Discussion of Legacy, 765 kV, and HVDC Bulk Transmission

Planning Advisory Committee
March 8, 2023

Updated line color on slide 34 on 3/6/2023

Purpose & Key Takeaways

- Purpose: This presentation discusses the various pros and cons of the transmission solution choices and how that should inform the specific solutions pursued.

Key takeaways:

- When new bulk transmission facilities are required, there are pros and cons to each of the transmission solution choices: 345 kV (500 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.
- Legacy transmission voltage levels in a sub-region or on the seam also play a role in determining potential transmission solutions moving forward.

Key Comparisons: 345 kV, 765 kV, and HVDC

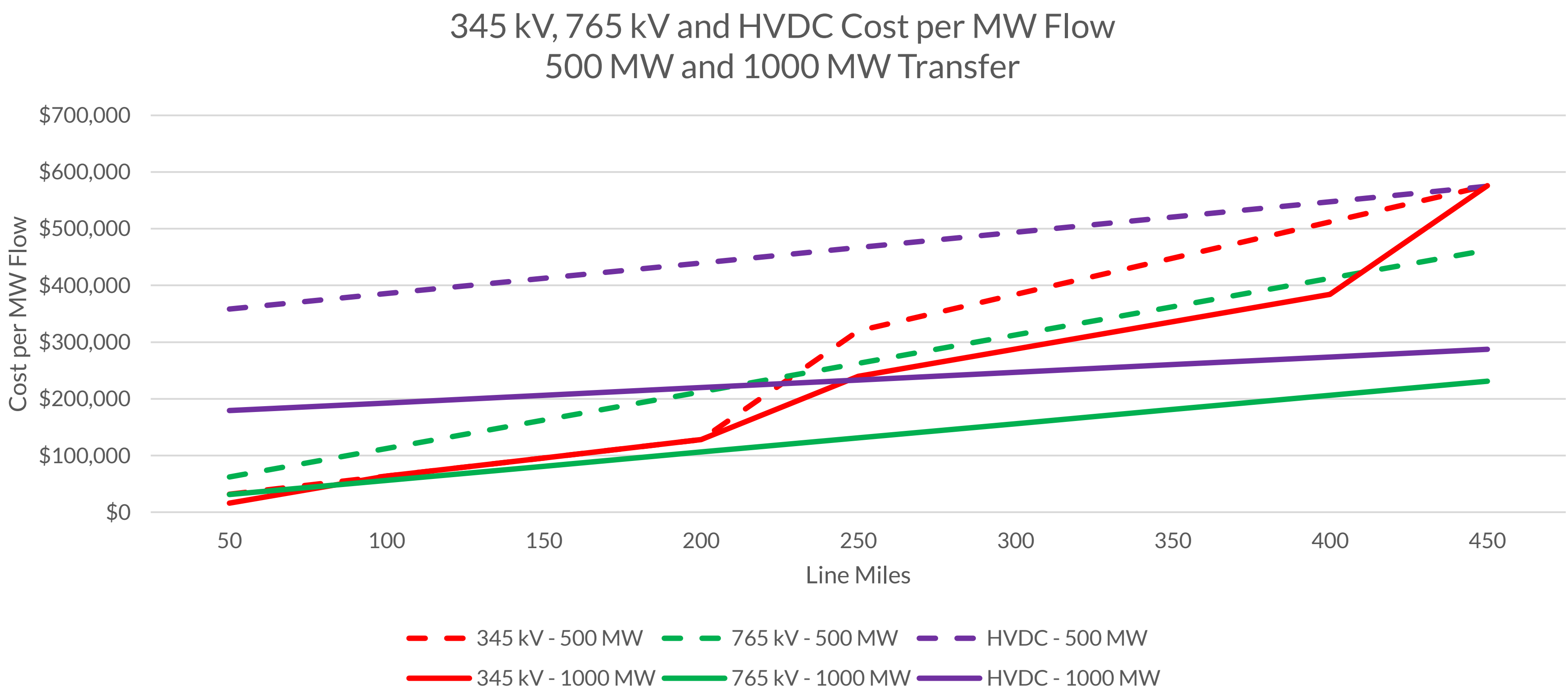
	345 kV	765 kV	HVDC
Incremental Need	Pro		
Cost per MW-Mile[1]		Pro	
Land Use per MW-Mile		Pro	Pro
Flow Control[2]			Pro
Long Distance Transmission Capabiliy[3]	Good	Better	Best
Contingency Impact	Pro		
Transmission Losses		Pro	Pro

Notes:
1) Pro for HVDC on very long lines
2) Flow control not needed everywhere
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**

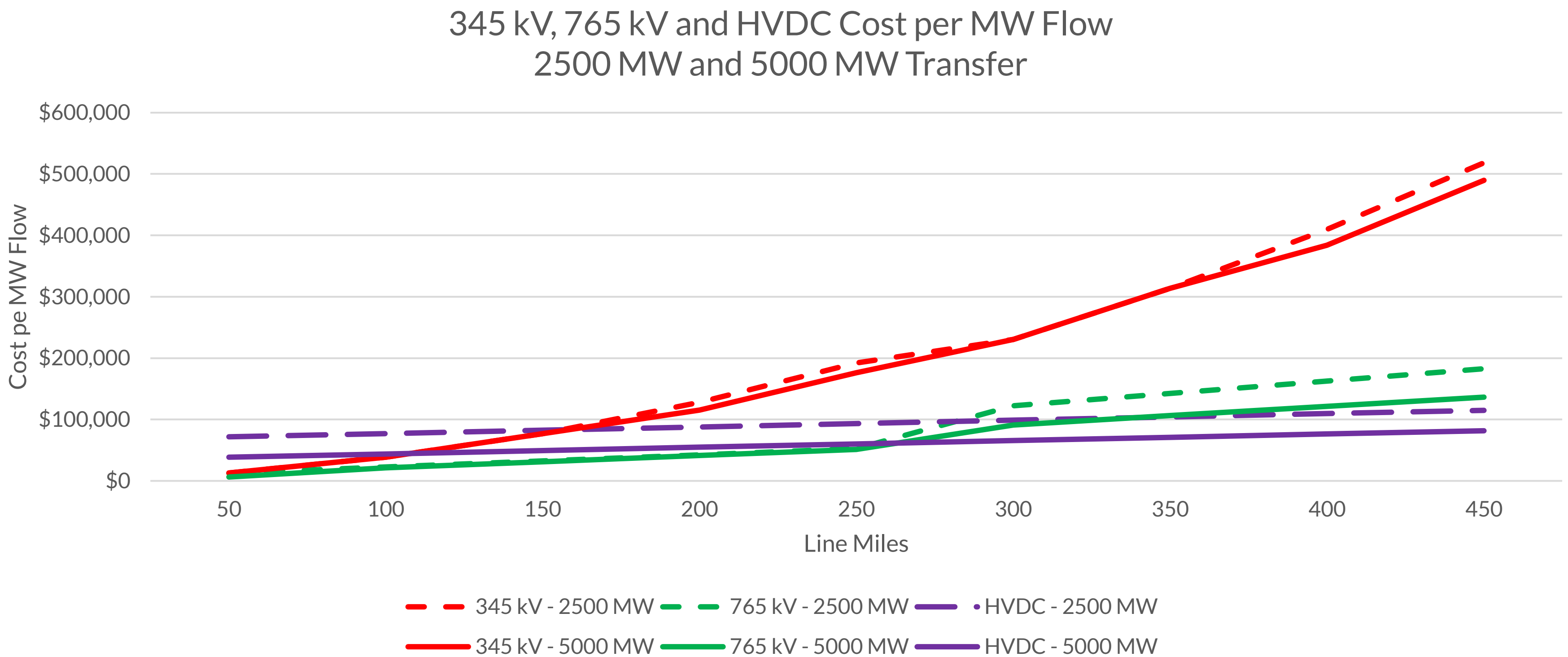
Comparison of **Typical** 345 kV, 765 kV and +/- 640 kV HVDC Costs to Transfer 500 MW and 1000 MW



SO WHAT?

- 345 kV provides the most cost effective means to transfer incremental amounts (e.g., 500 MW up to 225 Miles).
- 345 kV provides the most cost effective means to transfer higher amounts shorter distances (e.g., 1000 MW up to 80 Miles).

Comparison of **Typical** 345 kV, 765 kV and +/- 640 kV HVDC Costs to Transfer 2500 MW and 5000 MW



SO WHAT?

- For transfers of 2500 MW and 5000 MW, 345 kV is not more cost effective than 765 kV, even for short distances.
- For transfers of 2500 MW and 5000 MW, HVDC becomes more economical at line lengths of 280 miles and 260 miles respectively

Transmission Limits

Types of Transmission Line Limits

Thermal Limits

- Applies to both AC and HVDC transmission lines
- Driven by facility temperature limits
- Independent of line length.
- Compliance and/or risk mitigation limit.

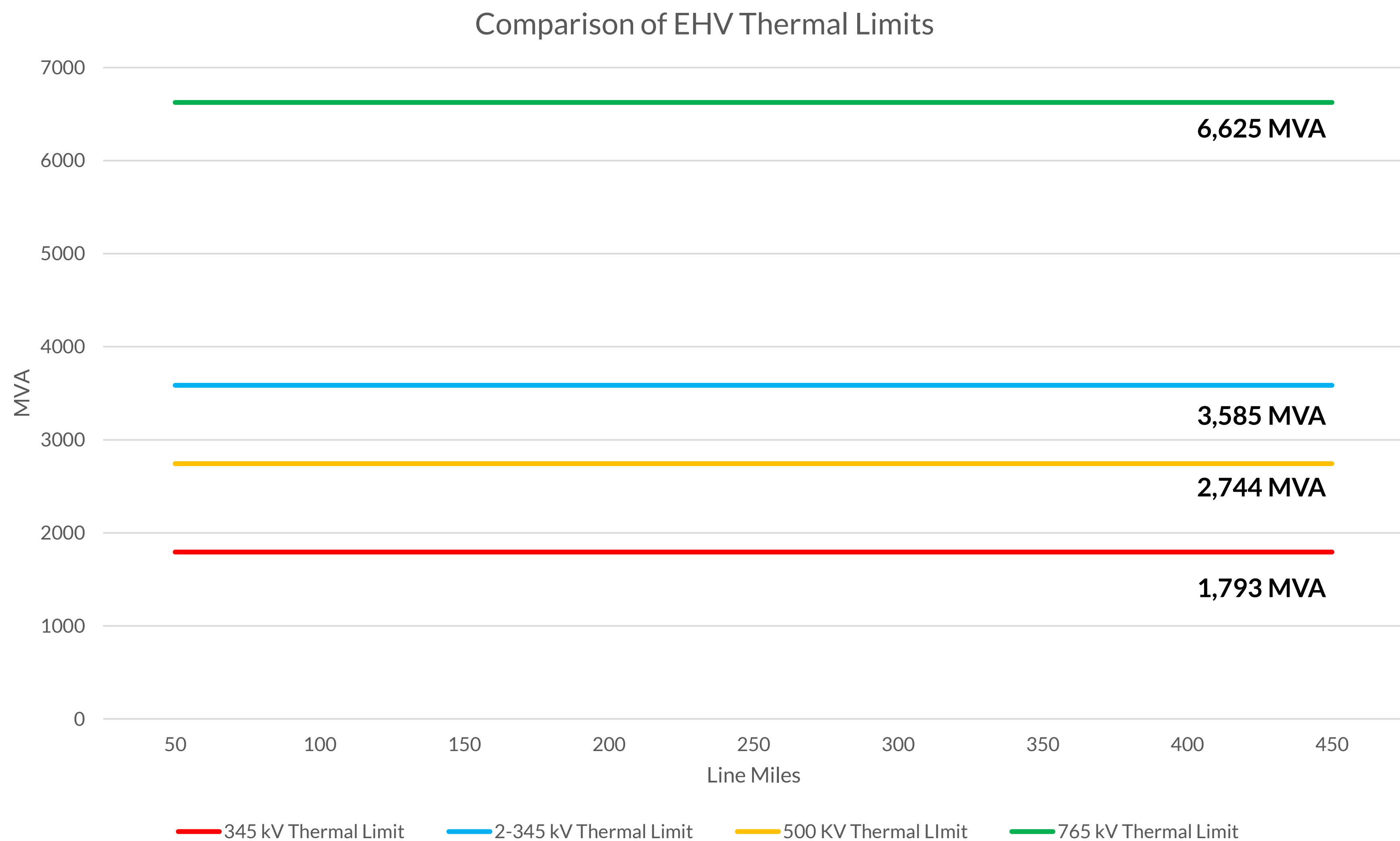
Safe Loading Limits

- Applies only to AC transmission lines
- Driven by operational risk management targets
- Safe loading limits decrease as line length increases.
- Risk mitigation limit.

