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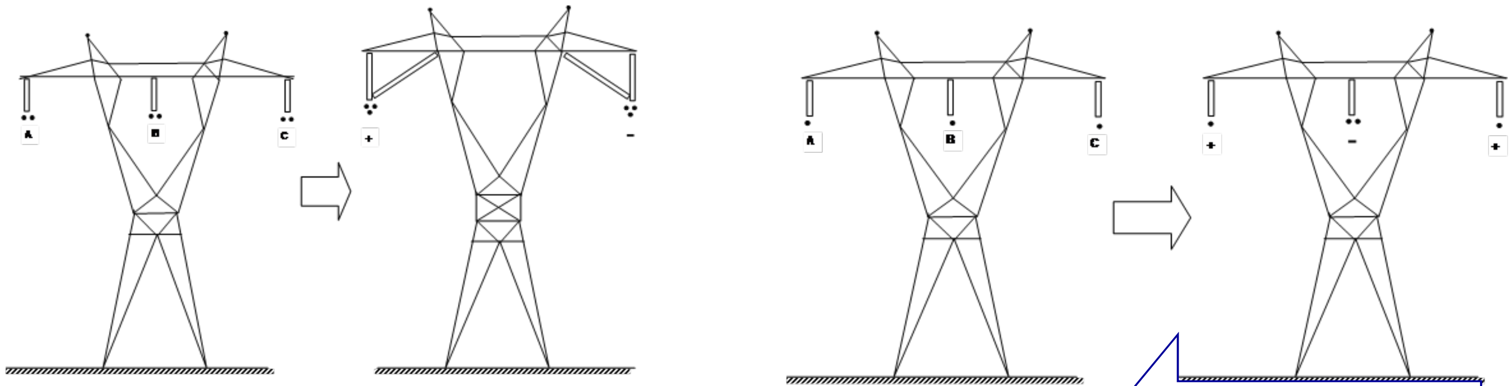
EPRI programs on AC to DC Line Conversion

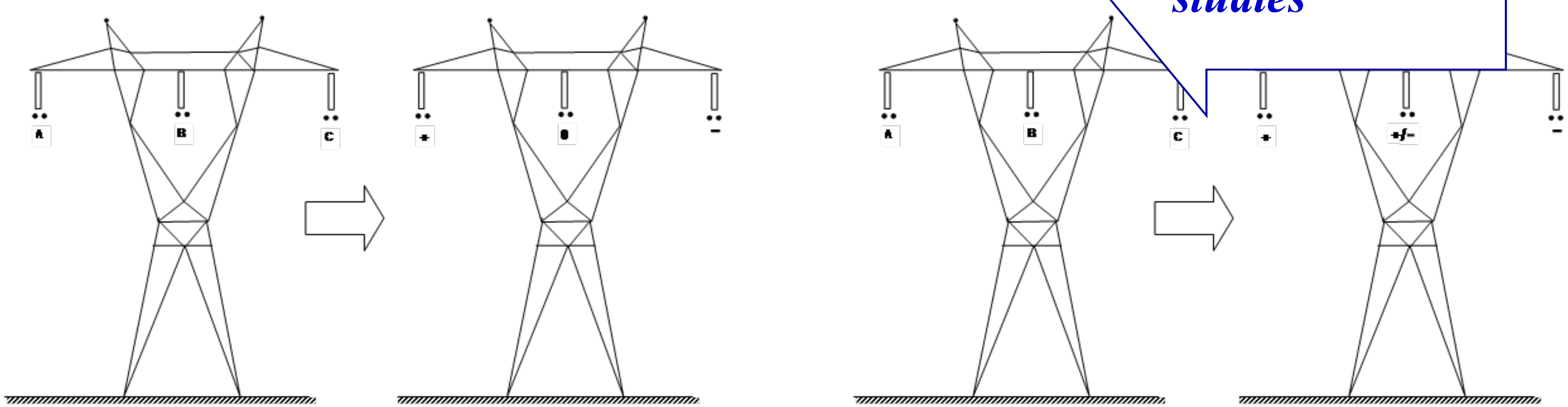
Two approaches:

1. Adapt ac towers to bipole dc



2. Adapt bipole dc to three phase positions

Focus of EPRI studies



EPRI AC to DC conversion studies:

1. Role of Bidirectional Valves (2005-2006)

2. Methods for Assessing the DC Capability of AC transmission lines (2005-2008)

   → "DC Convert Software"

3. DC capability of example ac line designs 138 kV to 765 kV (2008-2009)

4. Consolidated Report (2009-2010)

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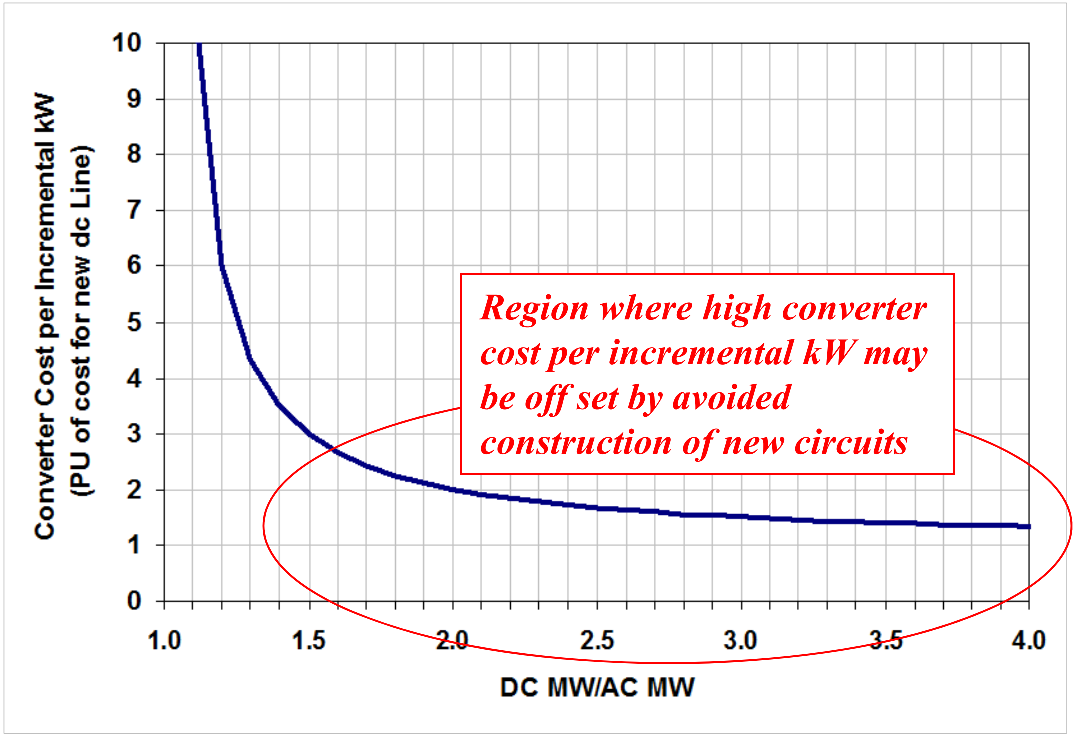
Economic viability of conversion depends on a high boost in MW rating

