determine potential issues and continue refining the formulations.
- The results are:
  - When offers are positive, the conceptual formulations worked as intended.
  - When offers are negative (driven by production tax credits), the real-time SCED objective function wants to maximize transmission losses, and this can create erratic and undesirable HVDC schedules.
  - MISO and NREL are working to resolve these issues.

VSC HVDC – Ancillary Benefits

VSC 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 distance AC lines and conventional HVDC Line Commutated Converters (LCC) 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 rather than consume net reactive power.

- The newer Voltage Source Converter (VSC) HVDC technology eliminates reactive power consumption issues associated with LCC HVDC converters

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

VSC HVDC Grid Forming Benefits

- Unlike LCC technology, VSC HVDC technology allows the HVDC converters to form AC voltage waveforms.

- Voltage waveform formation has been a crucial, and often overlooked, function of synchronous machines in the past and will not be available from LCC HVDC converters or grid following inverters.

- The grid forming benefits provided by VSC HVDC converters can help ensure continued reliable formation of grid voltage waveforms (magnitudes, phase angles, and frequencies) across the interconnection in a future world where there are substantially fewer synchronous machines on-line.

- In addition, VSC HVDC technology will allow resources in an asynchronous area to provide black start capacity via VSC HVDC back-to-back asynchronous ties, which is not available with asynchronous ties using back-to-back HVDC LCC technology.

Assessing VSC HVDC Ancillary Benefits

- While there are specific dynamic reactive power and voltage waveform formation benefits provided by VSC converters, quantifying the specific value of these benefits must consider if there are other sources for these benefits.
- To the extent synchronous machines are displaced by grid forming inverter-based resources, the grid forming inverter-based resources can replace the lost dynamic reactive power and voltage waveform generation capabilities of synchronous machines.
  - Grid following inverters can also provide dynamic reactive power capabilities.
- While the power factor ratings of inverters may not be as great as traditional synchronous machines, these inverters in aggregate will likely provide sufficient dynamic reactive power capability anyway because:
  - The aggregate nameplate capacity of inverters will be higher than synchronous machines due to lower capacity credits assigned to renewable resources
  - Inverters can be configured to remain on-line supplying reactive power at all times.
- In the end, the value of the ancillary benefits of VSC converters will come down to whether or not these benefits are already available from other sources.

765 kV vs. HVDC – Contingency Impacts

765 kV vs. 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 considered a NERC TPL-001 N-2 contingency (P7) whereas the loss of a 765 kV circuit or one pole of an HVDC bi-pole is considered a NERC TPL-001 N-1 contingency (P1).

- 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.

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

Interchangeability between 765 kV and HVDC

What is an Interchangeable Line Design?

- An interchangeable line design provides flexibility by allowing a line to initially be operated as a 765 kV AC line and then converted to HVDC later by:
  - Adding converters at the terminating substations.
  - Using the middle phase conductor as a metallic return conductor.
  - Replacing the transposition structures if used for 765 kV.
- The high thermal current capability of 765 kV 6-conductor bundles could allow for a 765 kV line to be converted to an HVDC bi-pole with a capability of up to 6,000 MW.
- A given interchangeable transmission line can:
  - Initially serve as a 765 kV AC line
  - Later convert to a 3000 MW HVDC bi-pole line by adding two converters
  - Later expand to a 6000 MW HVDC bi-pole line by adding two additional converters
- At a future date, an HVDC line could be converted back to 765 kV to avoid aging converter replacement if HVDC is no longer needed.
- NOTE: In 2020, MISO staff consulted with EPRI, a major HVDC converter manufacturer, industry consultants and a major insulator manufacturer to further explore this concept.

Interchangeable Line Design Details – Maximum Peak AC Voltage vs. Maximum Sending-end HVDC Voltage

- The nominal <u>peak</u> line-to-ground AC voltage for a 765 kV transmission line is:
  - Nominal Peak LG Voltage (765 kV) = $(2)^{1/2}$ * 765 kV / $(3)^{1/2}$ = 624 kV

- Assuming 765 kV is designed to operate continuously at 105% of nominal voltage, the maximum <u>peak</u> line-to-ground AC voltage for which a 765 kV transmission line is designed is as follows:
  - Maximum Peak LG Voltage (765 kV)= 624 kV * 105% = 655 kV

- The maximum continuous line-to-ground DC voltage for high-capacity HVDC circuits at the sending-terminal are:
  - Maximum Sending-end LG Voltage (+/- 500 kV HVDC) = 500 kV *1.05 % = 525 kV
  - Maximum Sending-end LG Voltage (+/- 640 kV HVDC) = 640 kV *1.05% = 672 kV

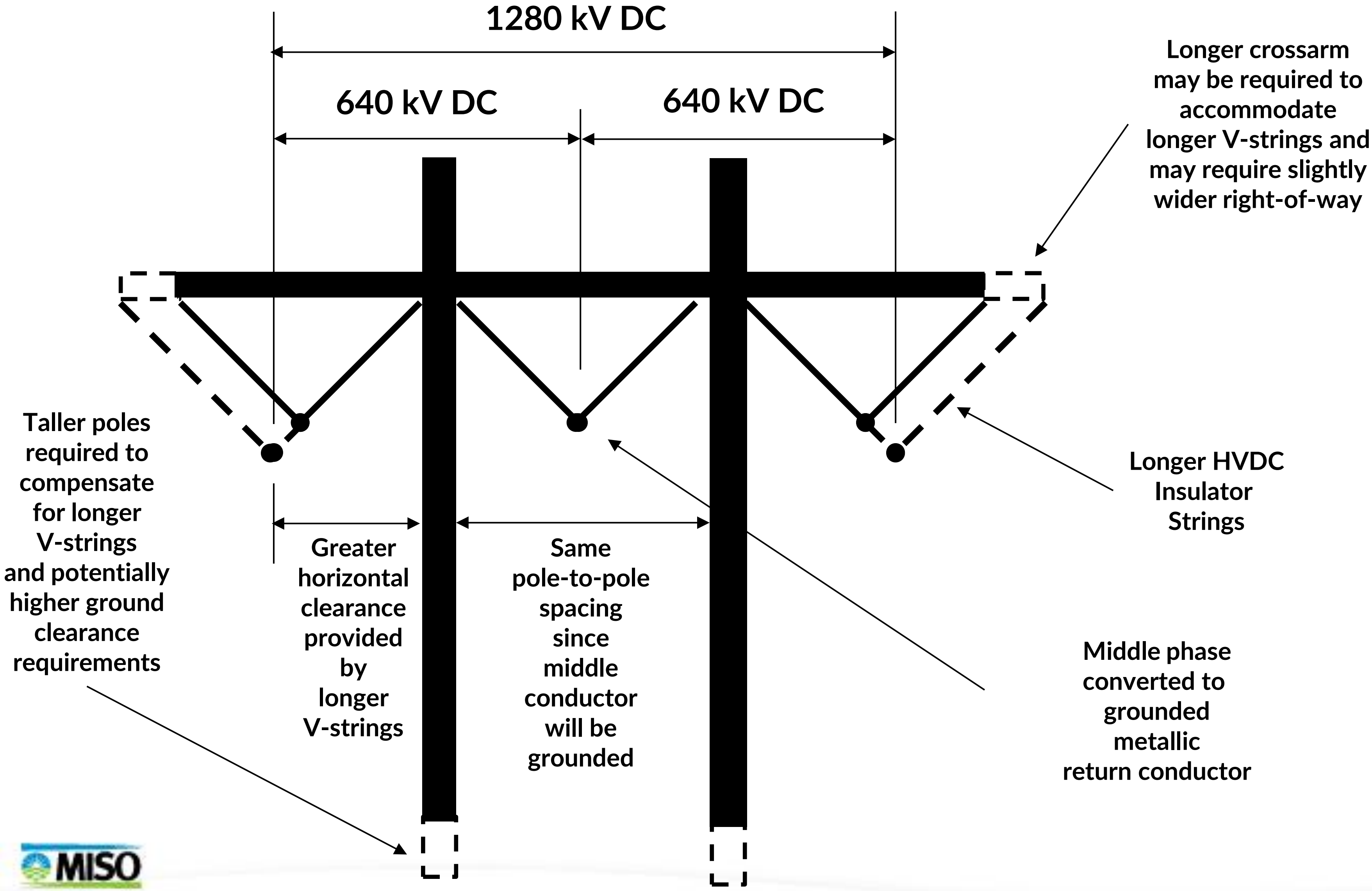
Interchangeable Line Design Details - Insulation and Clearance Requirements

- When comparing the maximum peak line-to-ground kV on a 765 kV line with the maximum sending-end line-to-ground kV on high-capacity HVDC bi-poles, the following is observed:
  - When comparing 765 kV with +/- 500 kV HVDC………

    the maximum peak ling-to-ground AC voltage is 125% of the maximum sending-end line-to-ground DC voltage.
  - When comparing 765 kV with +/- 640 kV HVDC…………

    the maximum peak line-to-ground AC voltage is 97% of the maximum sending-end line-to-ground DV voltage.
- Based on the above:
  - Existing 765 kV lines could be repurposed as +/- 500 KV HVDC lines by adding converters at the terminals with no change to the 765 kV line other than replacing transposition structures.
  - Future 765 kV lines could be built for eventual conversion to +/- 640 kV HVDC with some minor design adjustments.