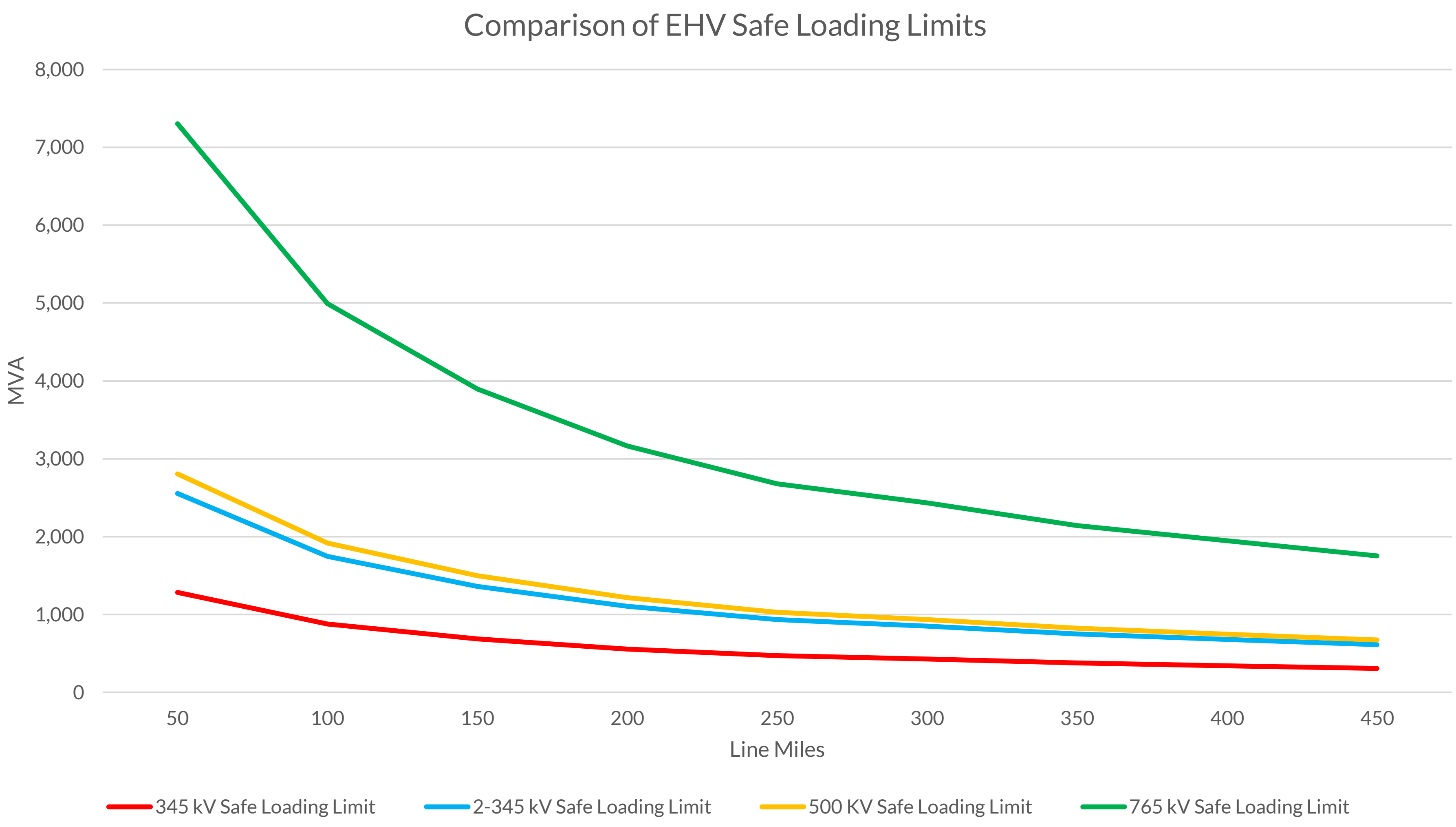
Absolute Limits

- Applies to both AC and HVDC transmission lines
- The lesser of:
    - Maximum Power Transfer Limit
    - Relay Trip Limit
- Absolute limits decrease as line length increases.
- Physical limit – Cannot be exceeded for any duration.

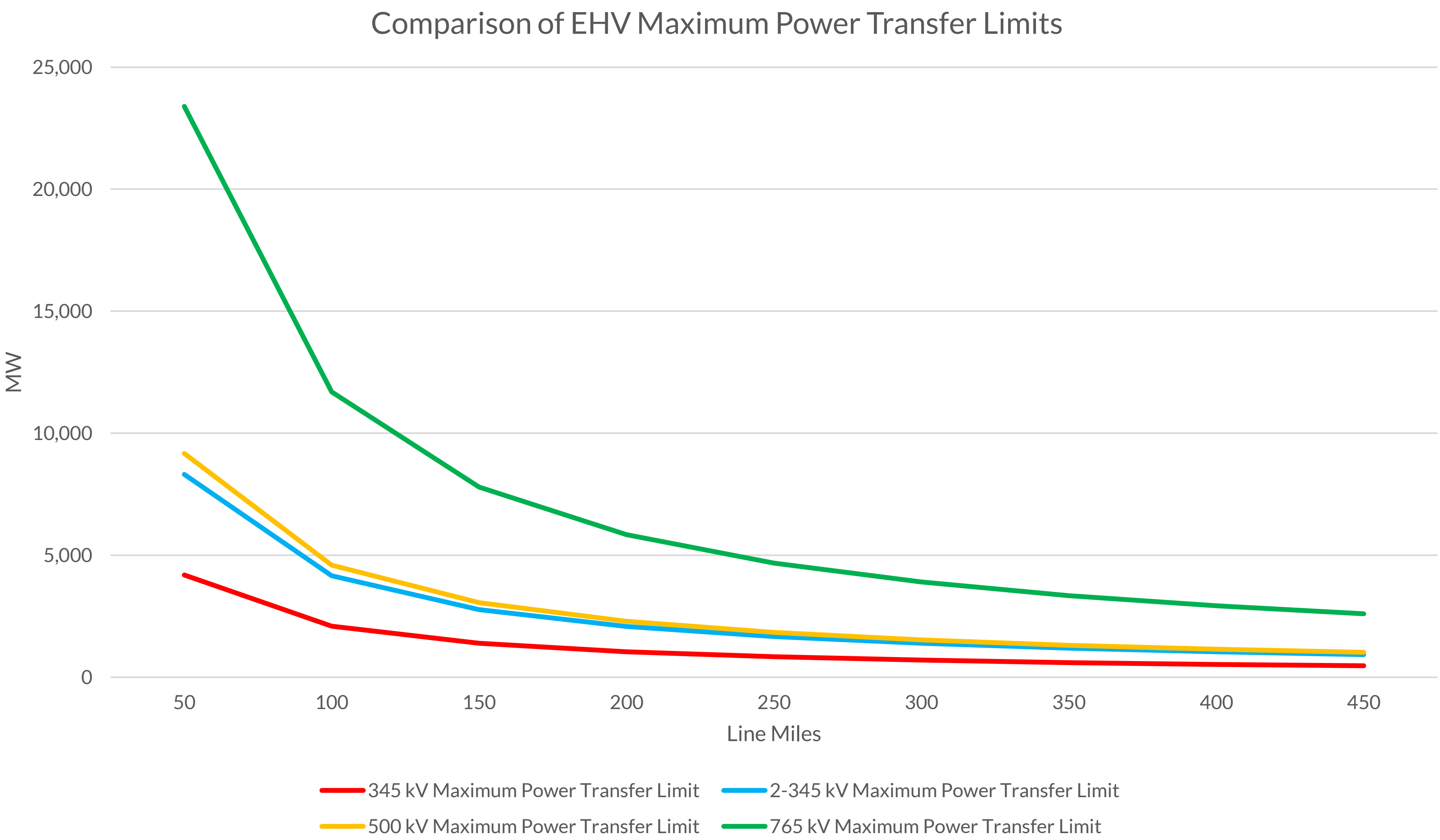
Comparison of **Typical** EHV Line Thermal Limits: Single Circuit 345 kV, Double Circuit 345 kV, 500 kV, and 765 kV



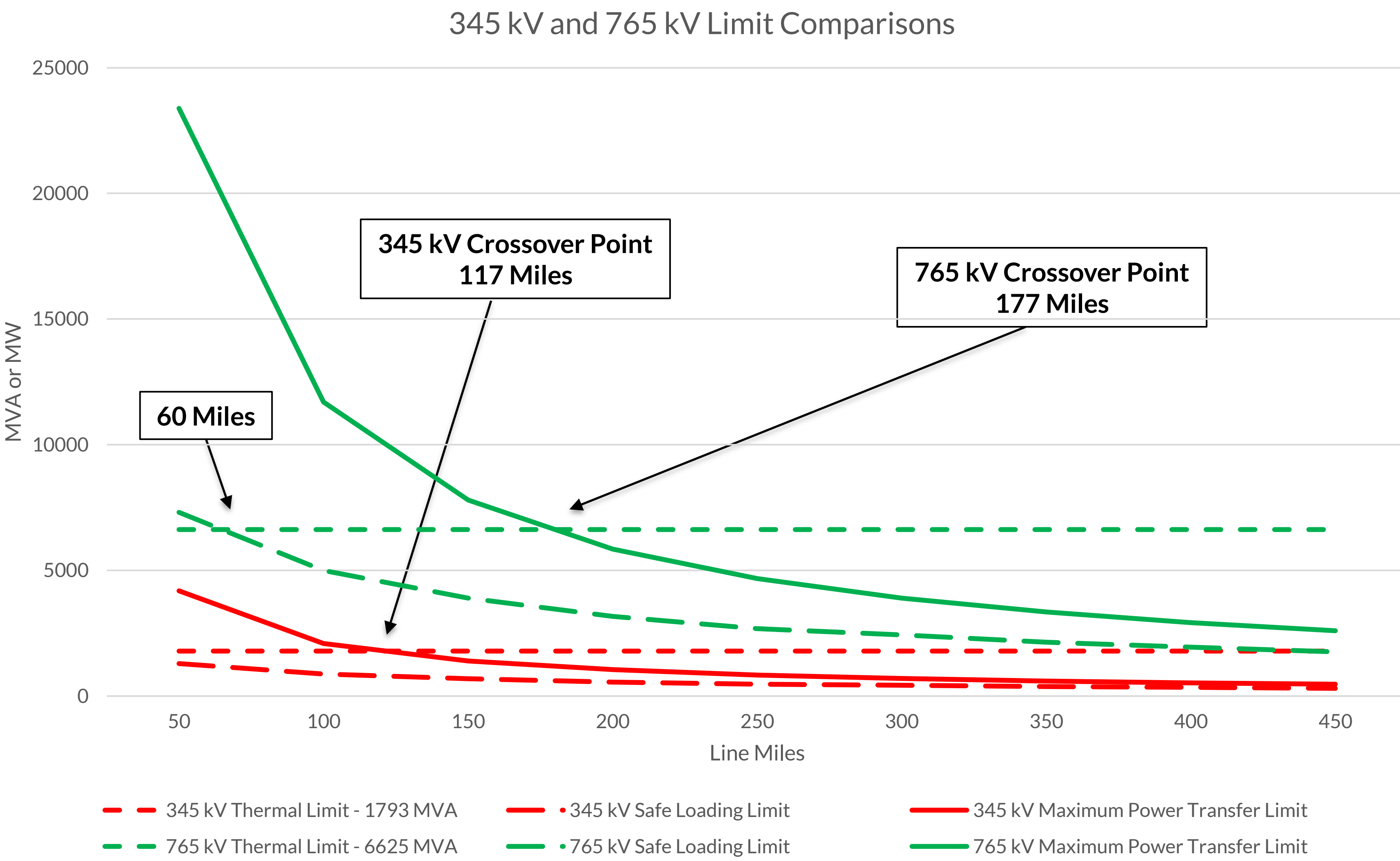
Comparison of **Typical** EHV Line Safe Loading Limits: Single Circuit 345 kV, Double Circuit 345 kV, 500 kV, and 765 kV



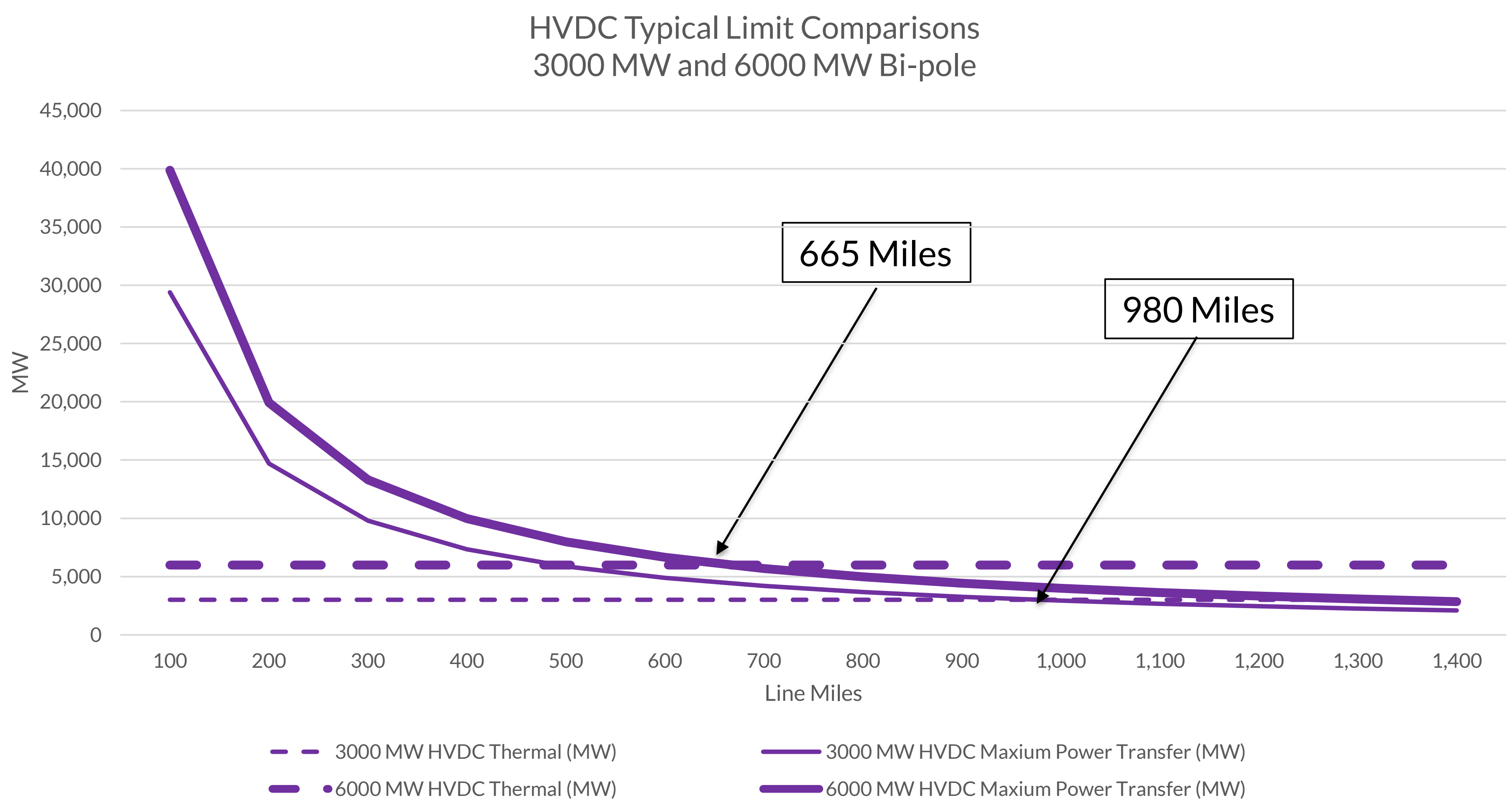
Comparison of **Typical** EHV Line Maximum Power Transfer Limits: Single Circuit 345 kV, Double Circuit 345 kV, 500 kV, and 765 kV