Conversion means buying converter capacity for the original ac MW as well as any incremental gain in MW



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MW gain by conversion is due to:

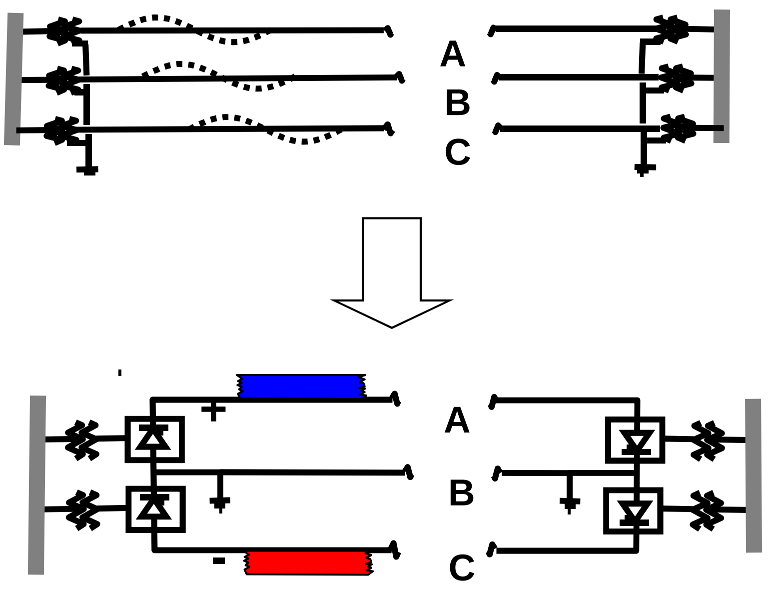
- Higher MW capability for equal current limits
- Ability to control flow
- DC's redundancy
- High momentary overload capability
- Var supply capability (VSC schemes)

Gain in specific cases depends on:

- Prior ac loading limit
- Allowable dc Voltage
- DC Configuration
- Effect of dc operation on parallel ac loading

Bipole Conversion Alternative

MW gain for bipole with metallic return?



Let:

$$k = \frac{V_{dc}}{2V_{ac\ l\text{-}g\ crest}}$$

pf = ac power factor

$$r_{ac} = \frac{MW_{ac\ actual}}{MW_{maximum}}$$

Then:

For $k=1$, $pf = 1$, $r_{ac} = 70\%$

$$\frac{P_{bipole}}{P_{ac}} = 1.18$$

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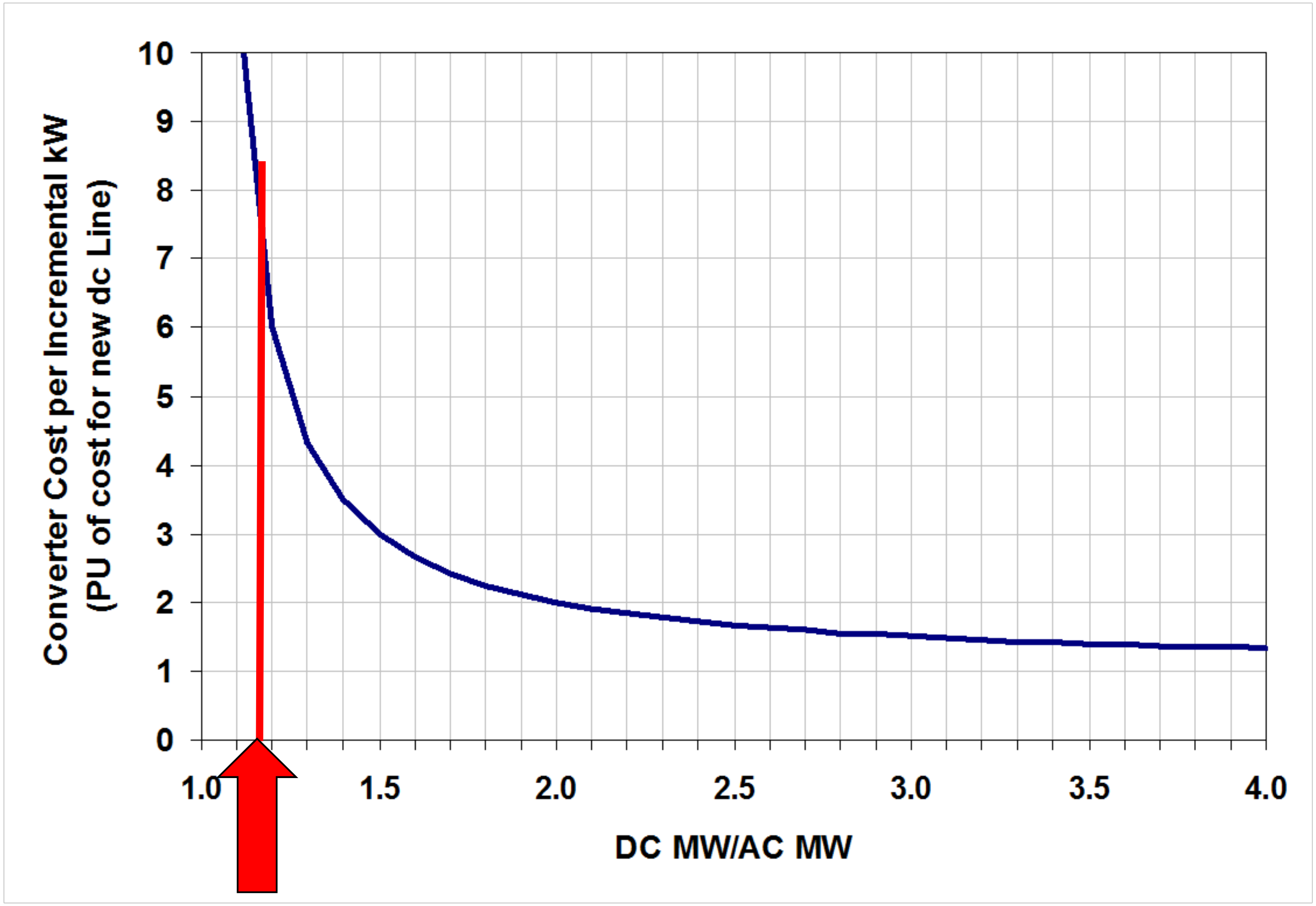
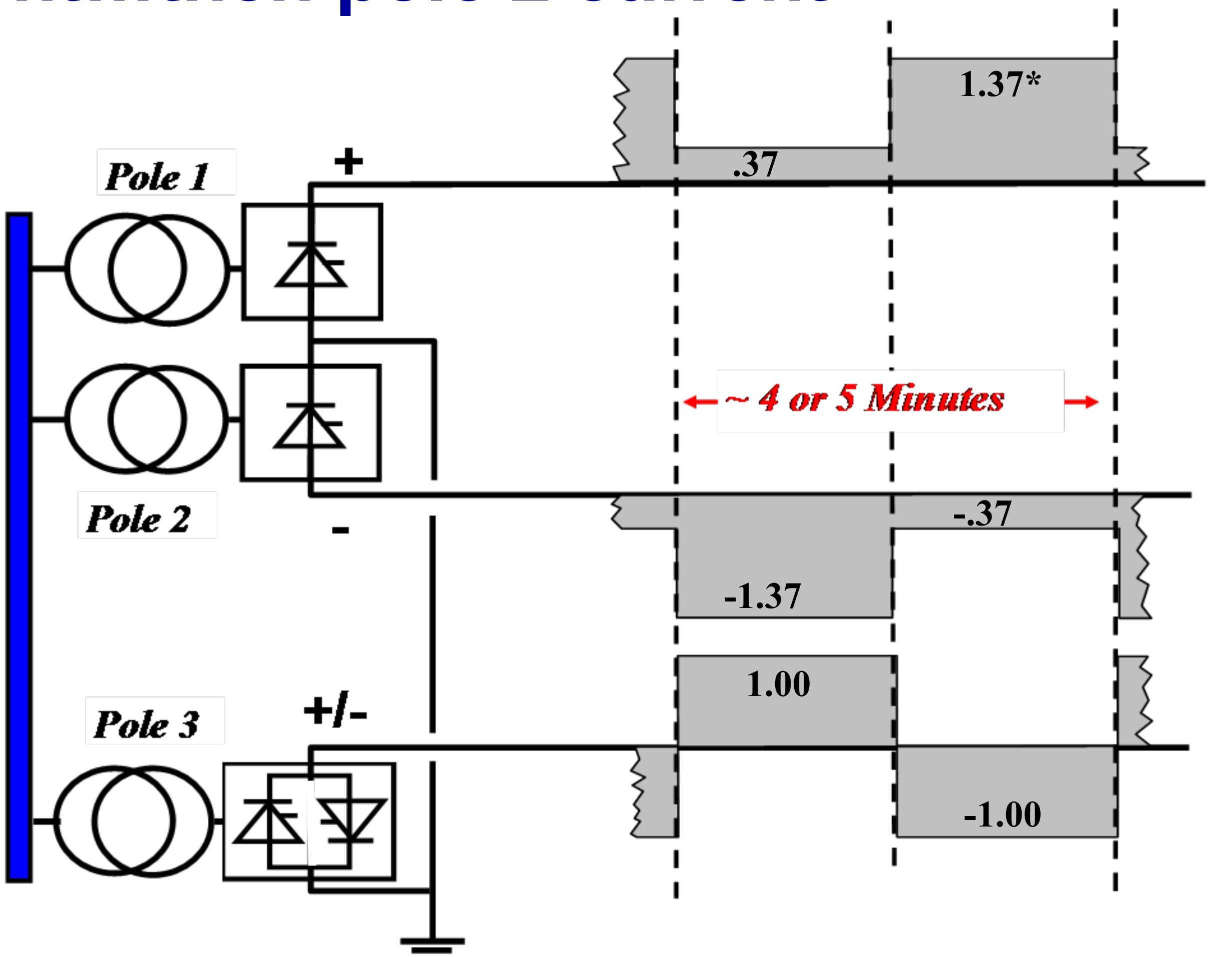
Economic feasibility sensitive to MW gain



Tripole Conversion Alternative

Pole 3 alternately relieves some pole 1 current…then pole 2 current



* .5 + √3/2

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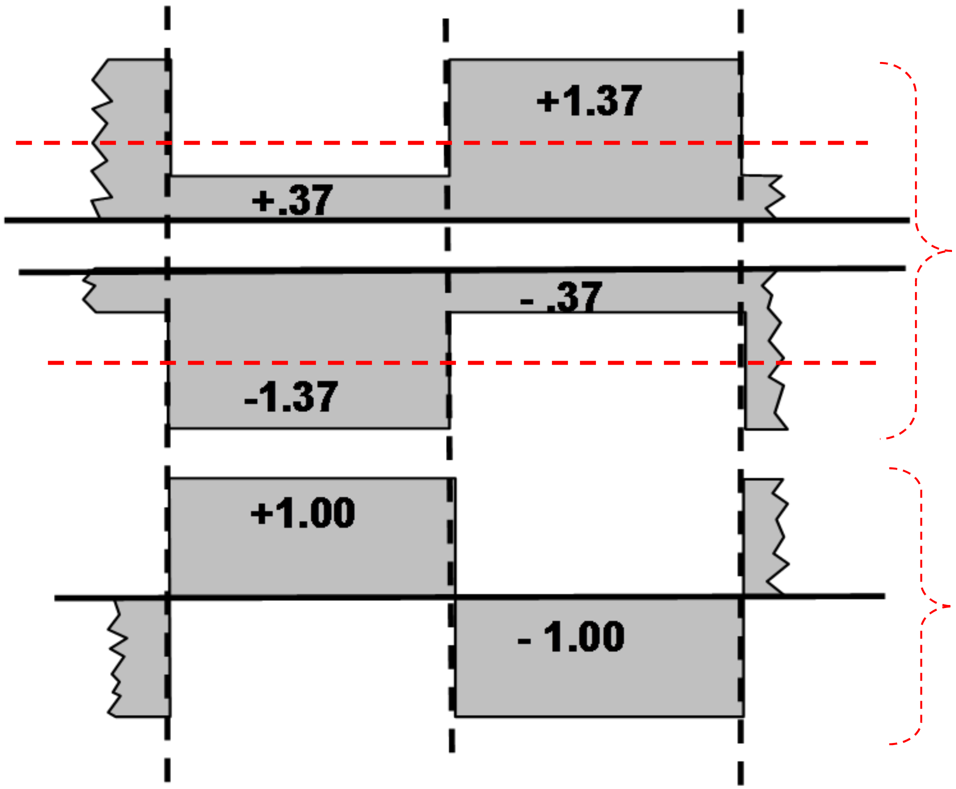
Thermal Averaging