Hypothetical Interchangeable Structure for +/- 640 kV HVDC Steel H-Frame



Conclusions

Key Conclusions and Takeaways

- The best transmission system plan is one with an "all things considered" strategy.
- When legacy voltages are preferable, such voltage levels should align with those that already exist in the area (345 kV or 500 kV).
- When considering 765kV, there should be sufficient justification to establish a 765 kV regional backbone or overlay, not just one or two 765 kV lines.

	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	• Better suited for incremental needs	• Lower capital cost • Lower land usage • Lower losses	• Lower 765 kV capital costs except for very long lines. • Natural flow response on 765 kV	• Lower HVDC capital costs on very long lines • HVDC flow control capabilities • HVDC reactive power mitigation
Cons	• Higher capital cost • Higher land usage • Higher losses	• Not suited for incremental needs	• Higher 765 kV capital costs on very long lines • No or limited flow control capabilities on 765 kV if needed • Potential reactive power issues	• Higher HVDC capital costs except for very long lines. • No natural flow response unless emulated • Not suited for incremental needs

Questions

Appendix 1
Transmission Limit Considerations

Historic Role of Limits

- Legacy transmission lines were constructed primarily for local purposes.
- The shorter lengths 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 most transmission systems in the past with some notable exceptions.

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 high-capacity conductors could increase thermal limits but will have little to 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 could reduce 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 (referred to as the MPTL) is a physical limit that cannot be exceeded.
- The maximum power transfer limit for an AC transmission line (also referred to as the steady state stability limit or SSSL) is inversely related to line length and given by the following formula:

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

where V_S = Voltage at Sending Terminal in $kV_{\varphi\varphi}$
V_R = Voltage at Receiving Terminal in $kV_{\varphi\varphi}$
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:

DC 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 Appendix 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 as guidance 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.
- See Appendix 3 for more details on Safe Loading Limits.

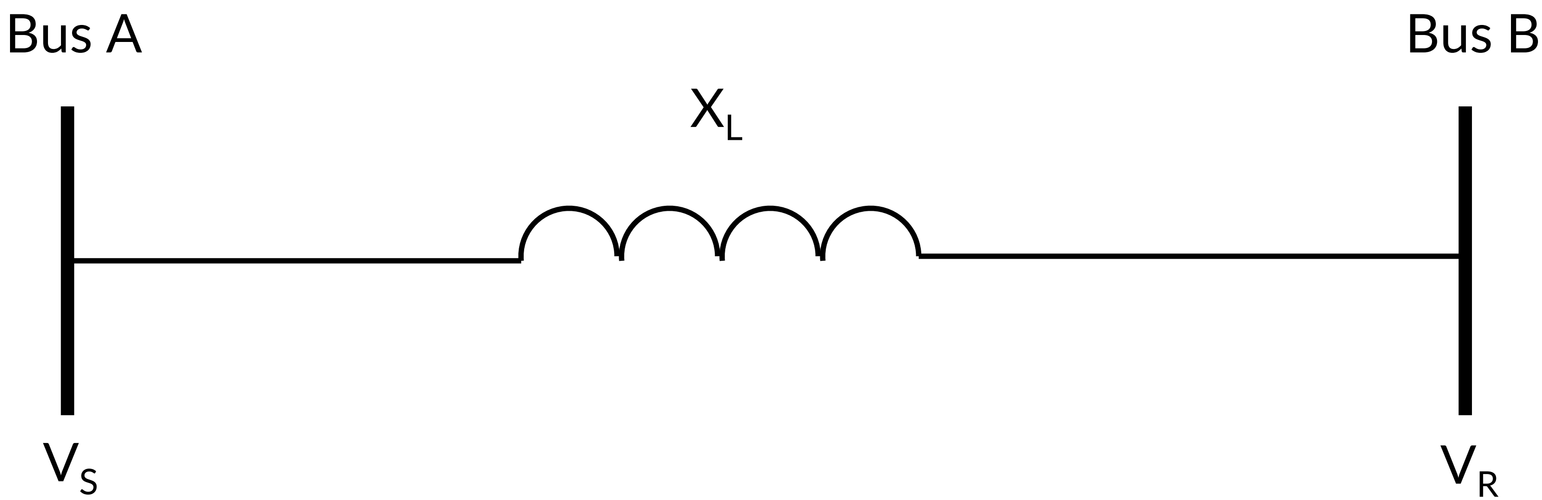
Appendix 2
Maximum Power Transfer Limits

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

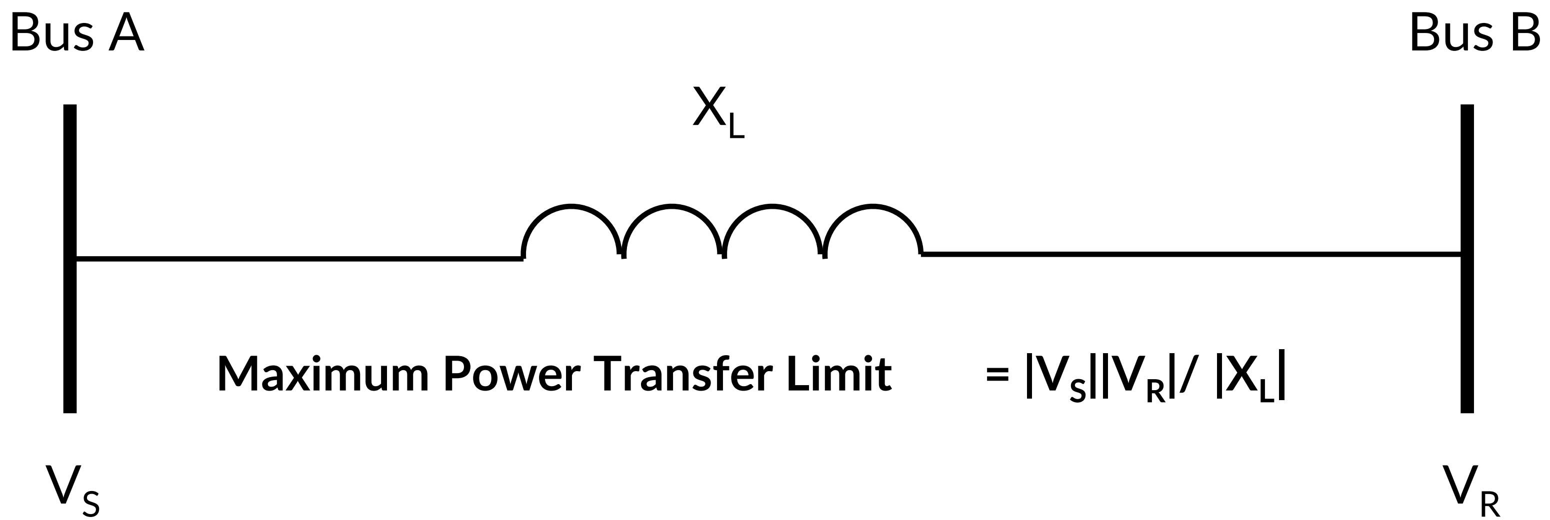


Maximum Power Transfer Limit - AC Transmission Line

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:

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

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



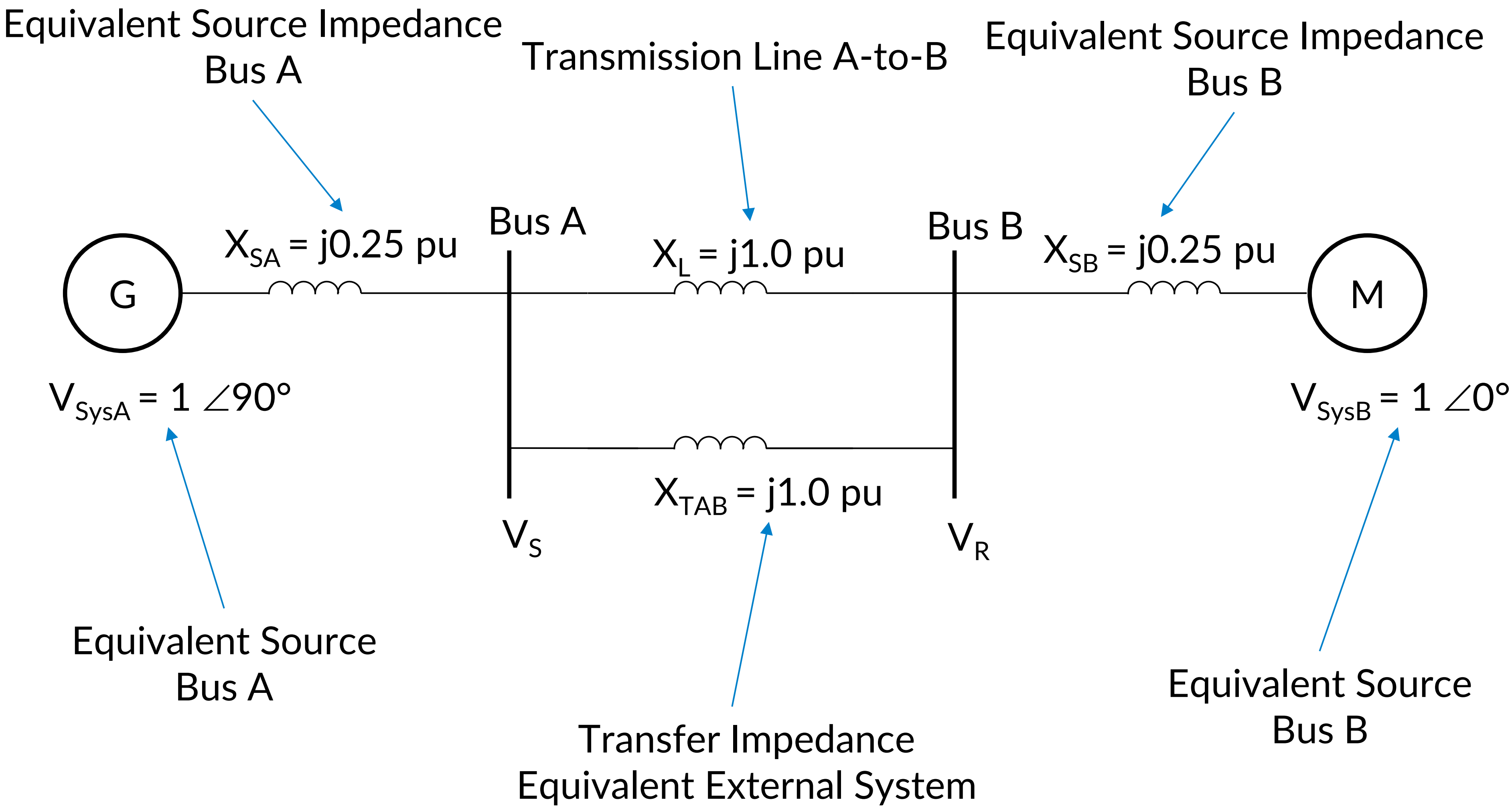
Maximum Power Transfer Limit
With and Without Consideration of External System

- 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%)

Two Maximum Power Transfer Limits for a Branch

- A transmission impedance branch has two maximum power transfer limits:
  - $\mathbf{MPTL_{Branch}}$ = The calculated limit when the external system is ignored.
  - $\mathbf{MPTL_{BranchSystem}}$ = The calculated limit when the external system is considered.

- The formulae for each type of maximum power transfer limit are as follows:
  - $\mathbf{MPTL_{Branch}} = |V_S||V_R|/|X_L|$
  - $\mathbf{MPTL_{BranchSystem}} = \{|V_{SA}||V_{SB}| \,/\, |[X_{SA} + X_{SB} + X_L||X_{TAB}]|\} * DF$

Where

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

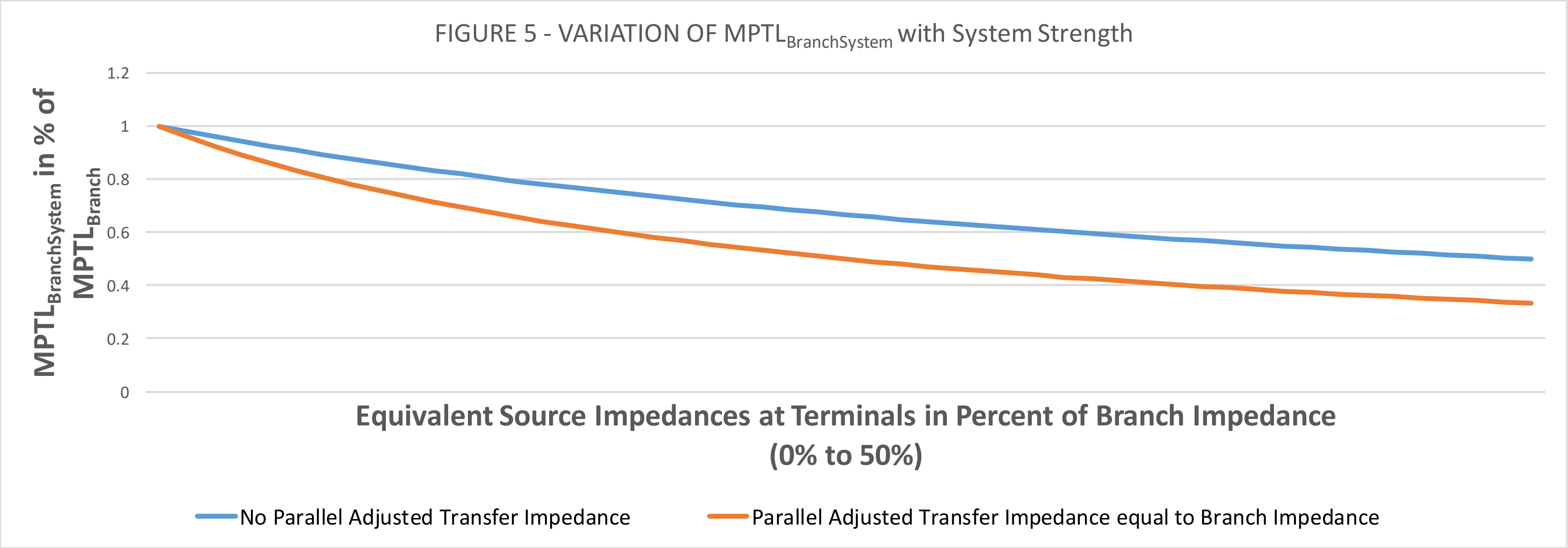
DF = $|X_{TAB} / [X_L + X_{TAB}]|$ if external transfer impedance is less than infinite

- $MPTL_{Branch} = MPTL_{BrnachSystem}$ 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 $X_{TAB} = X_L$

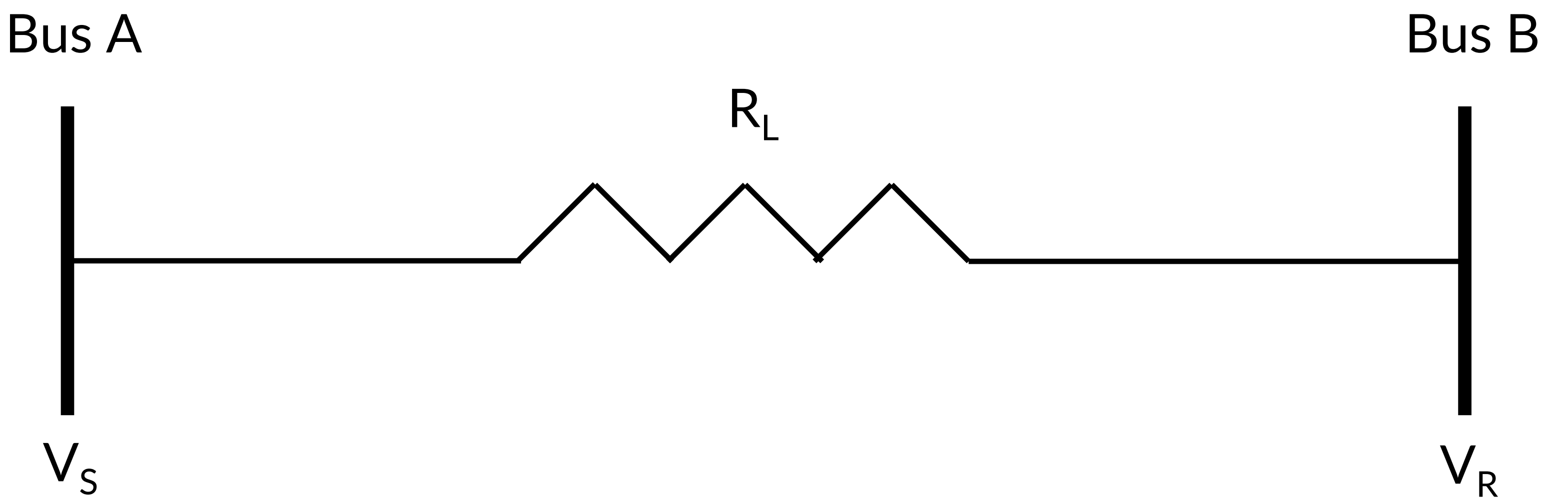


Power Transfer through an HVDC Bi-pole

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:

$$\text{Power Flow (Per Unit or MW)} = 2^*[V_S][V_S - V_R] / R_L$$

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



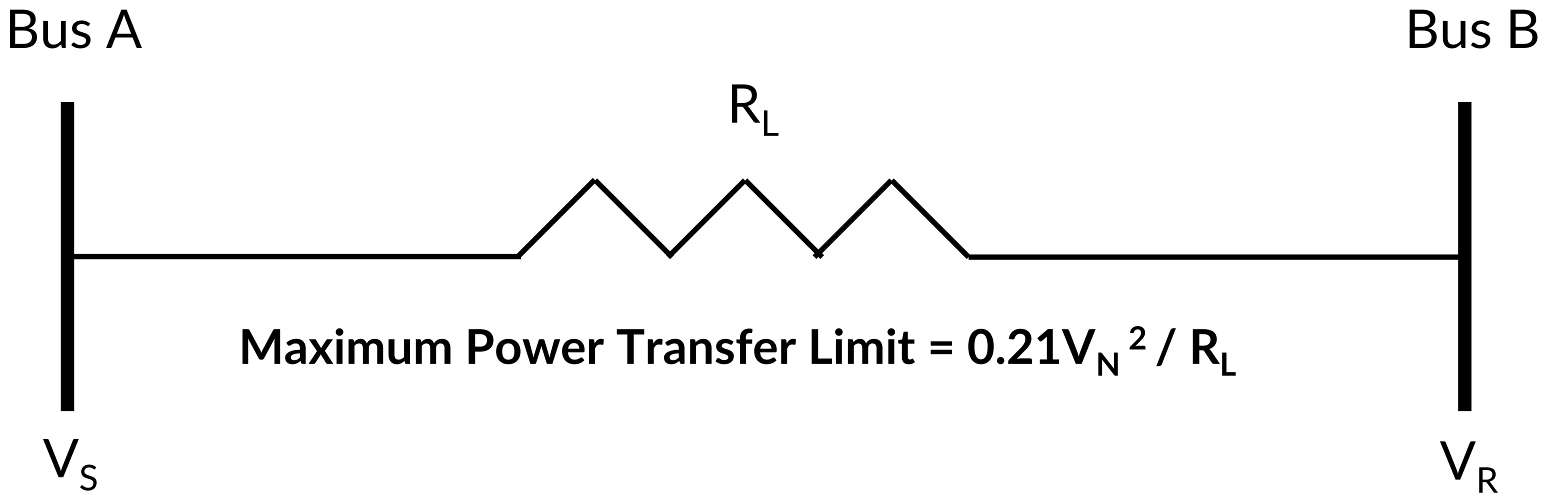
Maximum Power Transfer Limit - HVDC Bi-pole

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

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

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 or steady state stability limit and the safe loading limit)
- In practice, for shorter lines (≤ 200 miles), the voltage drop criteria (≤ 5.0%) tends to drive the safe loading limit and for longer lines (>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.
- $SIL = (V_{\phi\phi})^2 / (L/C)^{1/2}$

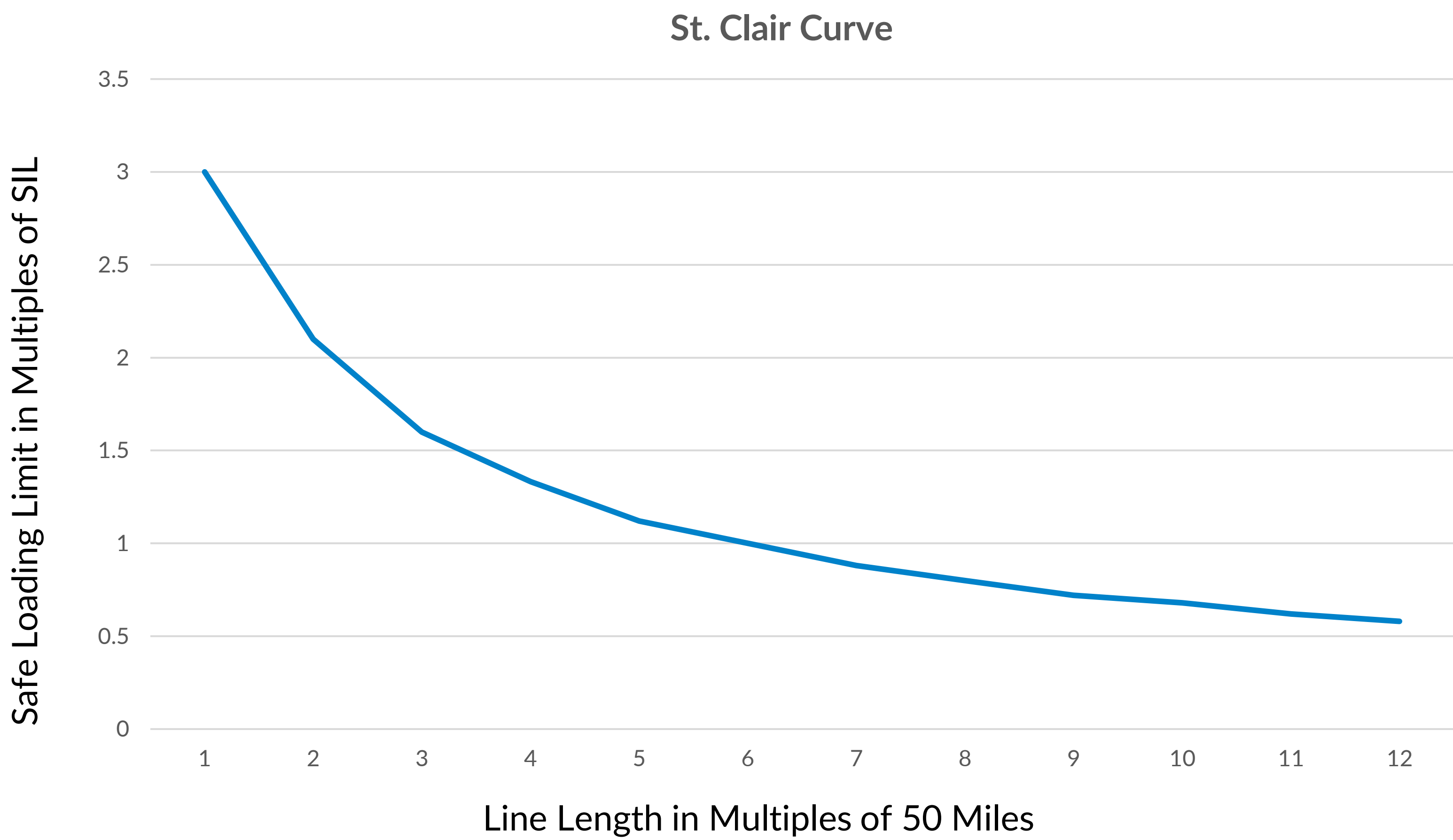
  where

  - 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 (200 miles and under) and angular displacement dominates for longer lines (above 200 miles).
- **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