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



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



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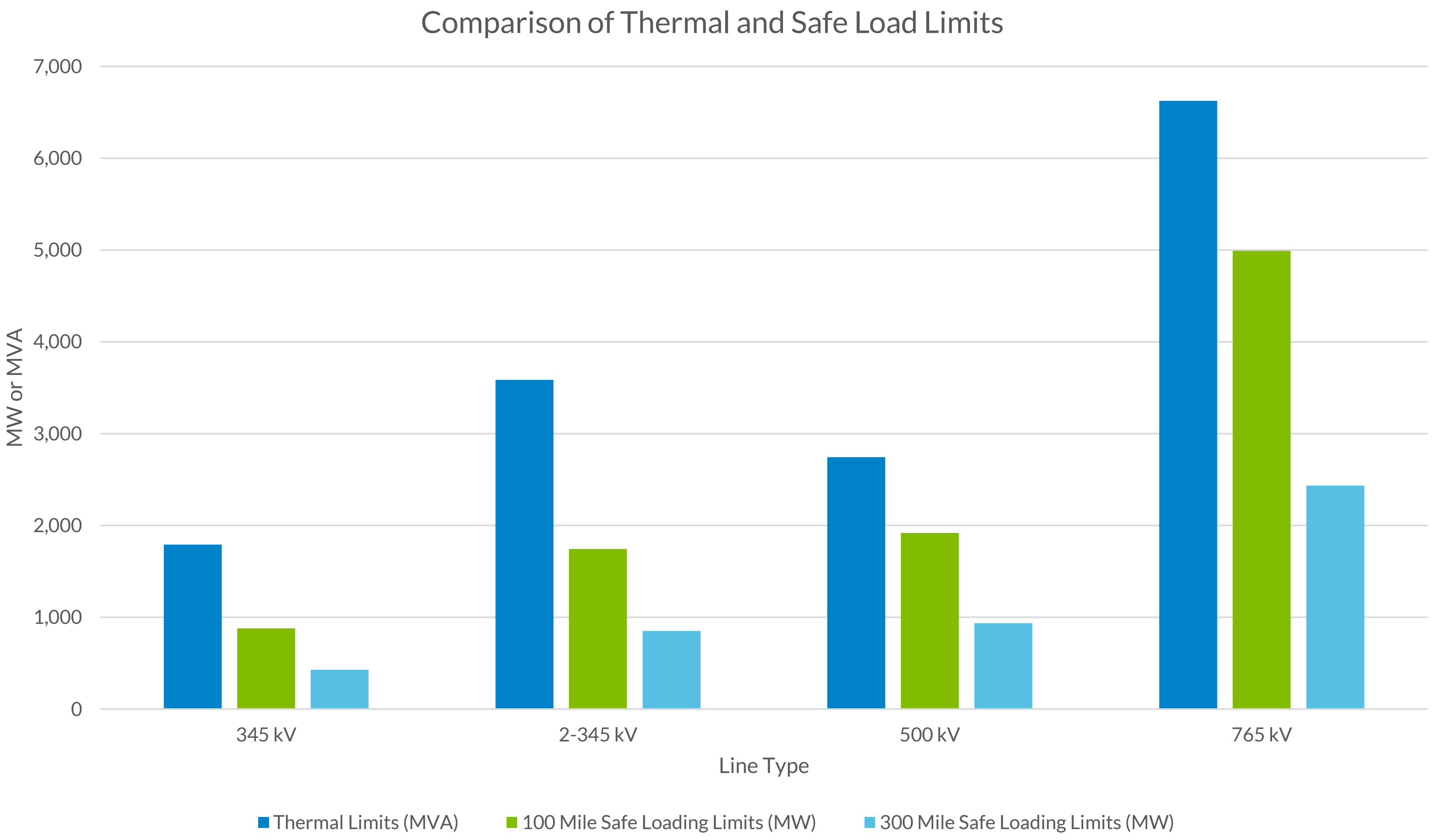
Comparison of Legacy Bulk Transmission with 765 kV

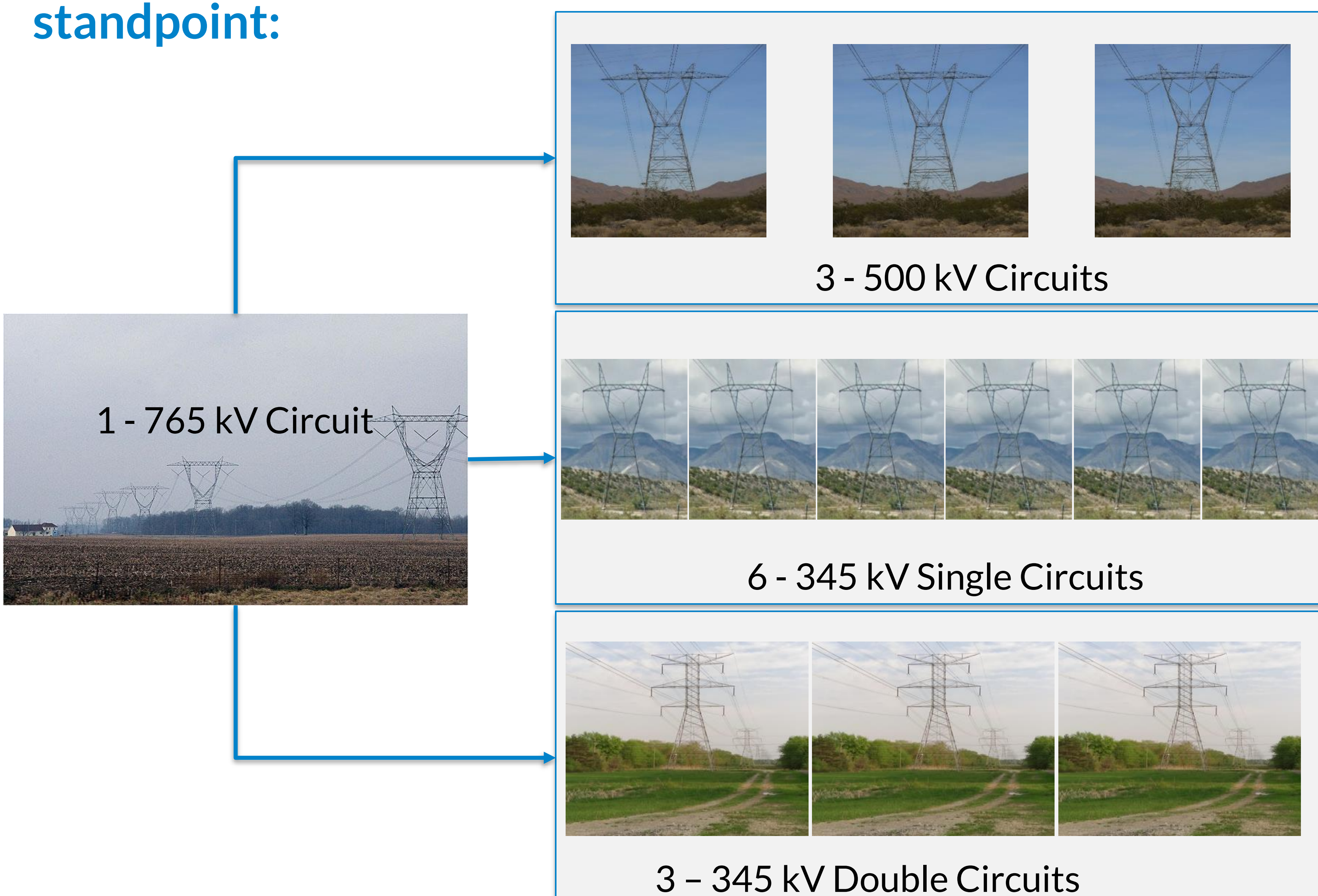
Key Takeaways for Comparison of Legacy Bulk Transmission with 765 kV

- 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

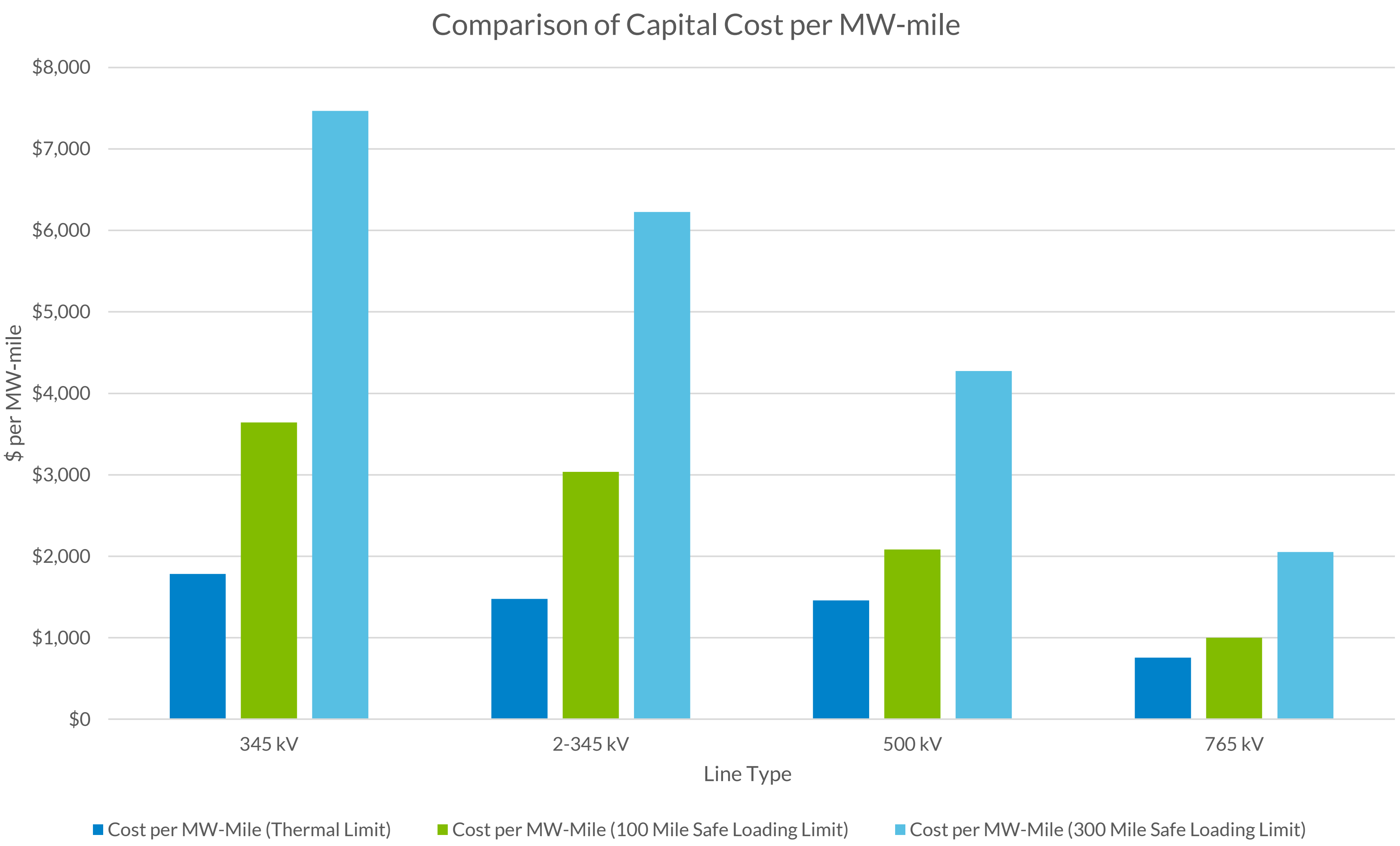
Comparison of Thermal and Safe Loading Limits
765 kV, 500 kV, Single-circuit 345 kV, Double-circuit 345 kV