RMS (Heating) Current is

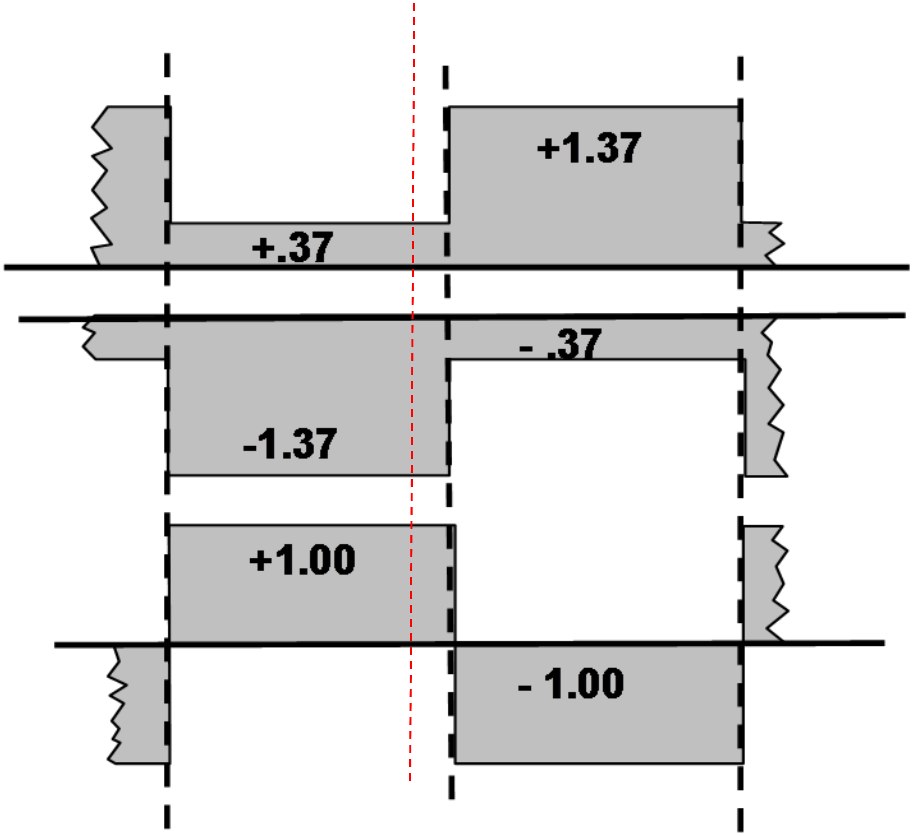
$(.37^2 + 1.37^2)/2 = 1.00$

RMS (Heating) Current is

$(1^2 + 1^2)/2 = 1.00$

Full use is made of thermal capacity of all phase positions

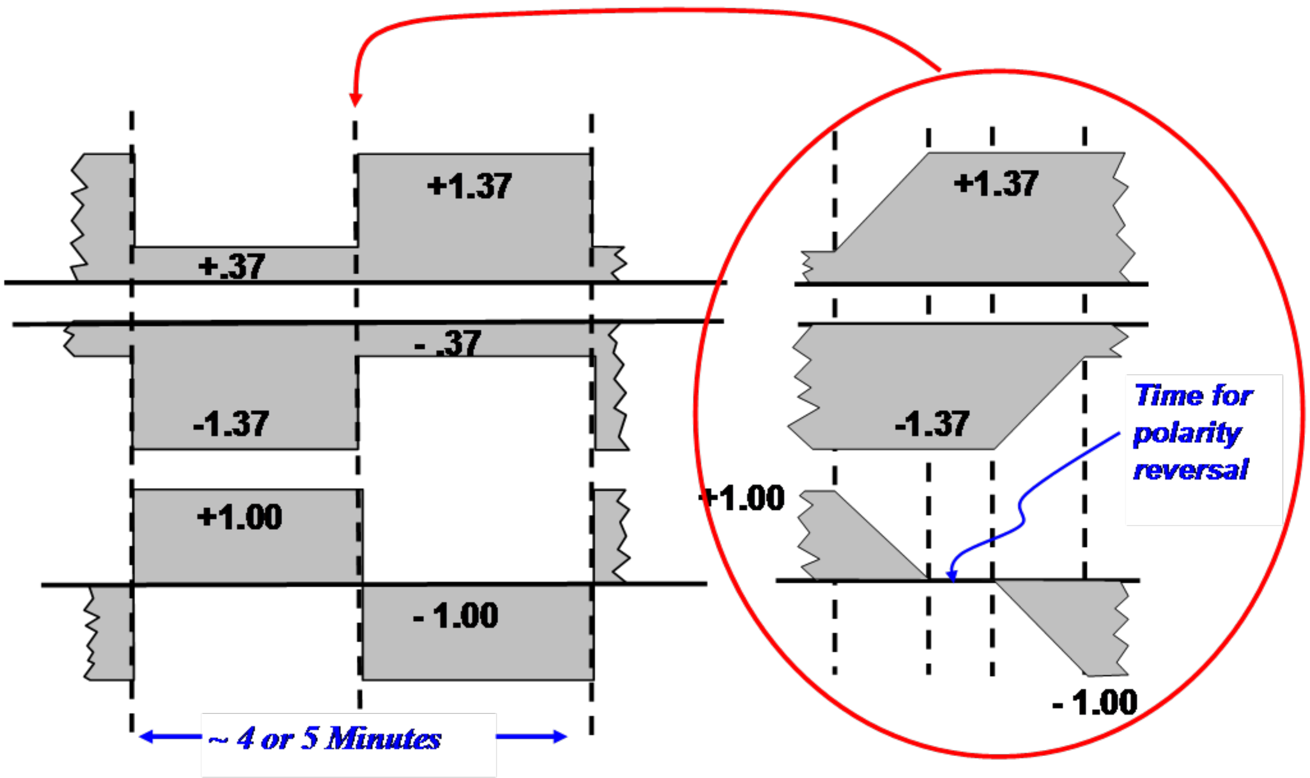
Tripole Power Capability



At any given time, P_{dc} = .37 +1.37 + 1 = **2.74**

Compared to 1 +1 = 2 for Bipole….**1.37 times greater**

Easy to create time for polarity reversal on pole 3

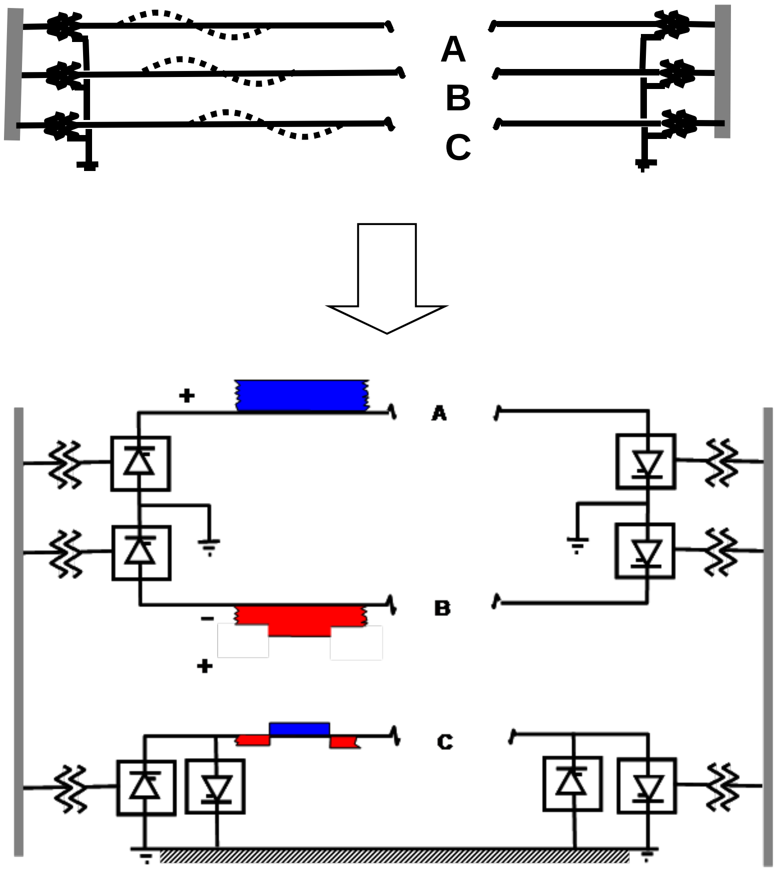


Tripole Terminal Requirements:

- **All equipment is standard**
- **Double the number of valve groups since pole three requires both + and – valves**
- **Current rating of valves and cooling systems must be 1.37 higher than bipole for the same rms current. ***
- **Transformer rating are unaffected by current modulation**

** Not a cost premium where a high emergency power rating is the objective.*

MW gain for Tripole without metallic return?

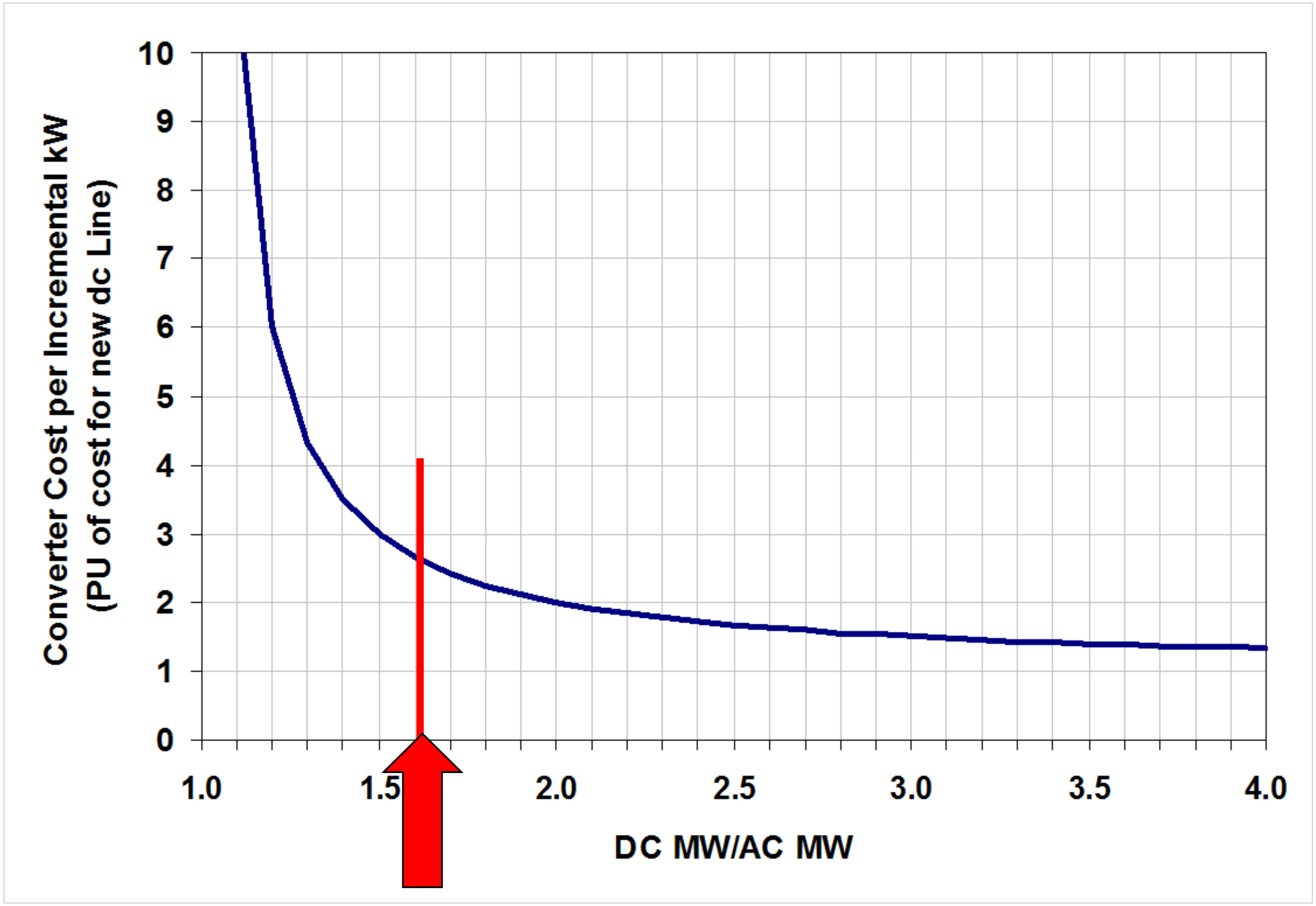


$$\frac{P_{tripole}}{P_{ac}} = \frac{2x\ 1.37k\sqrt{2}}{3pf} \times \frac{1}{r_{ac}}$$