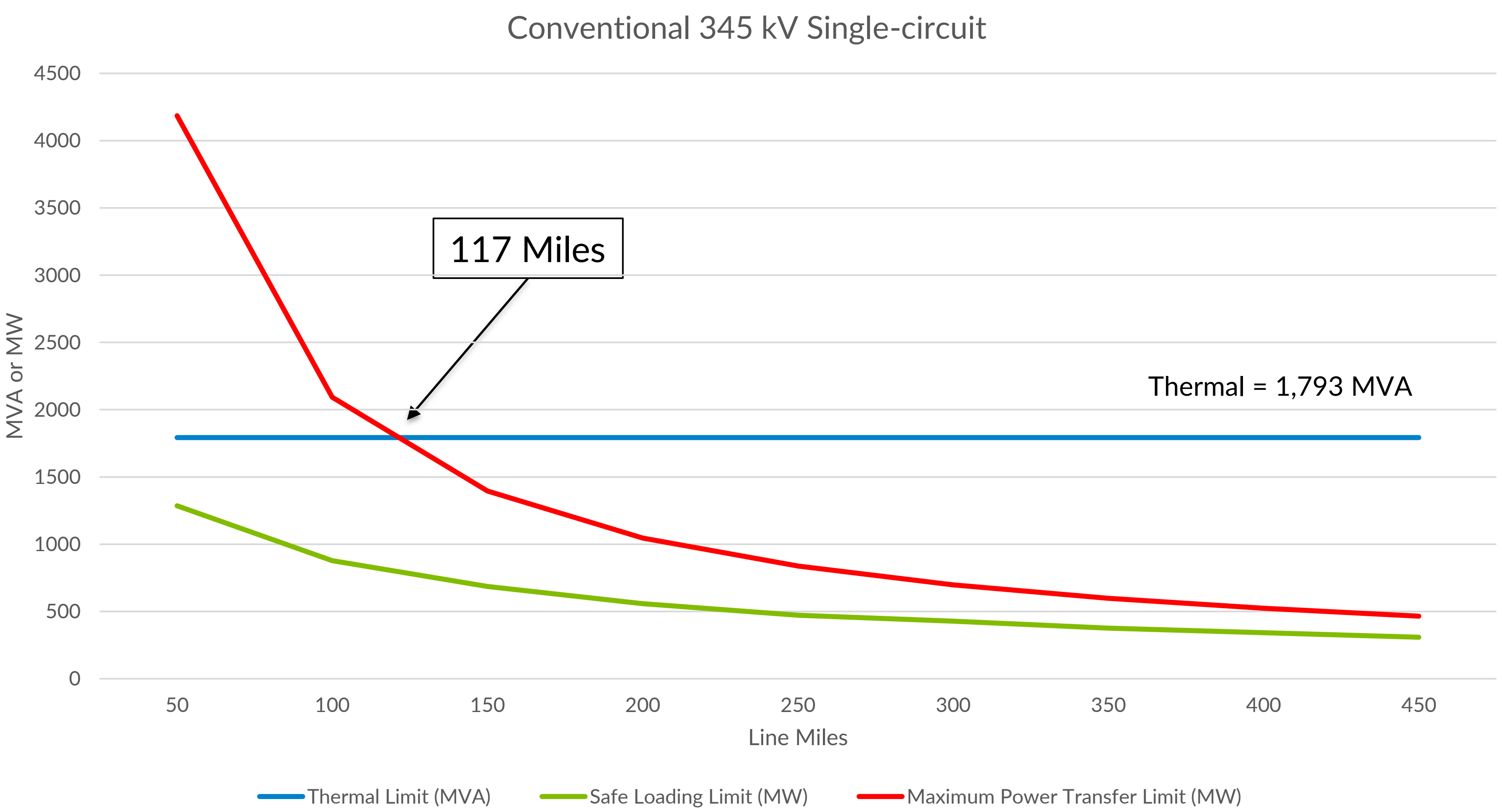
St. Clair Curve**



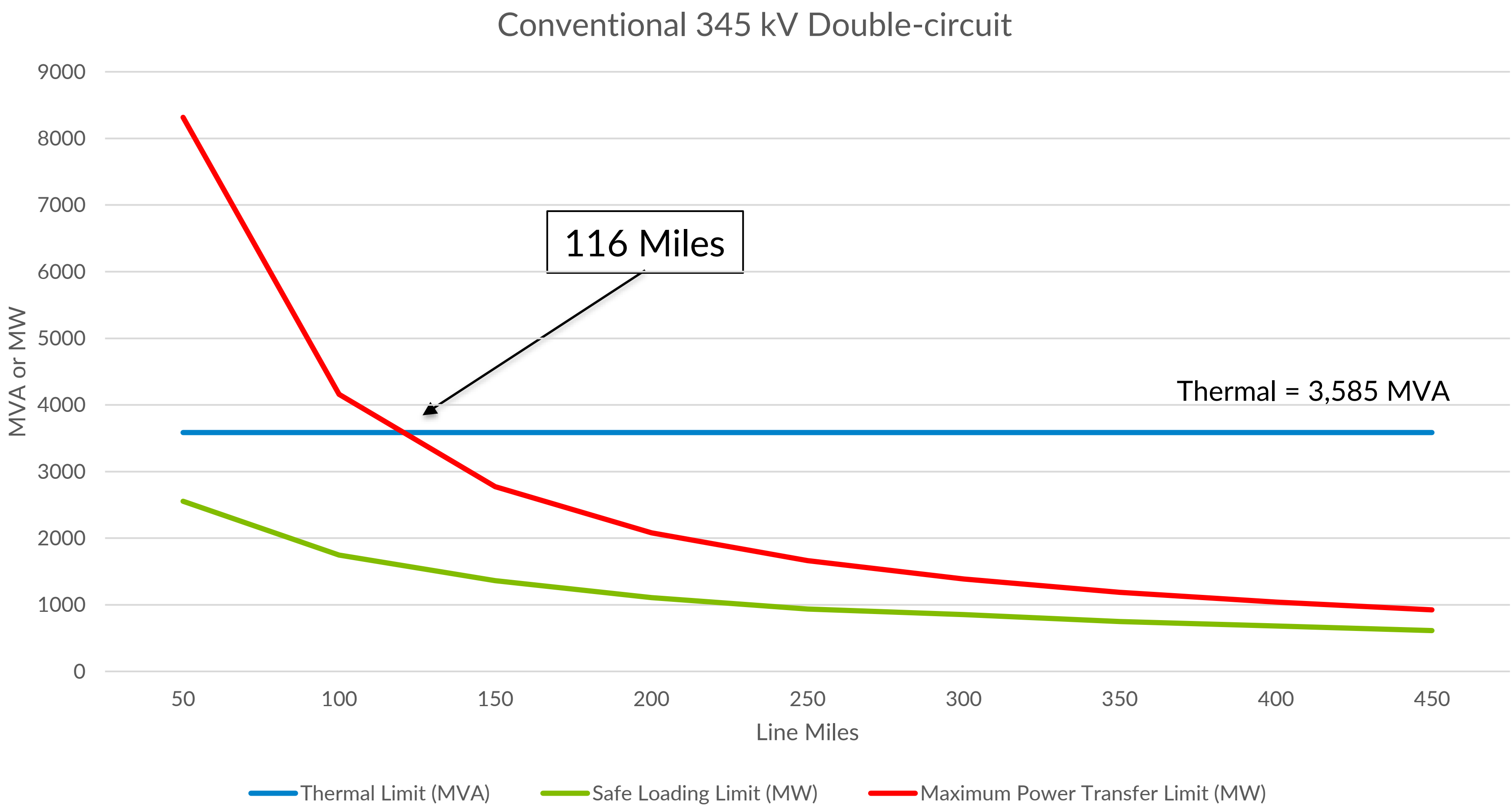
**Dunlop, R.D., Gutman, R., Marchenko, P.P., *Analytical Development of Loadability Characteristics for EHV and UHV Transmission Lines,* IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 2, March/April 1979.