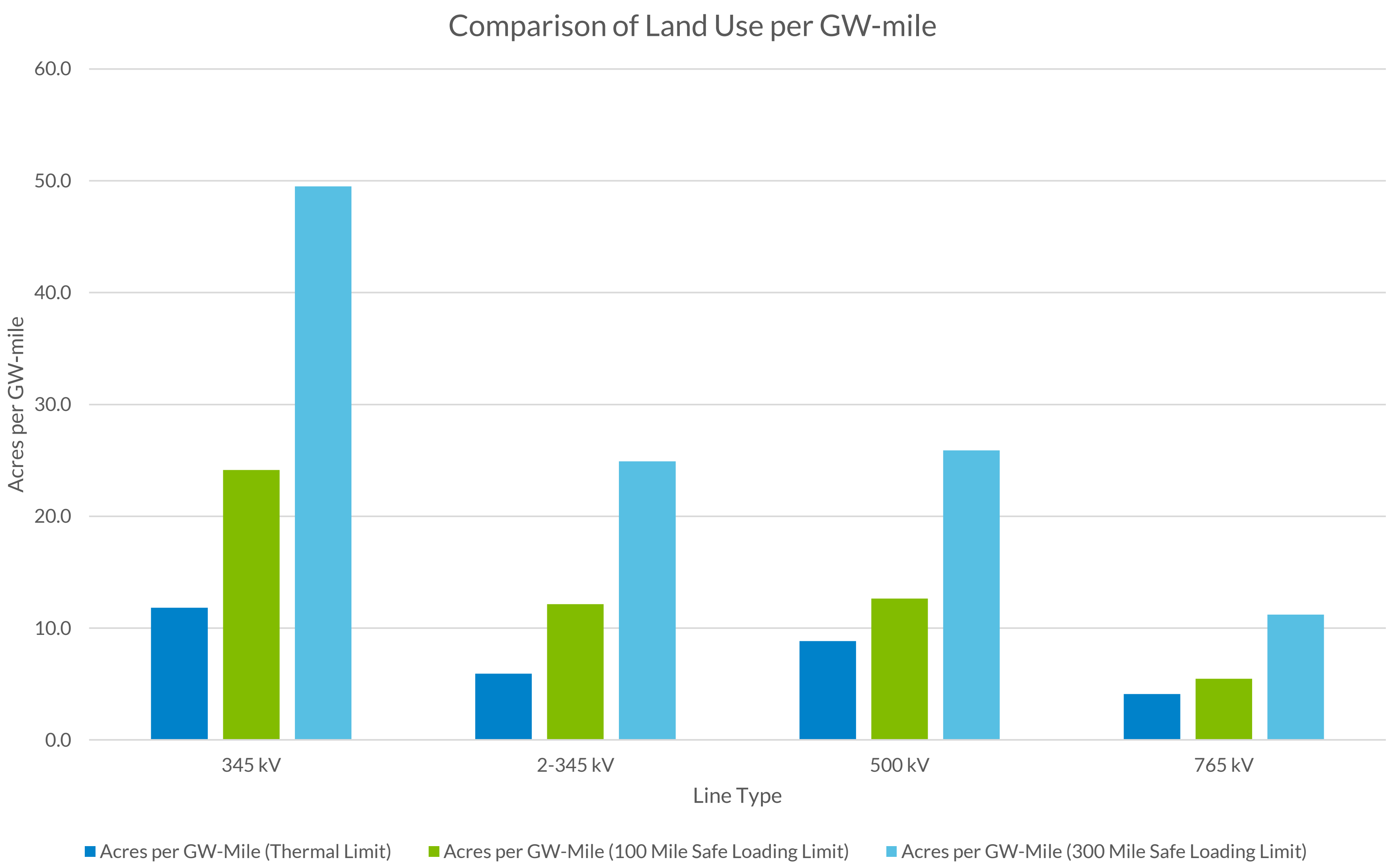
Based on the Previous Slide, from a Safe Loading Limit standpoint:



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



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



Contingency Impacts

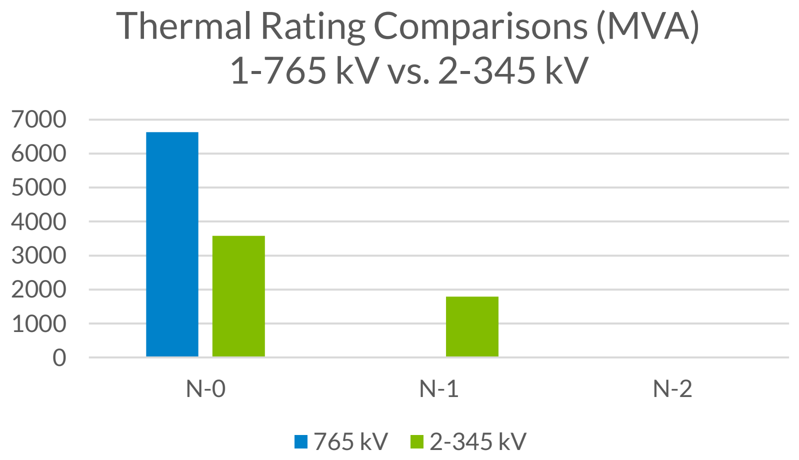
- While 765 kV costs less per MW-mile than 345 kV and requires less land per MW-mile than 345 kV, there is a concern that a 765 kV continency will have a greater impact on the system than a 345 KV contingency.

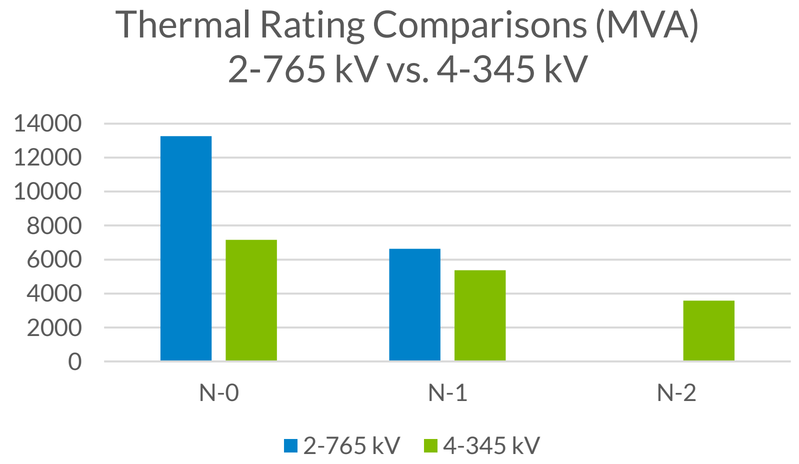
- To further explore this concern, comparisons will be made between the N-0, N-1 and N-2 capabilities of 765 kV vs. 345 kV under four scenarios.

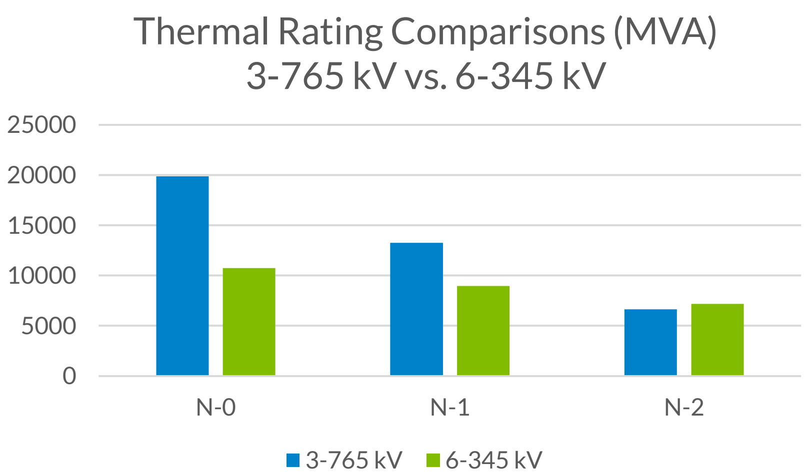
- The per mile cost of a double-circuit 345 kV line is slightly above that of a single-circuit 765 kV line and the per mile land-use of a double-circuit 345 kV line is slightly below that of single-circuit 765 kV line, so they are comparable options from a cost and land-use standpoint.

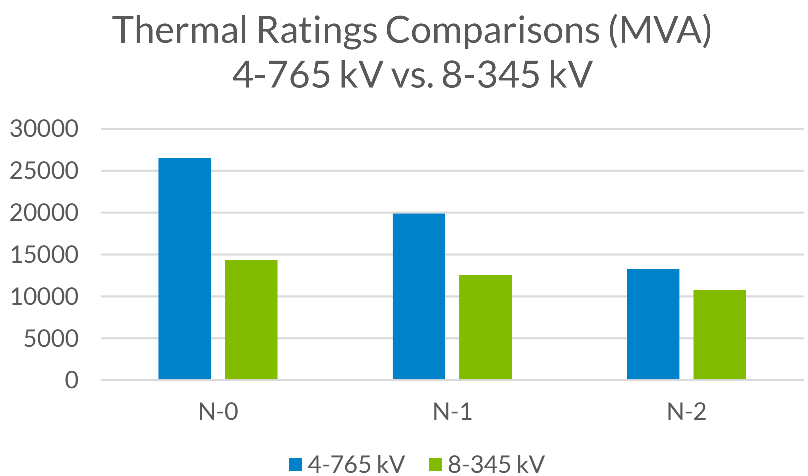
- A hypothetical 150-mile interface will be considered under the following four scenarios:
  - 1 – 765 kV circuit vs. 2-345 kV circuits
  - 2 – 765 kV circuits vs. 4 – 345 kV circuits
  - 3 – 765 kV circuits vs. 6 – 345 kV circuits
  - 4 – 765 kV circuits vs. 8 – 345 kV circuits

Comparison of Thermal Capability for Four 150 Mile Interface Scenarios

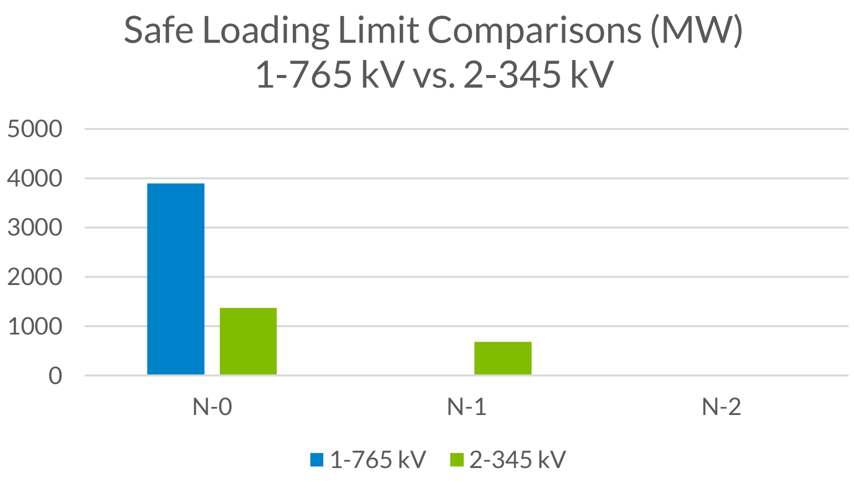


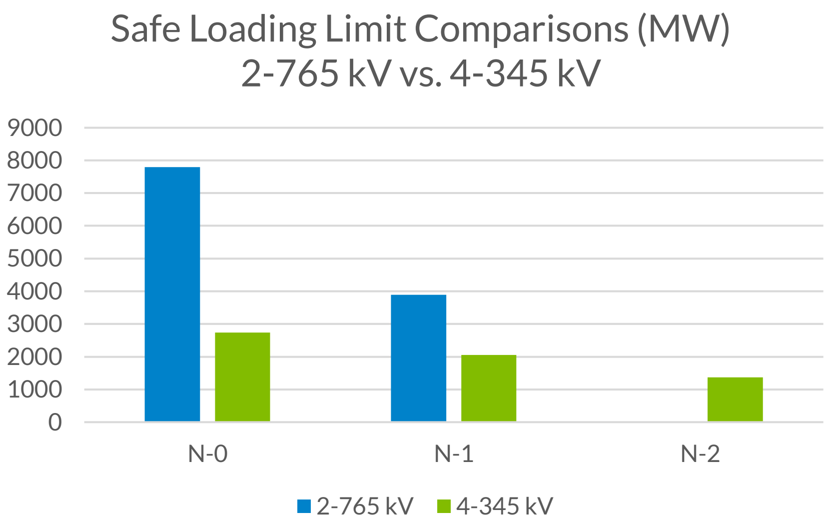


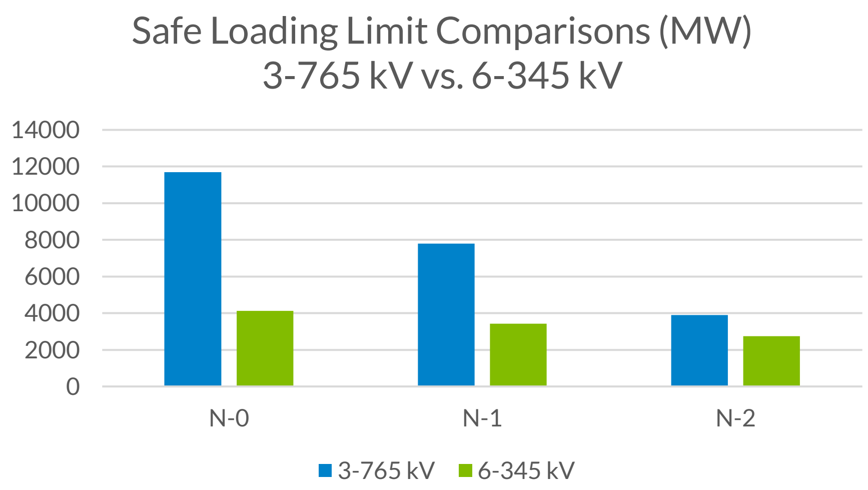


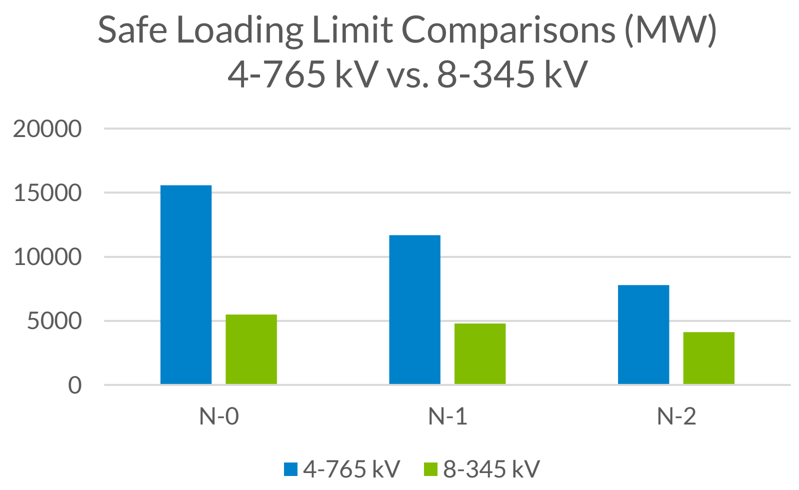


Comparison of Safe Loading Limit for Four 150 Mile Interface Scenarios









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Key Takeaways on Contingency Impacts

- As the 765 kV backbone grows, the issue of contingency impact is eliminated.