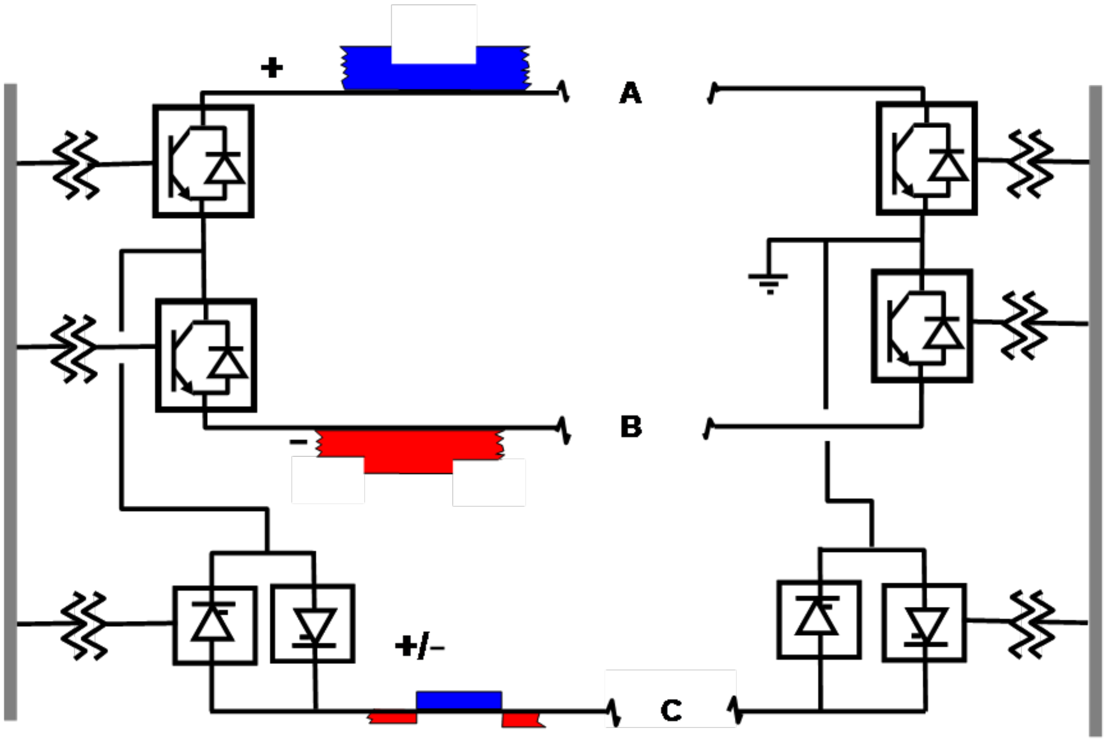
For k=1, pf = 1, r=70% :

$$\frac{P_{tripole}}{P_{ac}} = 1.62$$

Economic feasibility sensitive to MW gain



VSC's will work with bipole or tripole options



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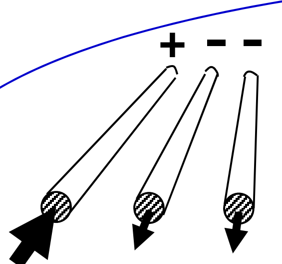
Comparison of line losses

If dc is operating at ac l-g crest voltage, then for equal transmitted power:

Bipole with metallic return $$\frac{L_{bipole}}{L_{ac}} = \frac{3p^2}{4}$$

Tripole $$\frac{L_{tripole}}{L_{ac}} = .6p^2$$

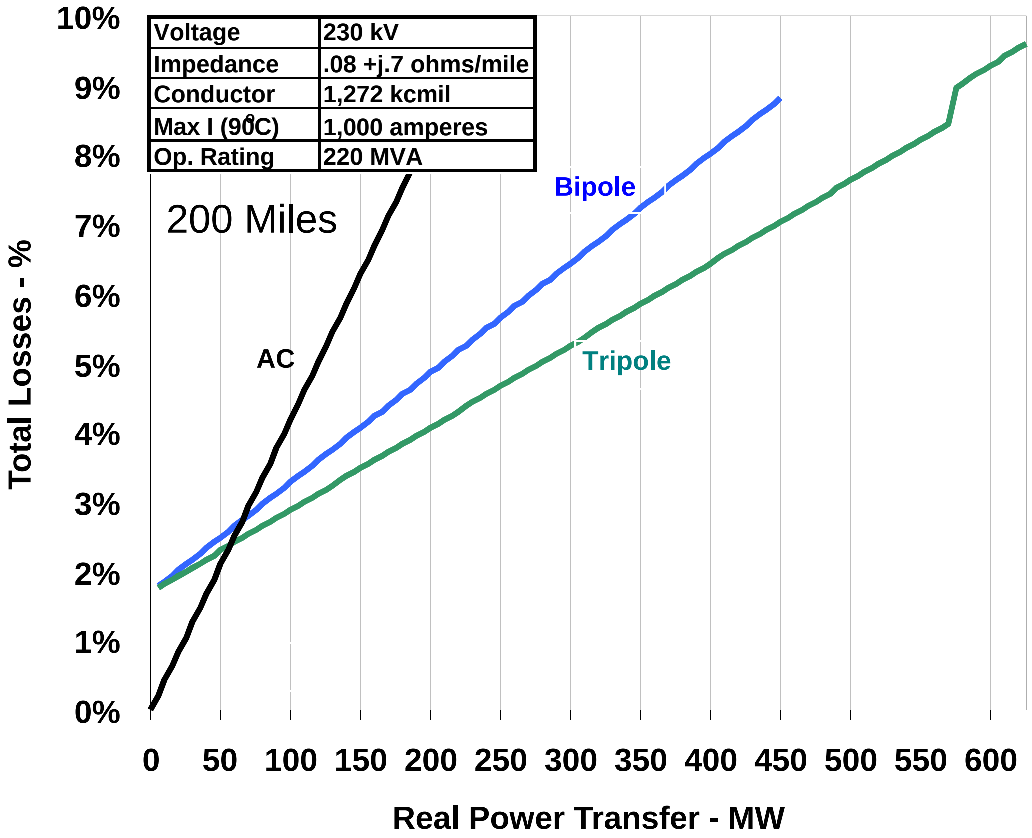
Split return operation $$\frac{L_{split}}{L_{ac}} = \frac{9p^2}{16}$$



Characterizes:

- ***Bipole where metallic return is forfeited***
- ***Tripole… up to 93% of maximum capacity***

Total Losses – 230 Kv example



Redundancy

$$\text{Redundancy} = \frac{\text{Max. MW with one pole out}}{\text{Total maximum MW}}$$

		Earth return	No earth return
ac		0%	0%
dc	monopole	0%	0%
	bipole	50%	0%
	tripole	73%	73%

Important because:

- *Need for earth return, ground electrodes can be eliminated*
- *Redundancy prevents the converted line from becoming a limiting outage case where a large boost in MW capacity is realized.*

Redundancy

Or…assuming 15% emergency overload capability:

		Earth return	No earth return
ac		0%	0%
dc	monopole	0%	0%
	bipole	57%	0%
	tripole	84%	84%

Emergency/Normal Capability

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P_{ac} = *Normal ac loading*