Appendix 4
EHV and HVDC Limit Curves

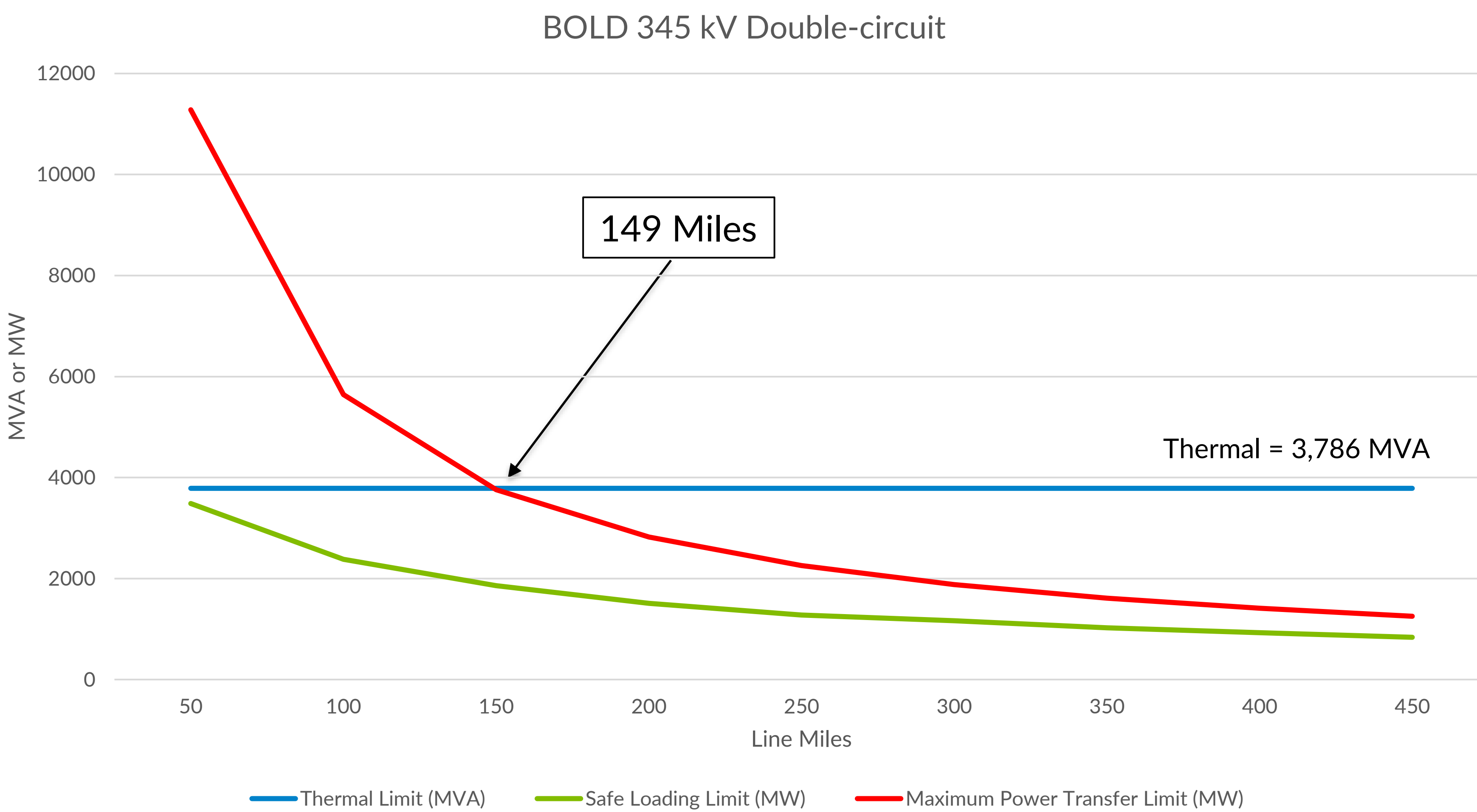
Comparison of Typical 345 kV Limits
Conventional Single-circuit, 2-Conductor Bundle
Surge Impedance Loading = 429 MW



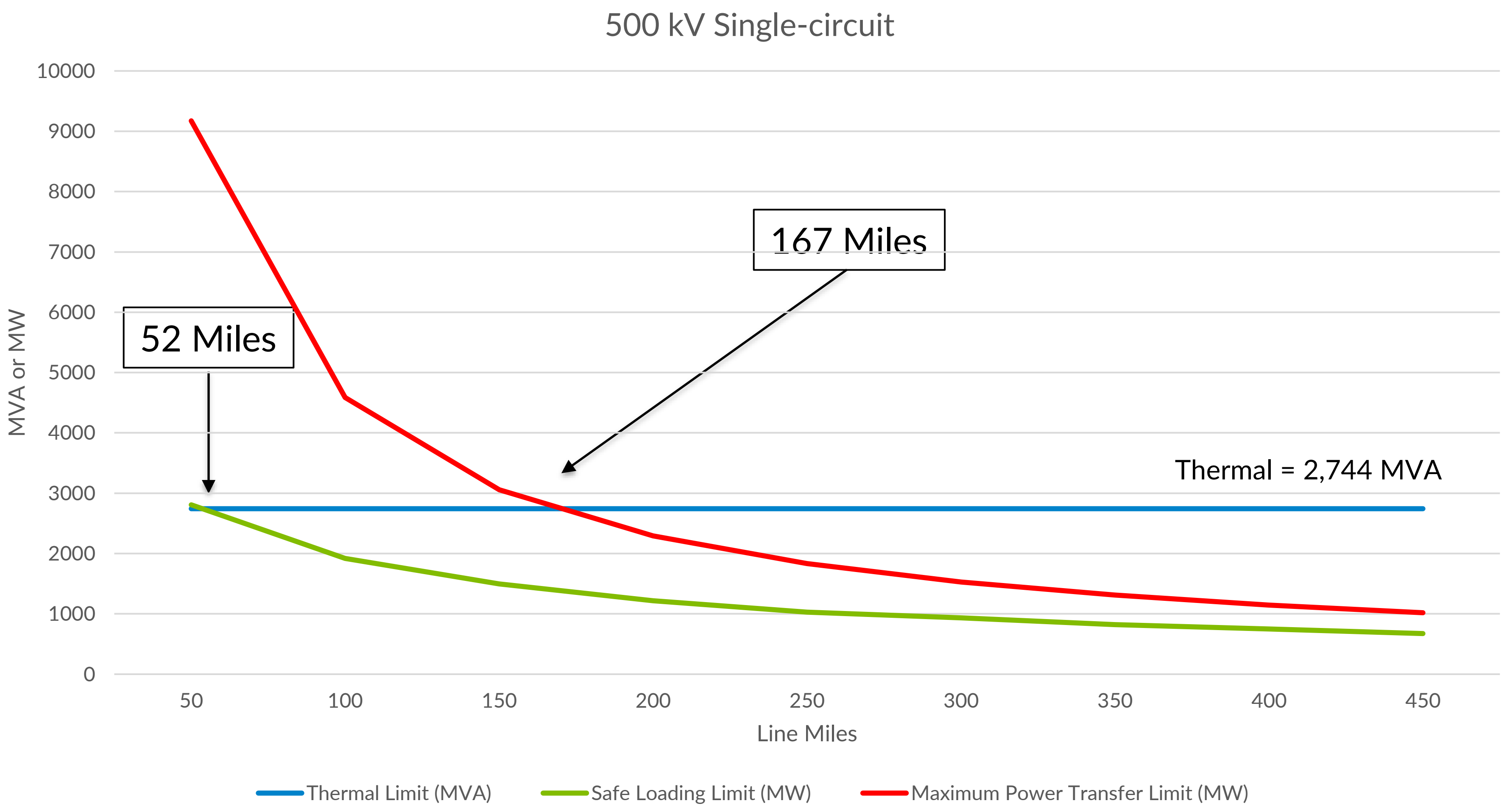
Comparison of Typical 345 kV Limits
Conventional Double-circuit, 2-Conductor Bundle
Surge Impedance Loading = 851 MW



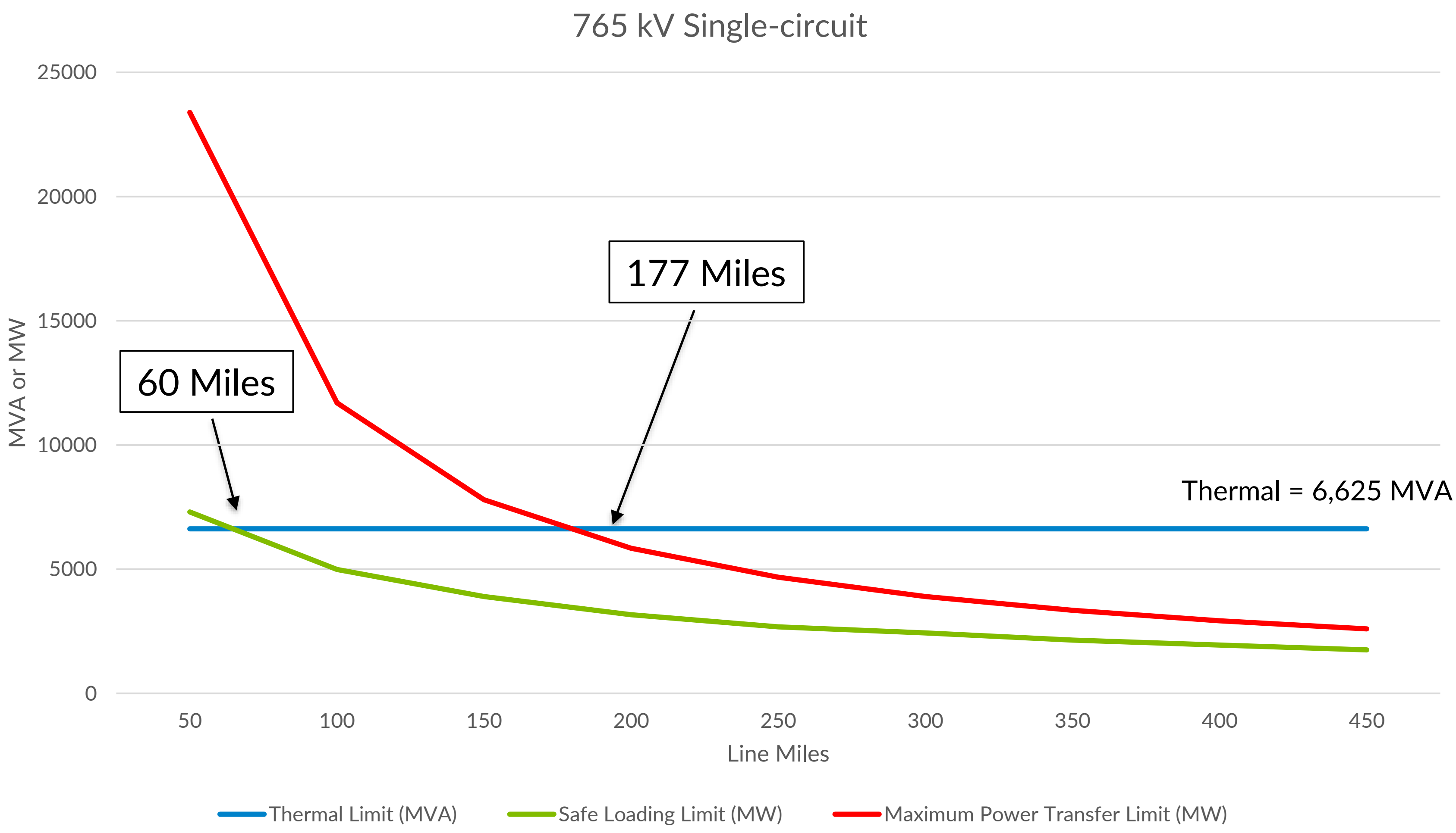
Comparison of Typical 345 kV Limits
BOLD Double-circuit, 3-Conductor Bundle
Surge Impedance Loading = 1,162 MW