- If there is sufficient justification to establish a 765 kV backbone in a sub-region where one does not currently exist, such a strategy will cost less and provide more capacity on both a pre-contingency and post-contingency basis.

- Because of the impact of a 765 kV contingency, pursuing 765 kV may not be the best option if only one or two lines are being considered with no plans to establish a future backbone.

- The benefits of 765 kV are maximized when there is a commitment to establish a 765 kV backbone and there is a sufficient business case to justify the 765 kV backbone.

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.

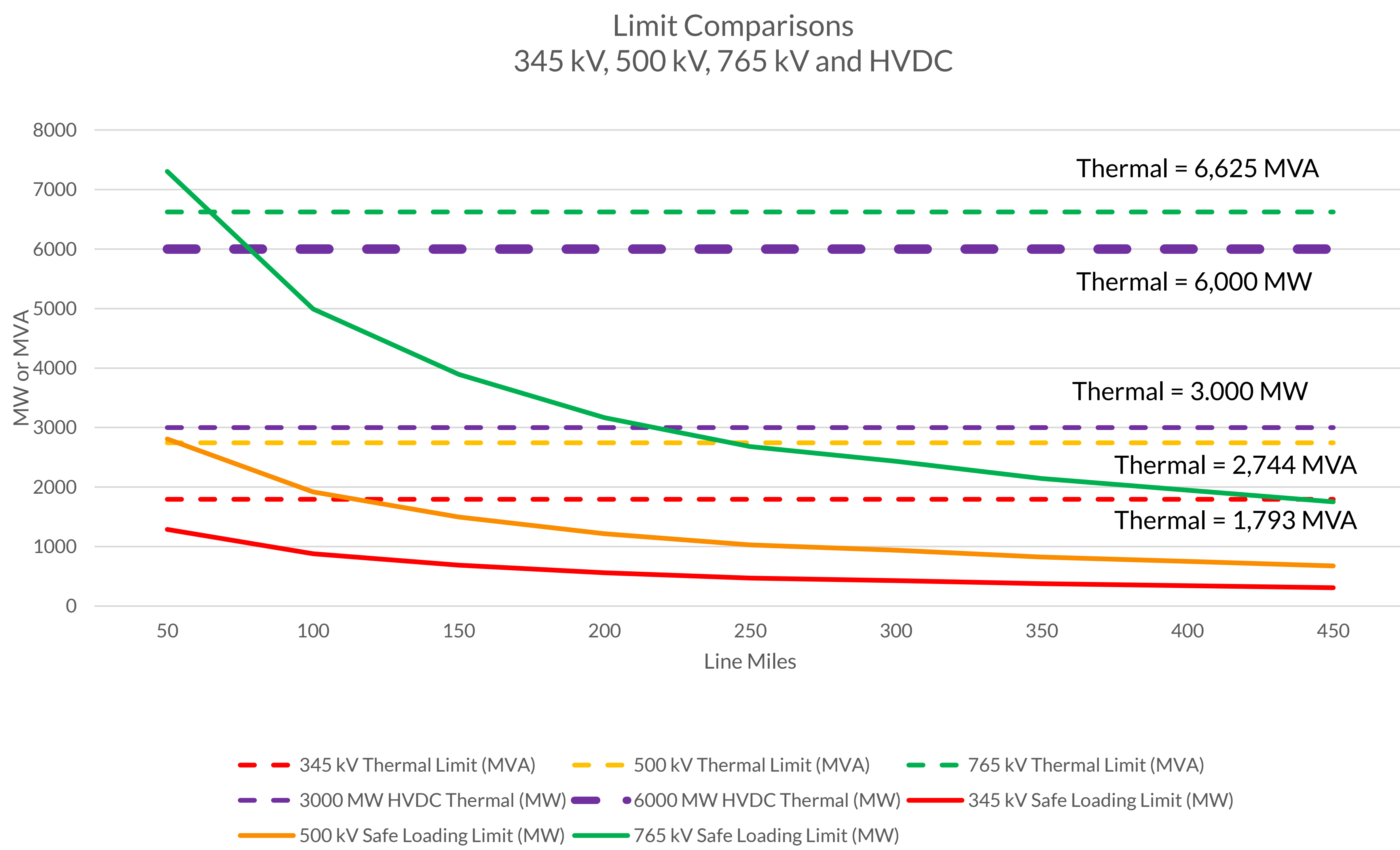
	345 kV	765 kV
Number Circuits	12	2
Circuit Length (Miles)	100	100
Thermal Capacity (MVA)	21,504	13,250
Assumed Flow (MW)	5,000	5,000
Phase Current per Circuit (A)	697	1,889
$R_{Conductor}$ (Ohms)	4.63	2.16
Capacity Losses (MW)	81	46
Annual Energy Losses (MWh)	710,374	403,628

Comparison of 765 kV with HVDC

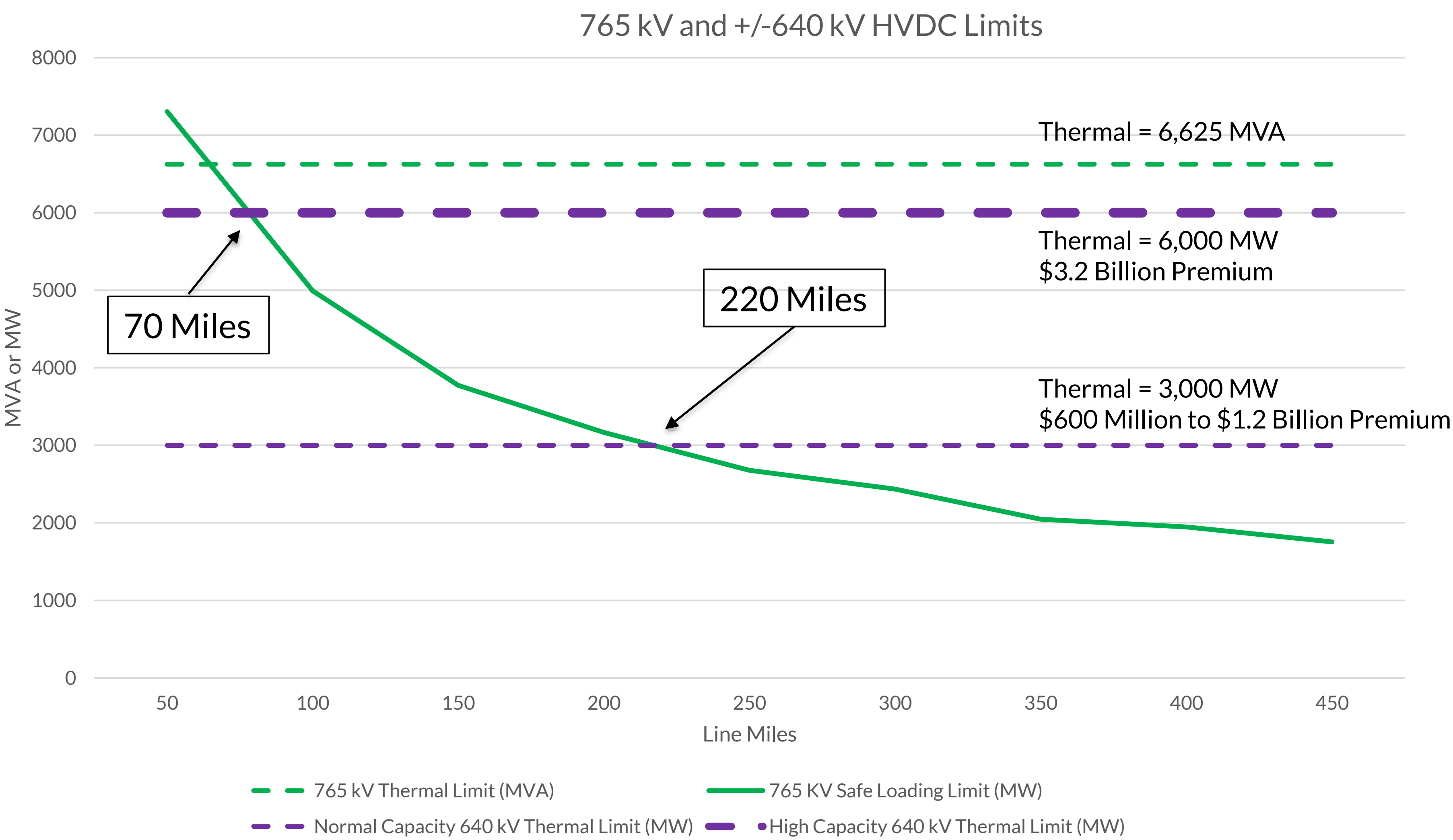
Key Takeaways for Comparison of 765 kV with +/-640 kV HVDC

- 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.
- 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)

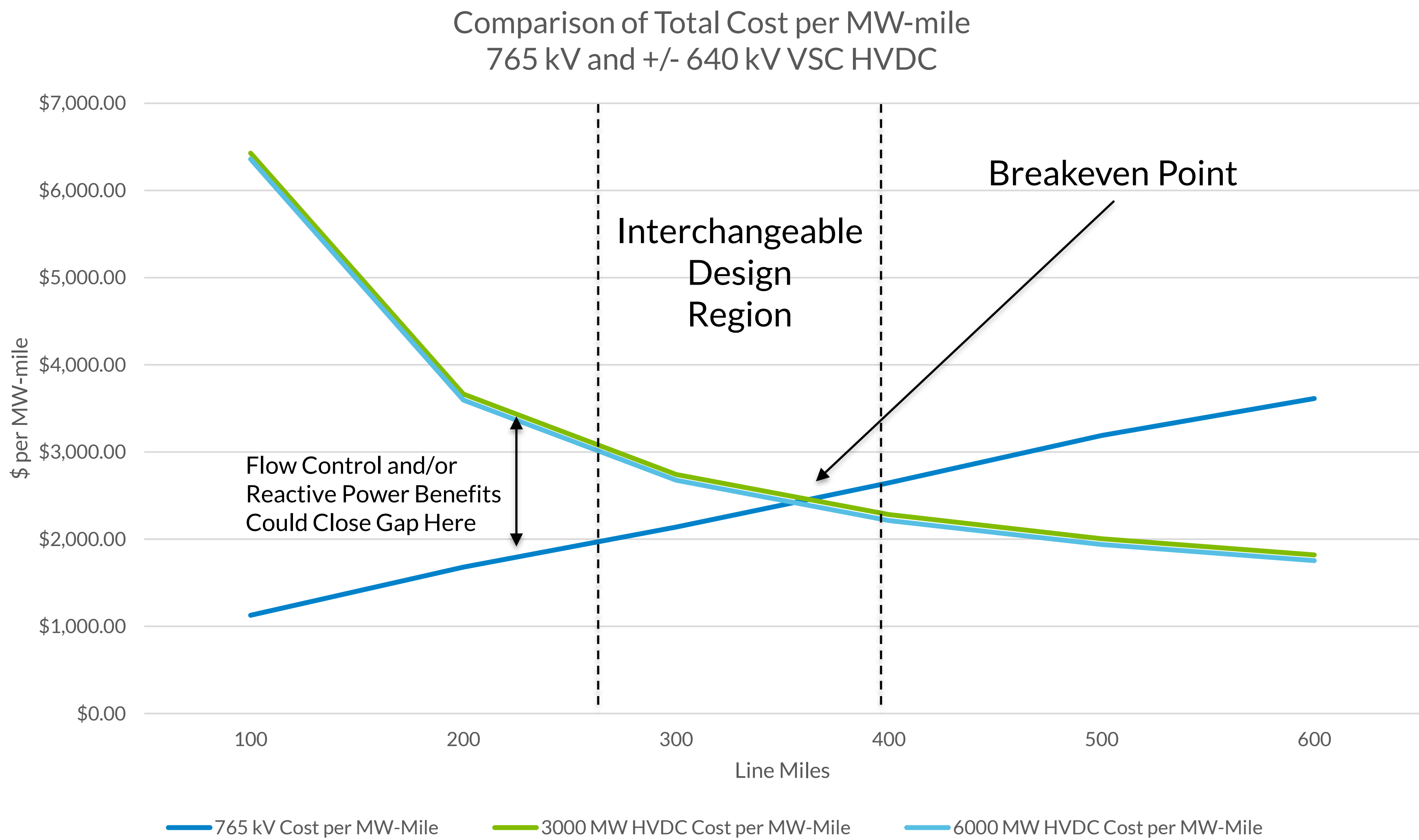
Comparison of **Typical** 345 kV, 500 kV, 765 kV and HVDC Limits