P'_{ac} = *Emergency ac loading*

Before Conversion | *After Conversion*

Emergency pick-up capability of the line to be converted

$$\Delta P_{ac} = P'_{ac} - P_{ac}$$

$$\Delta P_{dc} = P'_{dc} - P_{dc}$$

Increase in parallel ac system loading:

$$\Delta MW_{ac} = \Delta P_{dc} - \Delta P_{ac}$$

Increase in flow on the converted line itself:

$$\Delta MW_{conv.\ line} = P_{dc} - P_{ac}$$

$$\Delta MW_{path} = \Delta MW_{ac} + \Delta MW_{conv.\ line} = P'_{dc} - P'_{ac}$$

DC Voltage sustainable by former circuits…

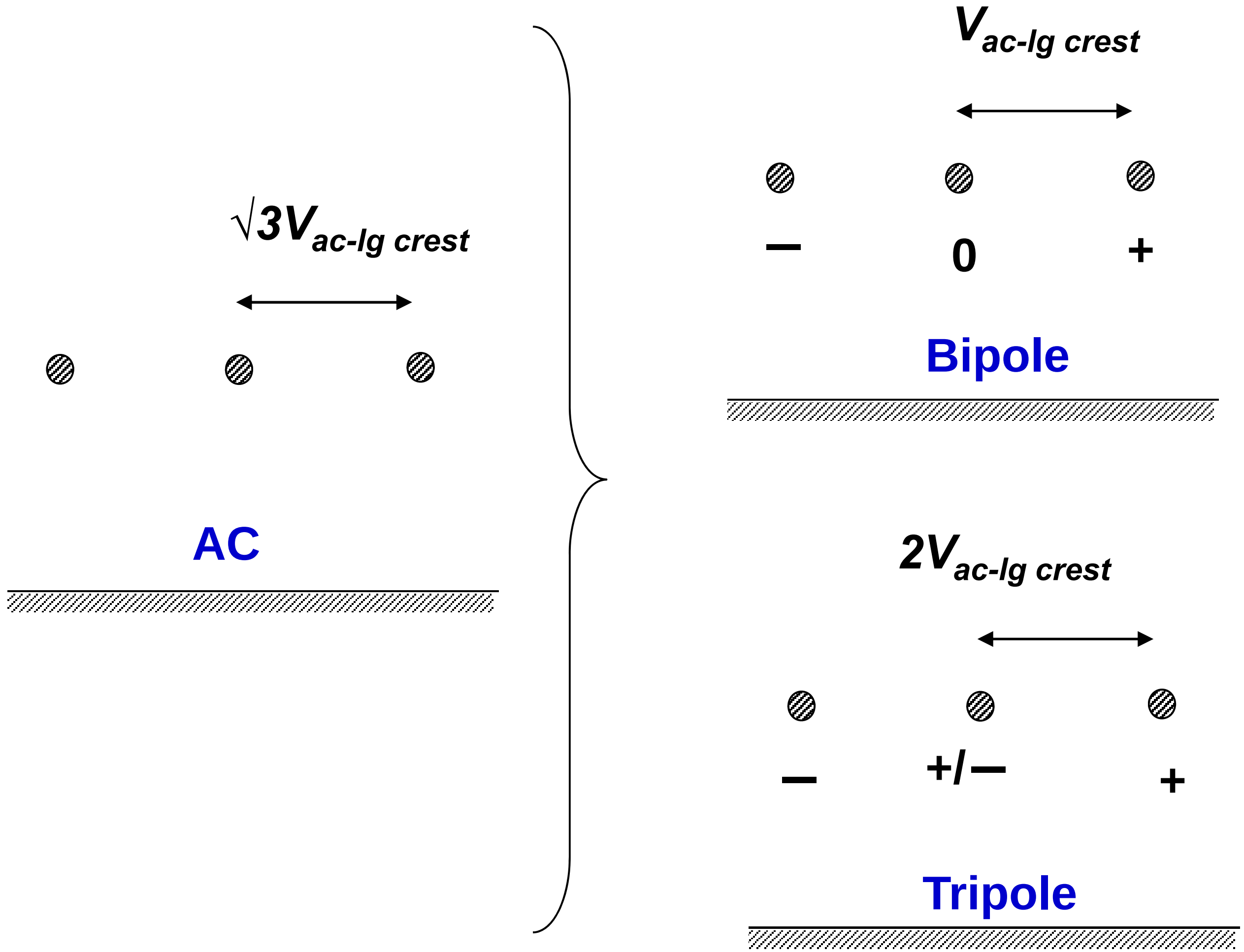
The lower of:

1. ***Conductor gradient limit (A/N)****
2. ***Insulation limit (Pollution)***
3. ***Clearance limit***
4. ***Ground-level electric field limit****

** Limits differ for different dc regimes*

1. Conductor Gradient limits
2. Earth surface gradient limits

Voltage between phase positions



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Example Gradient Precedents:

Circuit	kV (+/-)	Pole Sp. (m)	Cond. Hgt. (m)		Conductors (cm)			E_c (kV/cm)	E_g (kV/m)
			Min.	Avg.*	Nr.	Diam	Space		
Hydro Quebec, Ca.	450	11	12.00	22.80	4	3.56	45.7	19.0	10.2
Nelson River, Ca.	500	13.4	8.90	16.90	2	4.06	45.7	27.6	17.0
Furnas, Brazil	600	13	15.40	29.30	4	3.41	45.7	25.1	9.5
Power Grid, India	500	13**	12.75	24.20	4	3.51	45.7	20.5	11.1
West Intertie, US	500	12.3	9.90	18.80	2	6.43	45.7	19.4	14.4