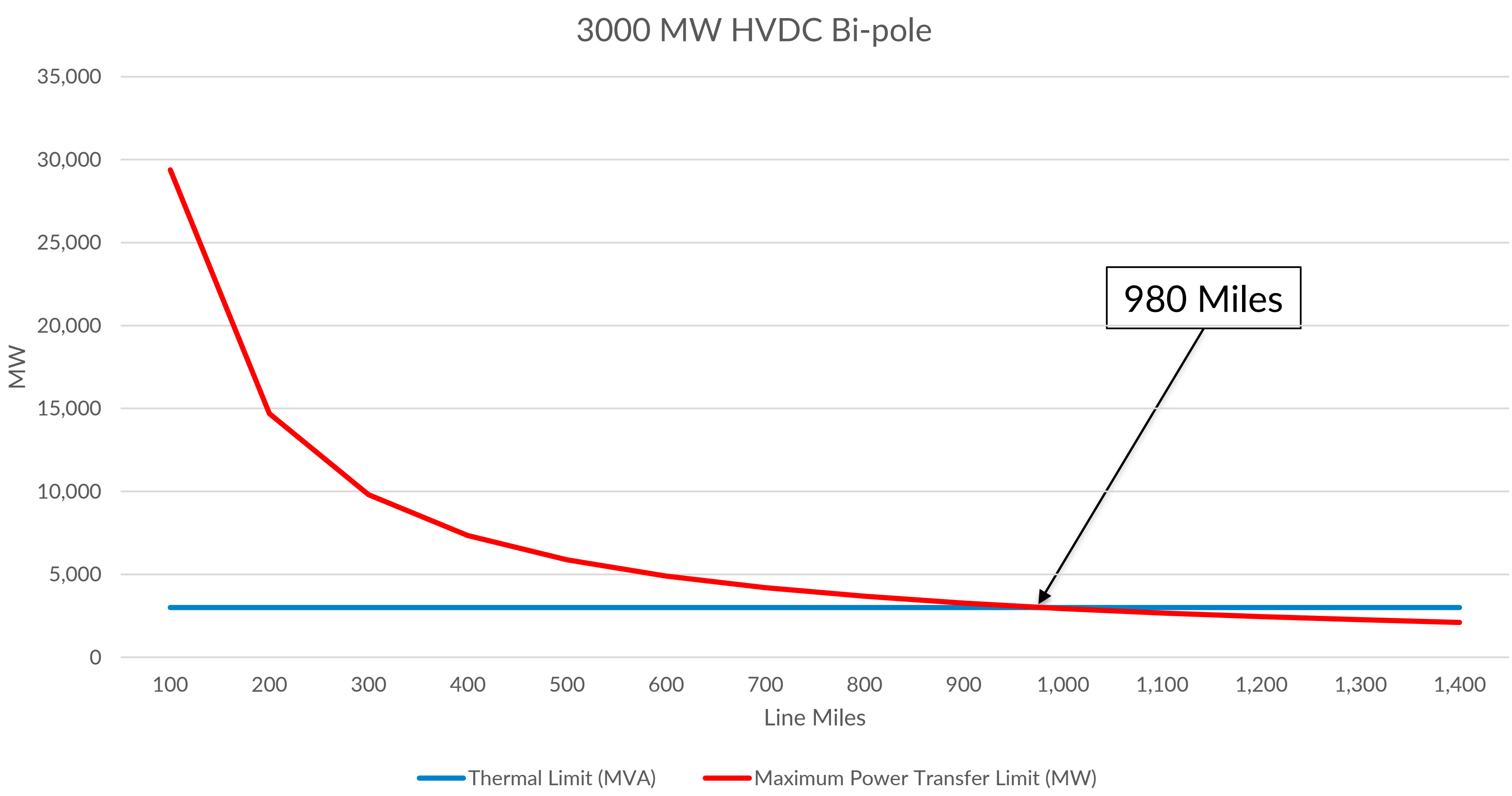
Comparison of Typical 500 kV Limits Single-circuit, 3 - Conductor Bundle Surge Impedance Loading = 936 MW



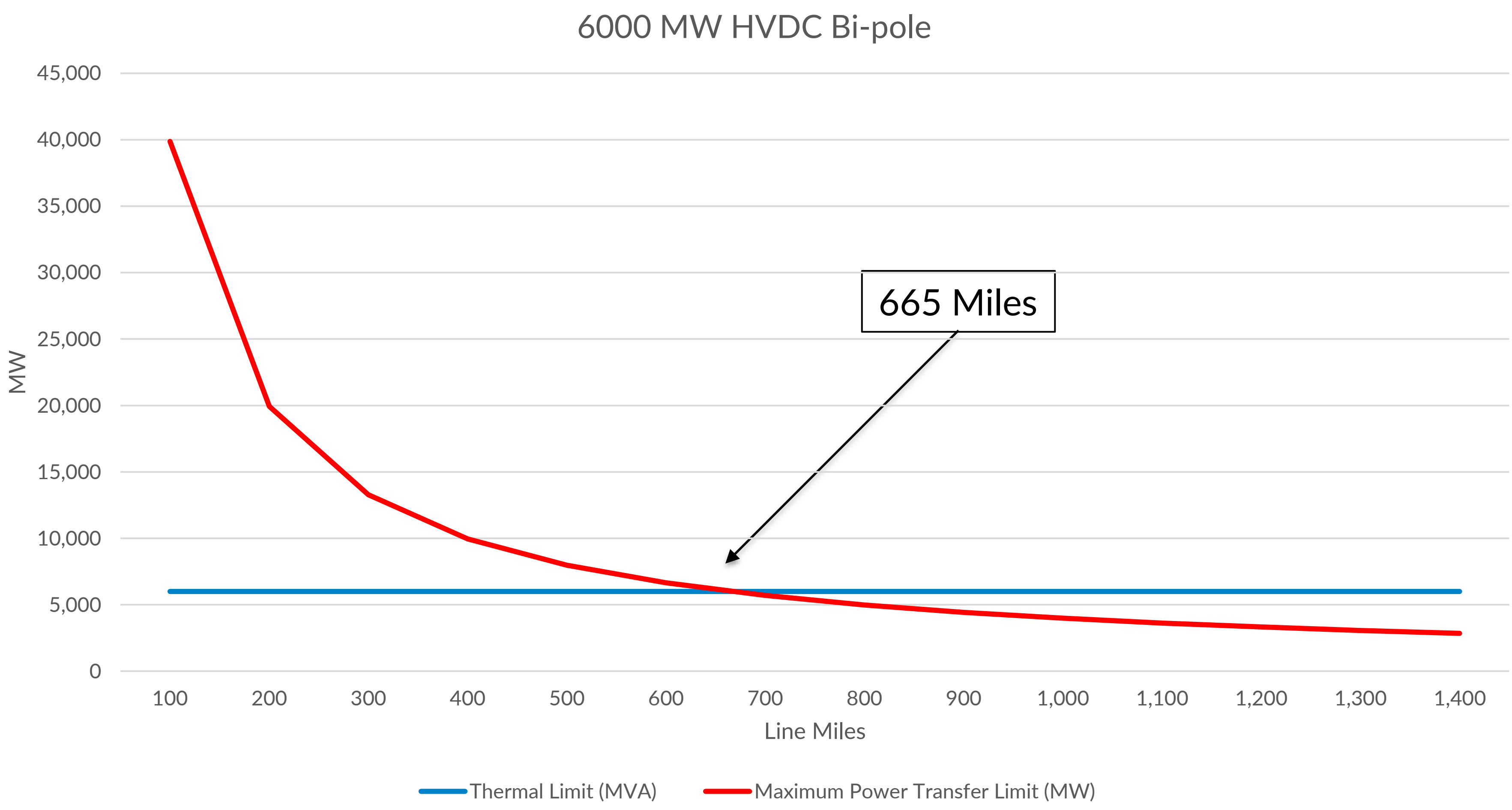
Comparison of Typical 765 kV Limits
Single-circuit, 6 - Conductor Bundle
Surge Impedance Loading = 2,435 MW