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 primary operational outcome is coordinating manual scheduling of several HVDC bi-poles

    - There may be more abrupt changes in resource output due to the future of generator volatility

HVDC Reactive Power Benefits

- Under steady state conditions, an HVDC bi-pole transmission line (not including converters) does not consume nor generate reactive power.
- Long AC lines and conventional Line Commutated Converter (LCC) HVDC bi-poles require substantial amounts of reactive power.
- The newer Voltage Source Converter (VSC) HVDC technology eliminates reactive power consumption issues associated with 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

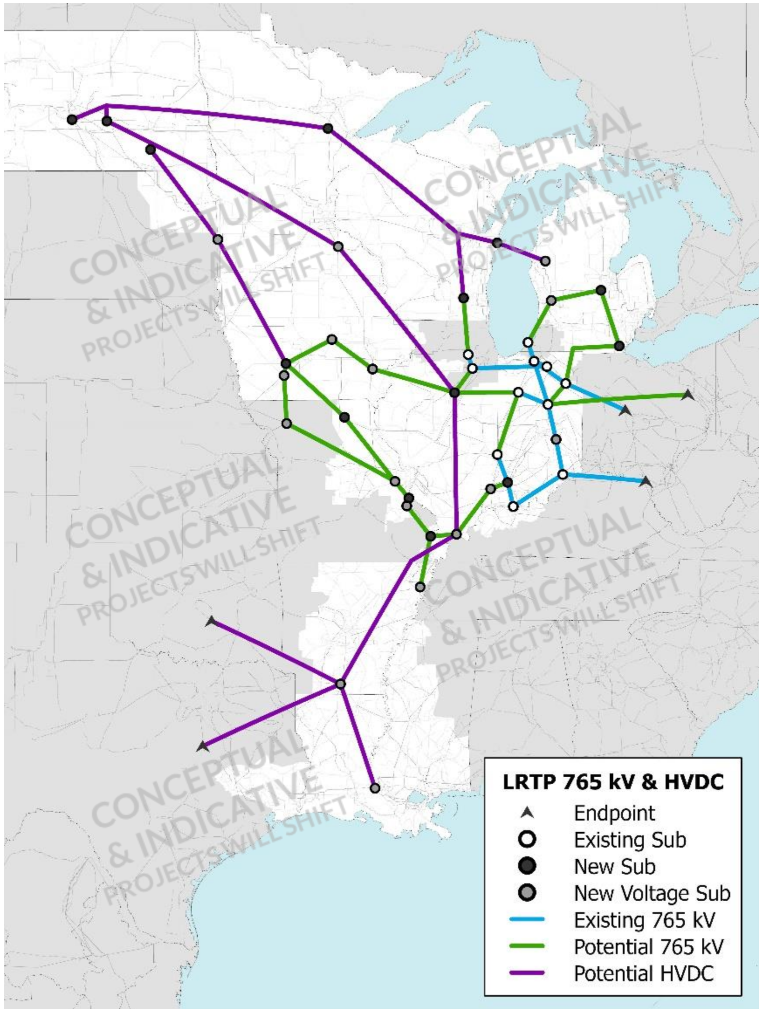
- HVDC contingency impacts would be comparable to those of 765 kV lines since the MW capabilities are comparable.
- It is important to note that a complete loss of an HVDC bi-pole is actually an N-2 contingency. A plus for HVDC
- It is also important to note that an HVDC bi-pole has only two conductors, 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

How These Principles Informed the LRTP Long-term Road Map

765 kV and HVDC Components of LRTP Indicative Long-term Road Map

Initially Presented in March 2021

HVDC backbone in MISO West and MISO South with connecting HVDC link through Iowa and Illinois



765 kV Backbone in MISO Central and MISO East with heavy ties to PJM West 765 kV

HVDC and 765 kV overlay legacy bulk transmission voltage levels as needed (345 kV in MISO North and 500 kV In MISO South)

CONCEPTUAL ONLY

Conclusions

Key Conclusions and Takeaways

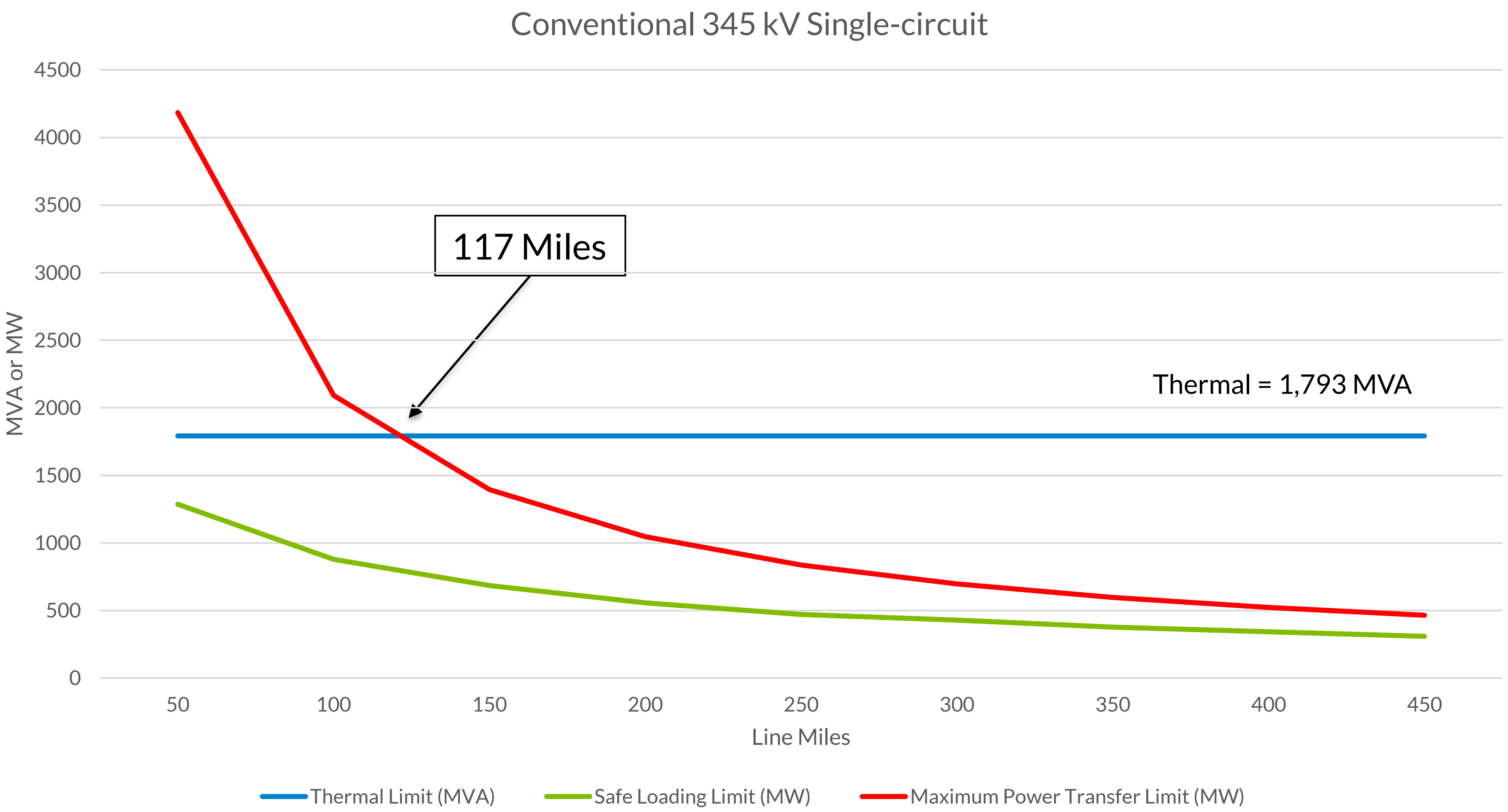
- The best transmission system is one that is planned with an "all things considered" strategy.
- When legacy voltages are preferable, such voltage levels should align with those that already exist in the area.

	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	• 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 • Higher capital costs on very long lines • Potential reactive power issues	• Higher capital costs except for very long lines. • Not suited for incremental needs