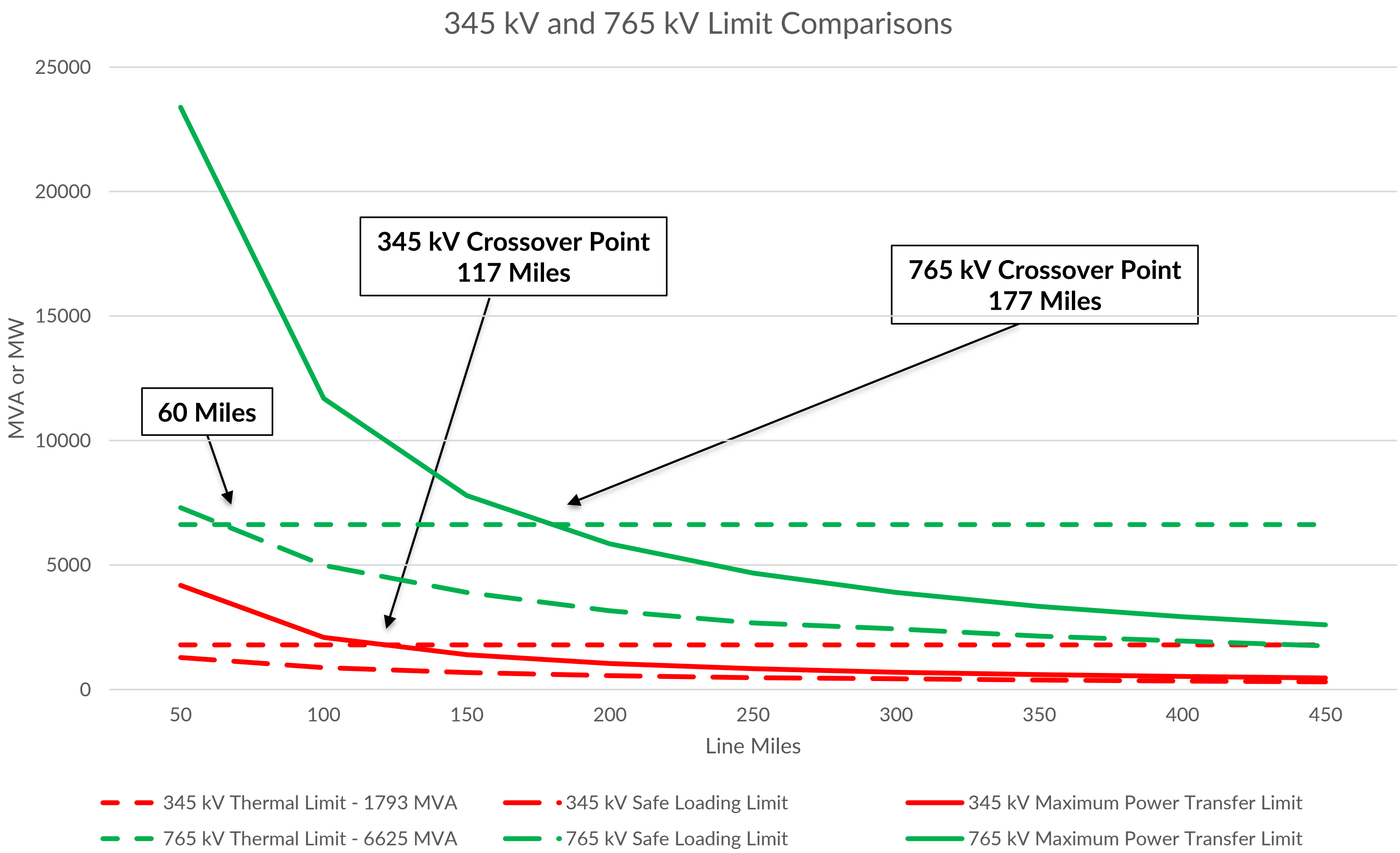
Comparison of Typical +/- 640 kV HVDC Limits
3000 MW Bi-pole
2-Conductor Bundle, 1 Converter per Terminal (2 Total)



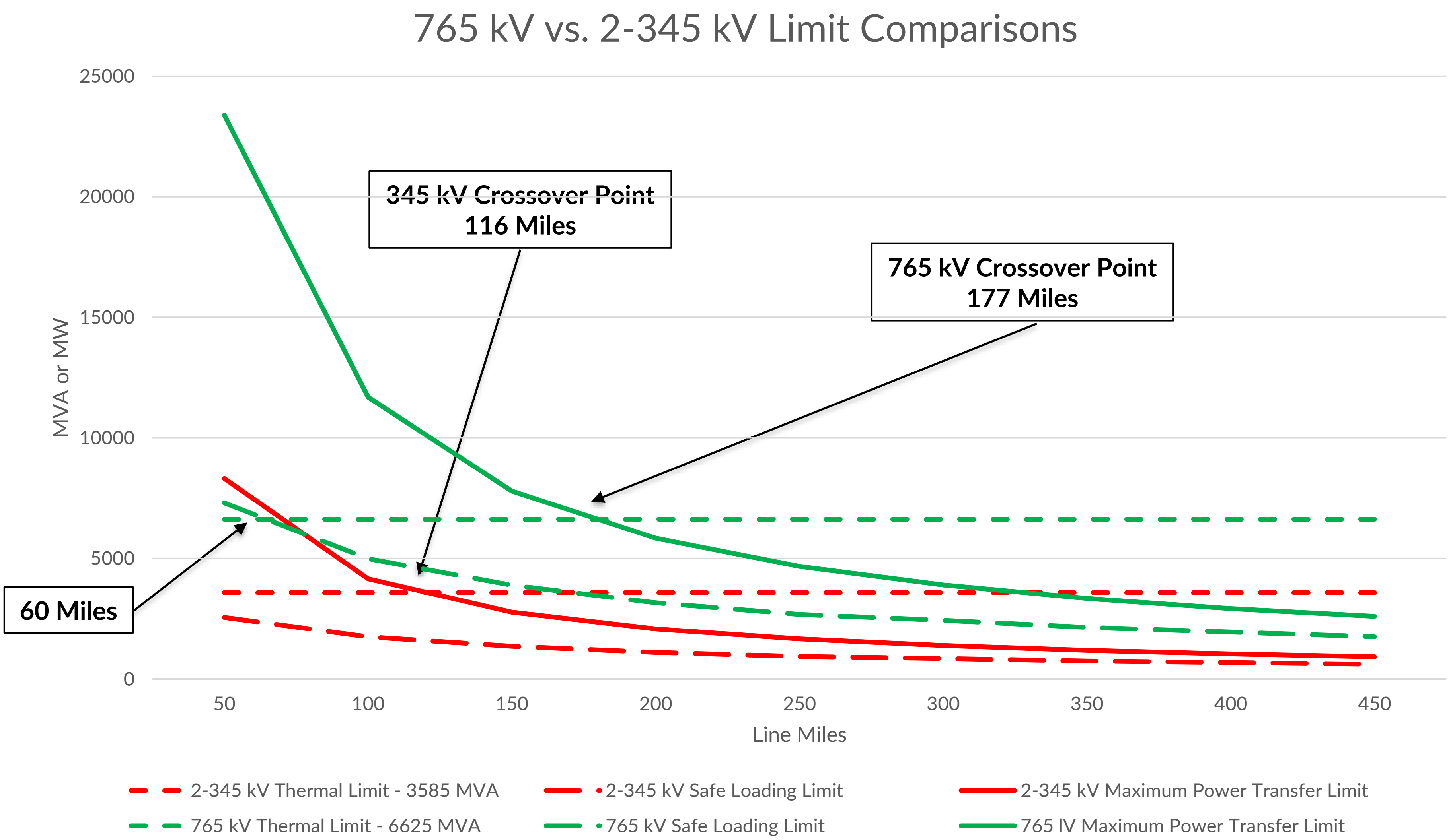
Comparison of Typical +/- 640 kV HVDC Limits
6000 MW Bi-pole
6-Conductor Bundle, 2 Converters per Terminal (4 Total)



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