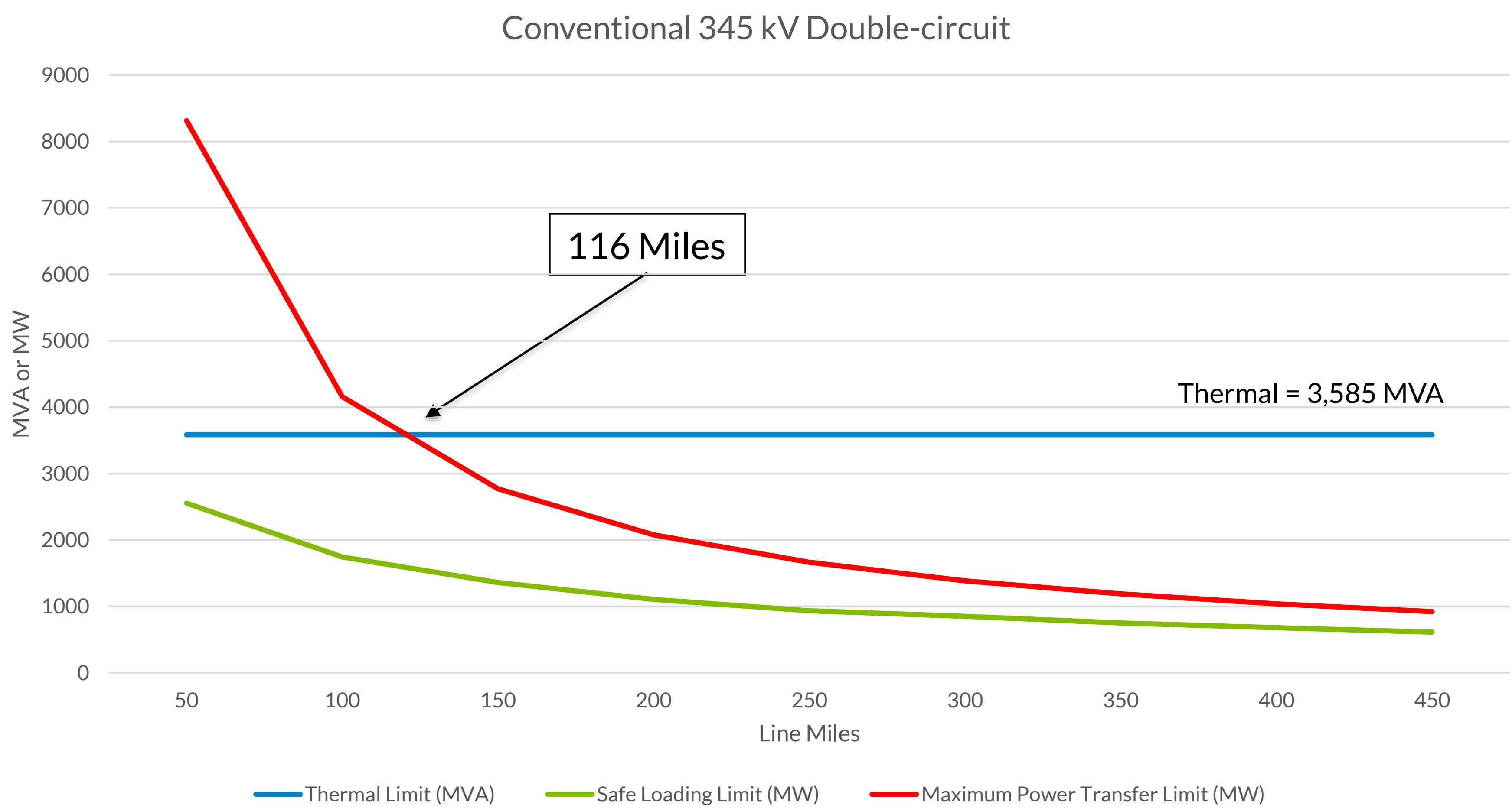
Questions

Appendix

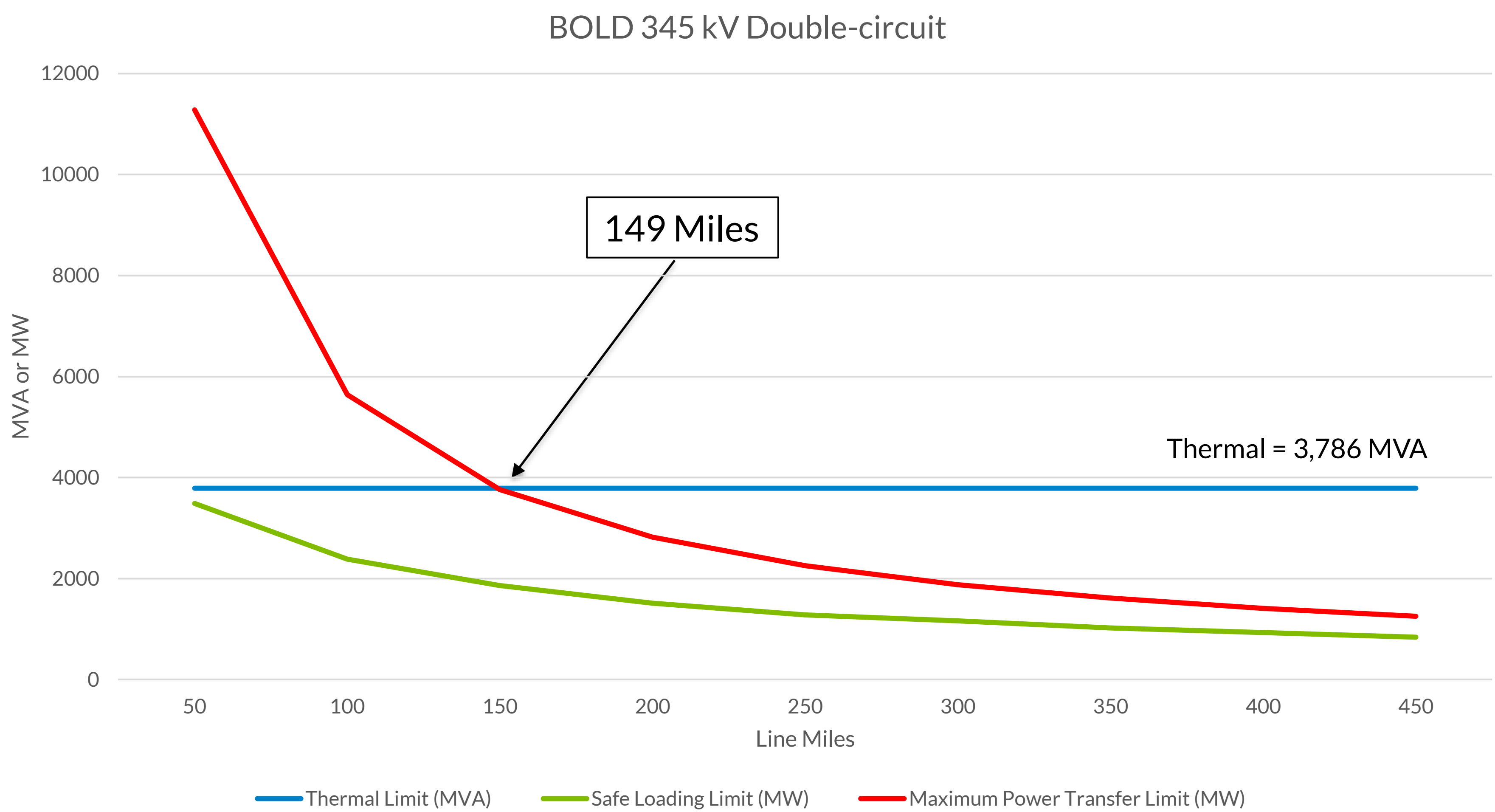
Comparison of Typical 345 kV Limits
Conventional Single-circuit, 2-Conductor Bundle
Surge Impedance Loading = 429 MW



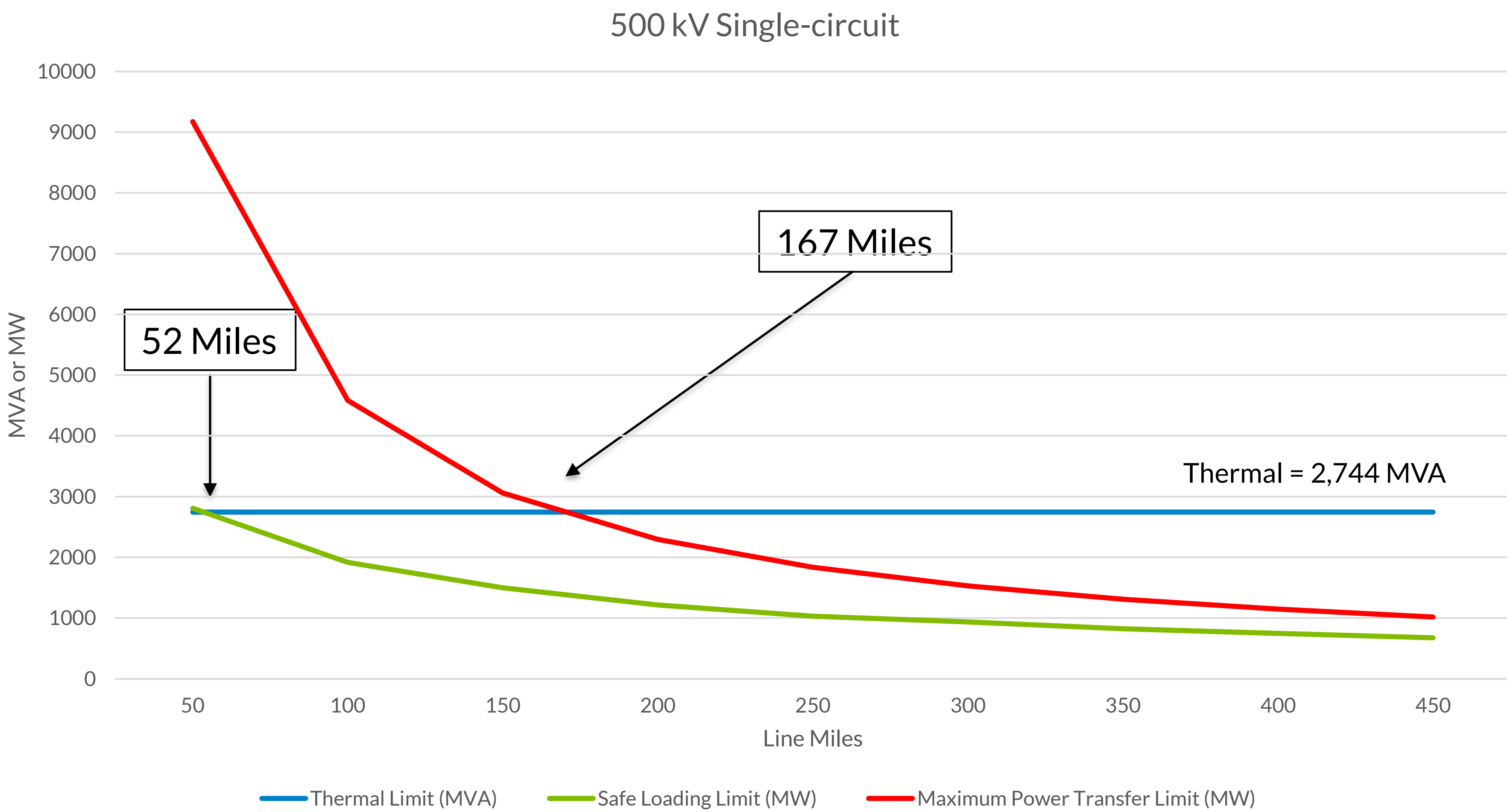
Comparison of Typical 345 kV Limits Conventional Double-circuit, 2-Conductor Bundle Surge Impedance Loading = 851 MW



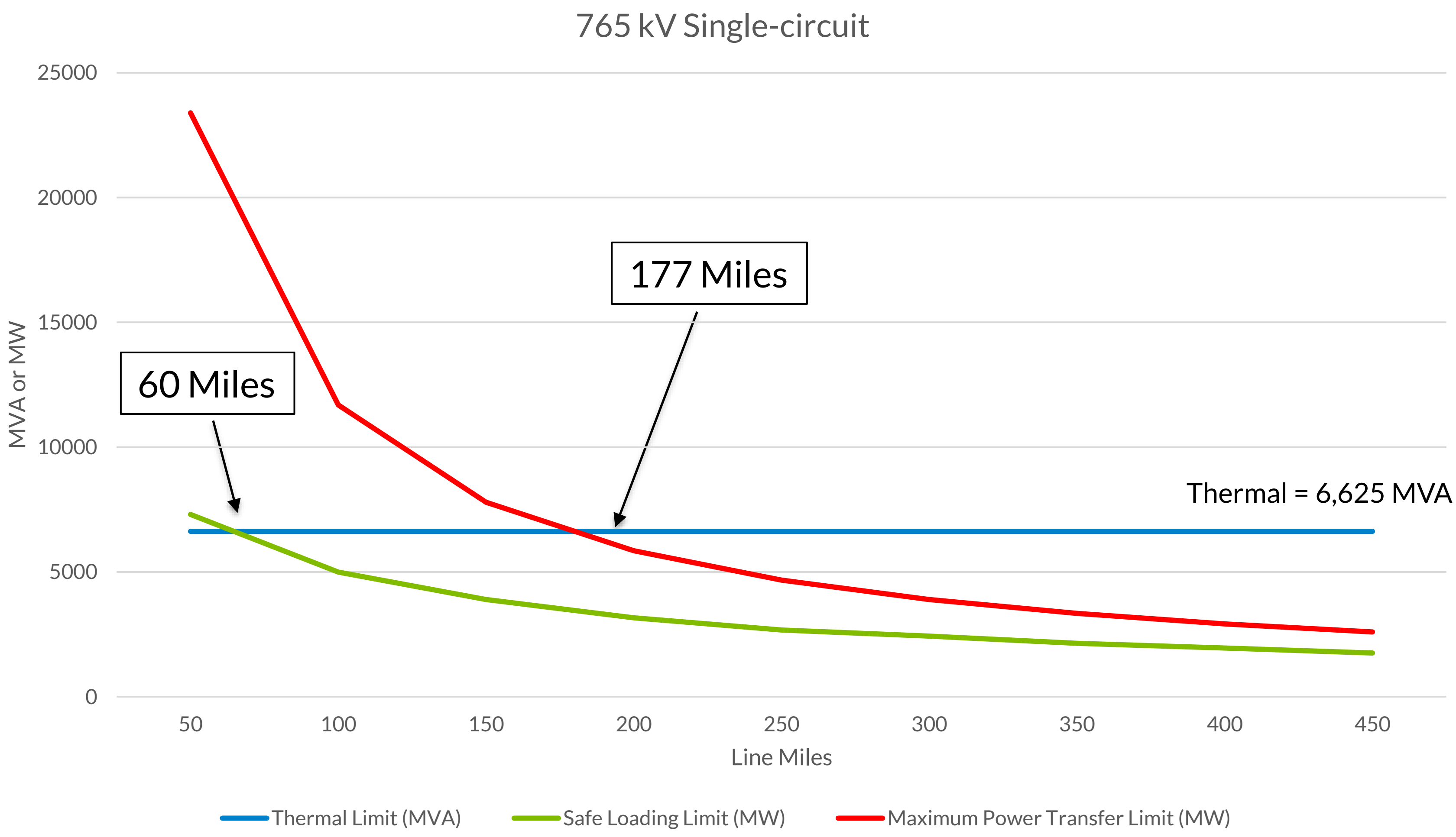
Comparison of Typical 345 kV Limits BOLD Double-circuit, 3-Conductor Bundle Surge Impedance Loading = 1,162 MW



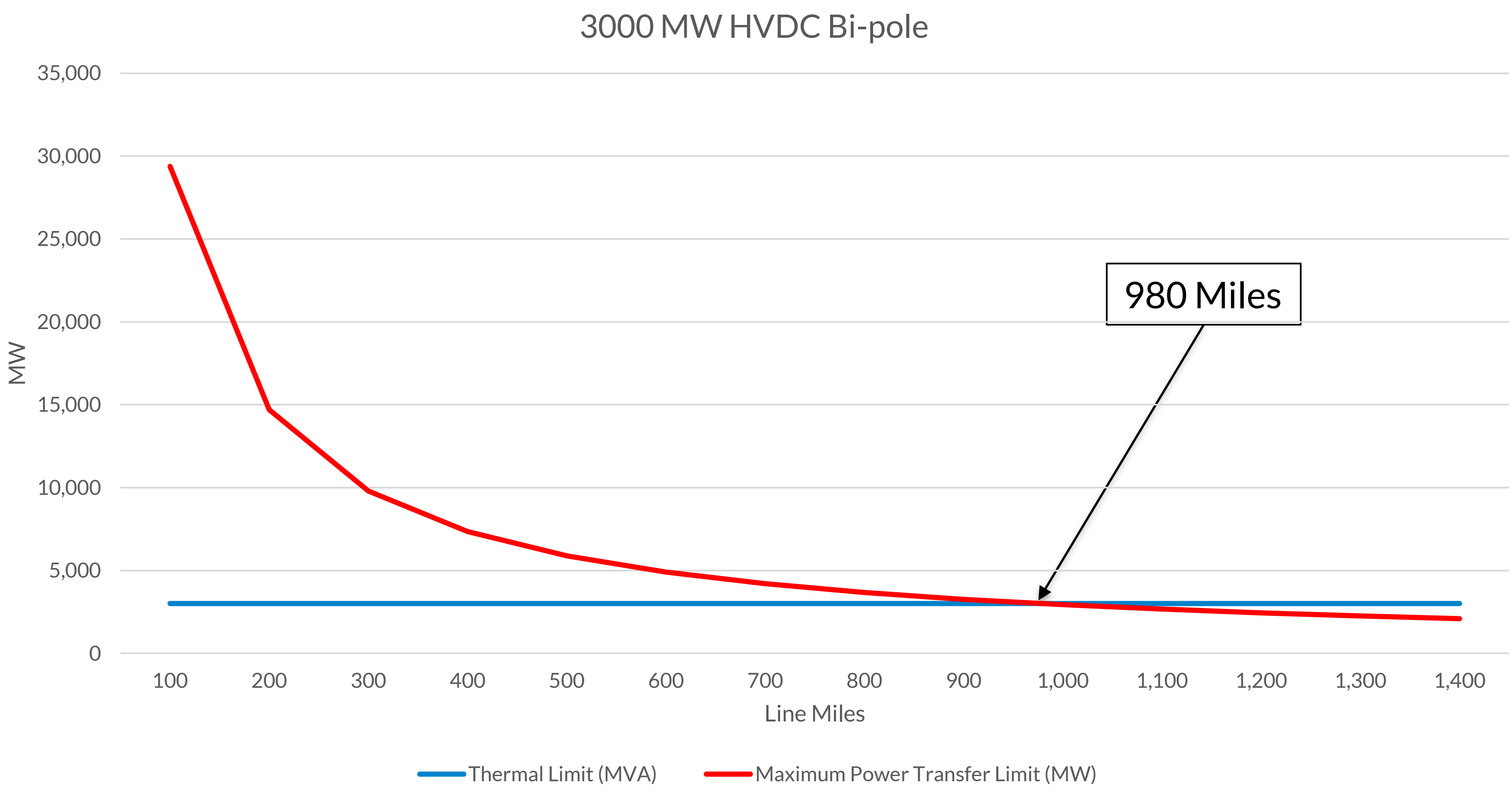
Comparison of Typical 500 kV Limits Single-circuit, 3 - Conductor Bundle Surge Impedance Loading = 936 MW



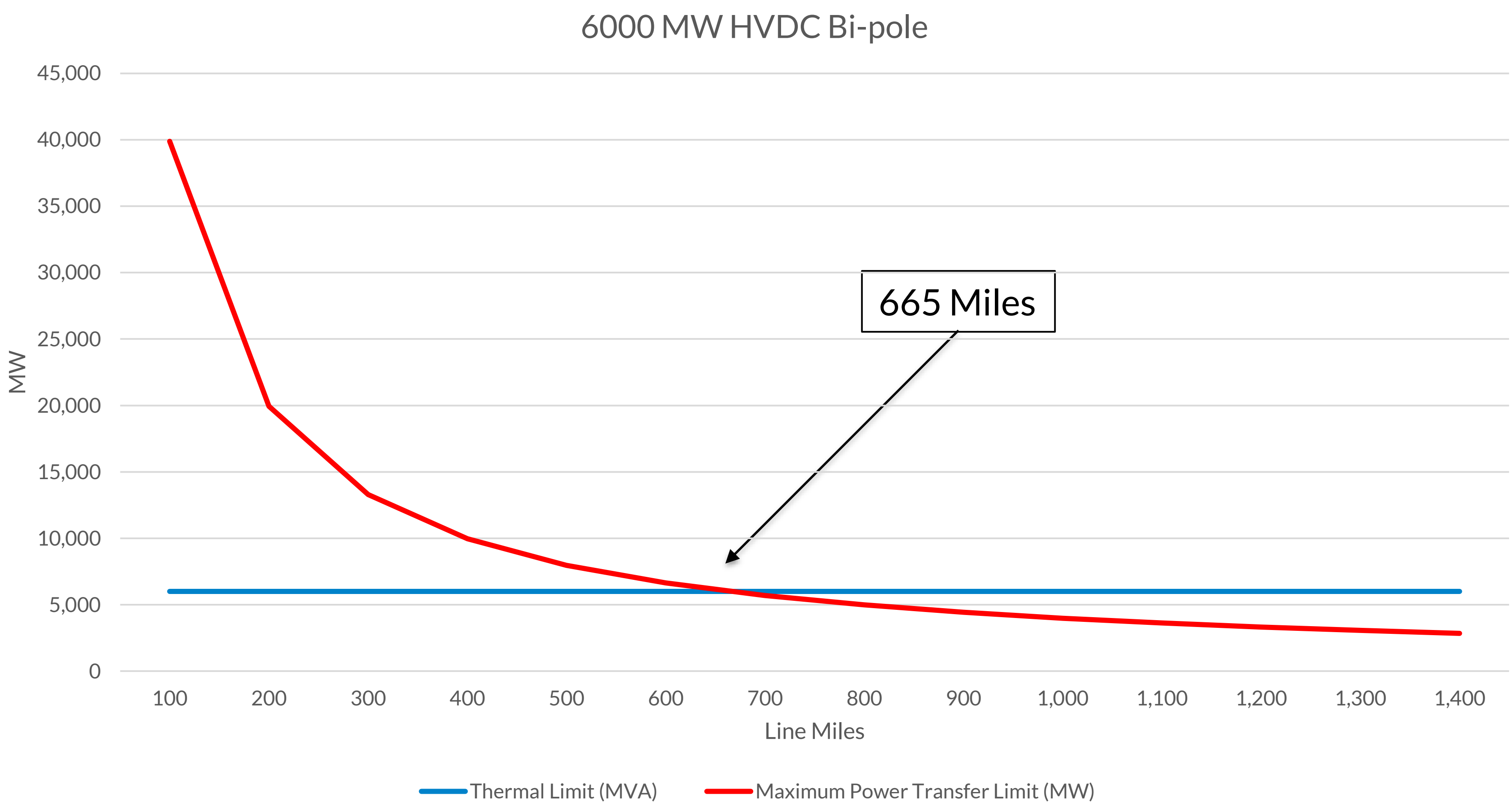
Comparison of Typical 765 kV Limits Single-circuit, 6 - Conductor Bundle Surge Impedance Loading = 2,435 MW



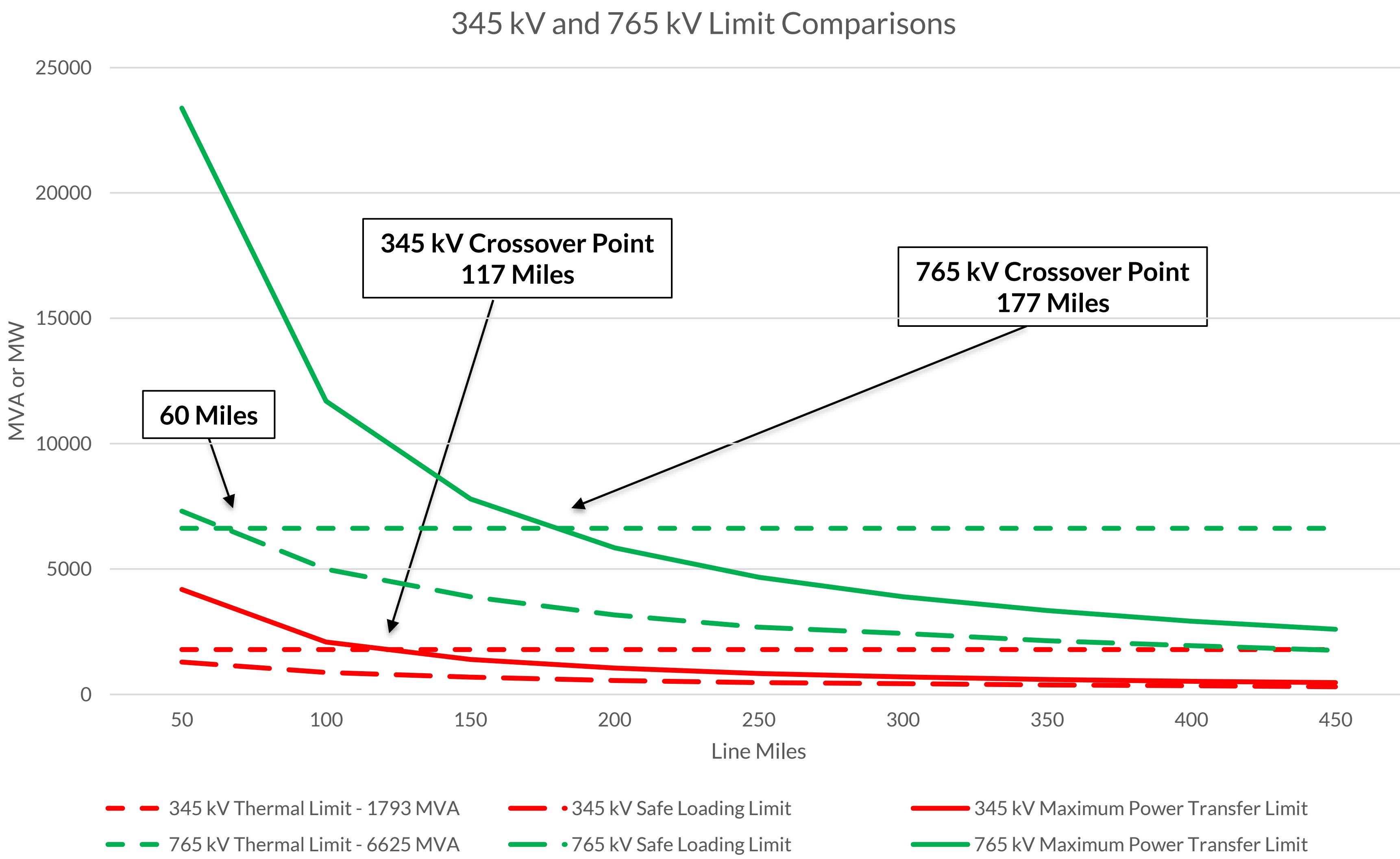
Comparison of Typical +/- 640 kV HVDC Limits
3000 MW Bi-pole
2-Conductor Bundle, 1 Converter per Terminal (2 Total)



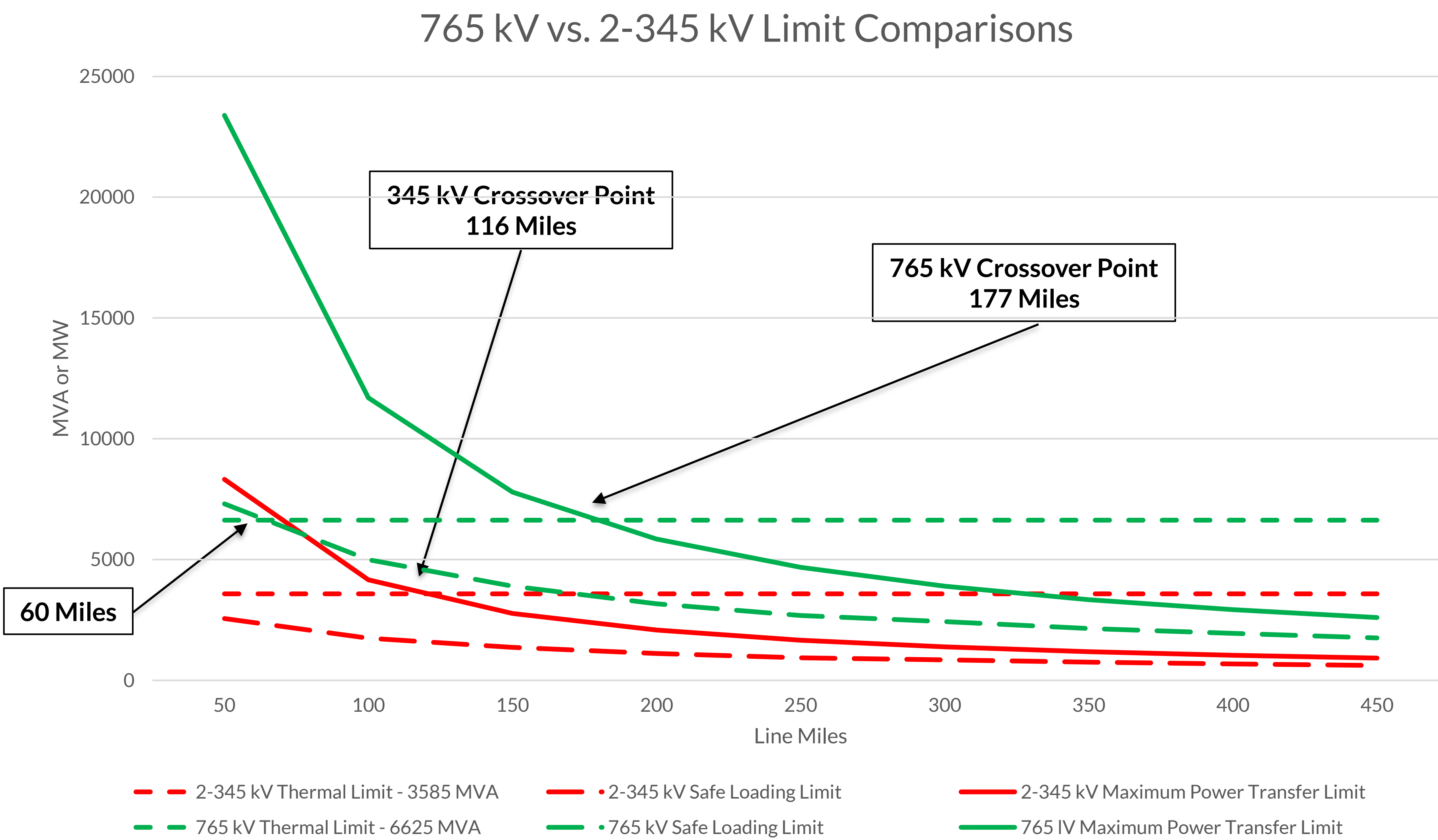
Comparison of Typical +/- 640 kV HVDC Limits
6000 MW Bi-pole
6-Conductor Bundle, 2 Converters per Terminal (4 Total)



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