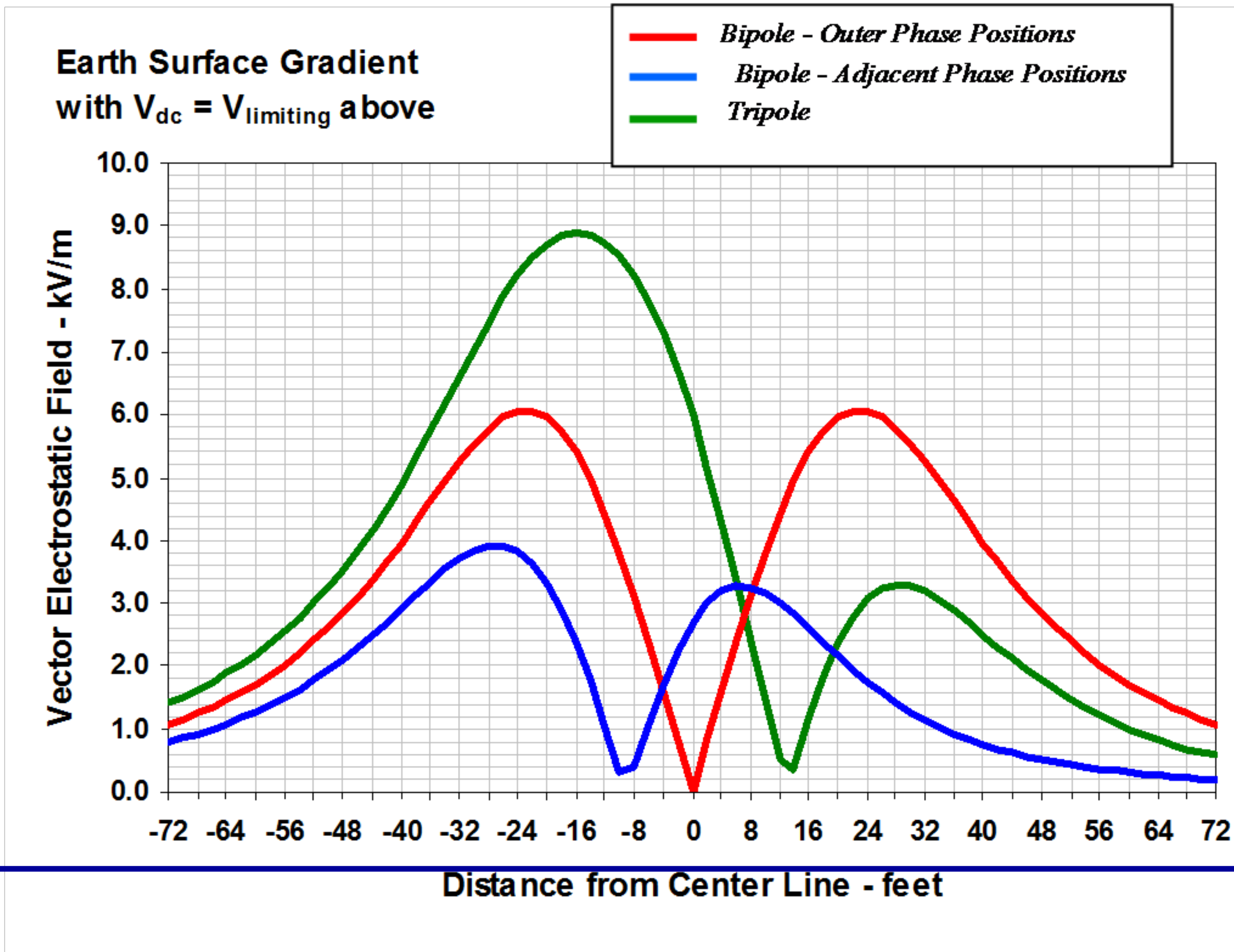
** Estimated* *** Average*

Example criteria:

	AC Voltage Class		
	0-150kV	151-300 kV	>300 kV
Conductor Gradient Criterion	22 kV/cm	24 kV/cm	26 kV/cm
Earth Surface Gradient Criterion	10 kV/m	13 kV/m	15 kV/m

Reduced criterion at lower voltages because of prior in-service ac precedent

Example earth-level field profile



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2. Insulation limit

3. Clearance limit

Joint solution

Insulation for HVDC:

- Assume ac insulators replaced by dc units
- Creepage distance criteria:

Creepage Criterion

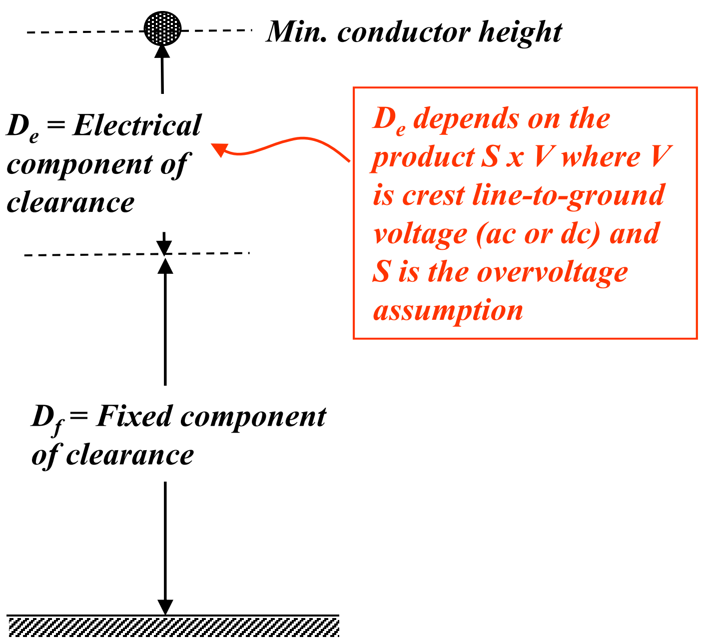
Zone	mm/kV	kV/ins.*
I Light	30	15.2
II Medium	38	12
III Heavy	56	8.1
IV Extreme	70	6.5

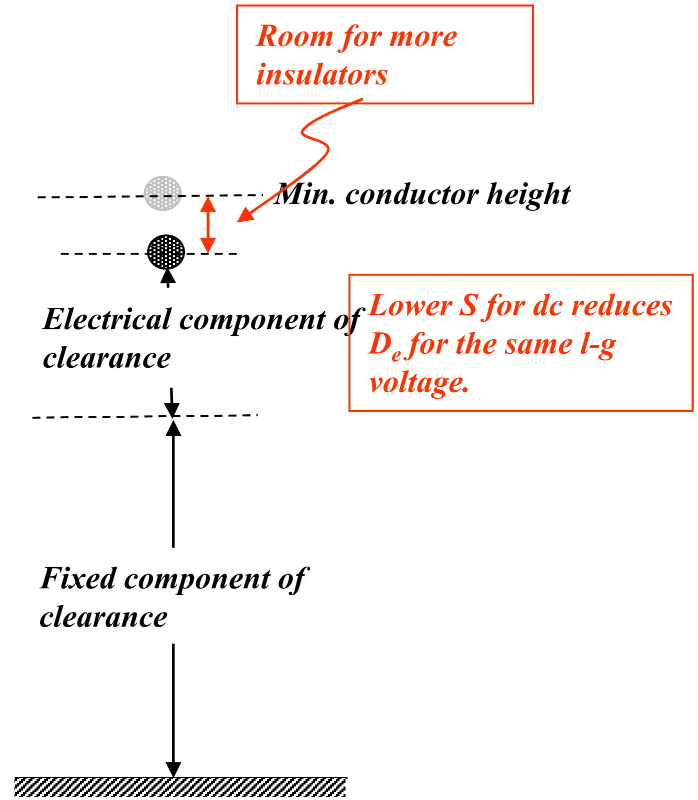
** 146 mm fog-type units*

- Need to add insulators to raise voltage?

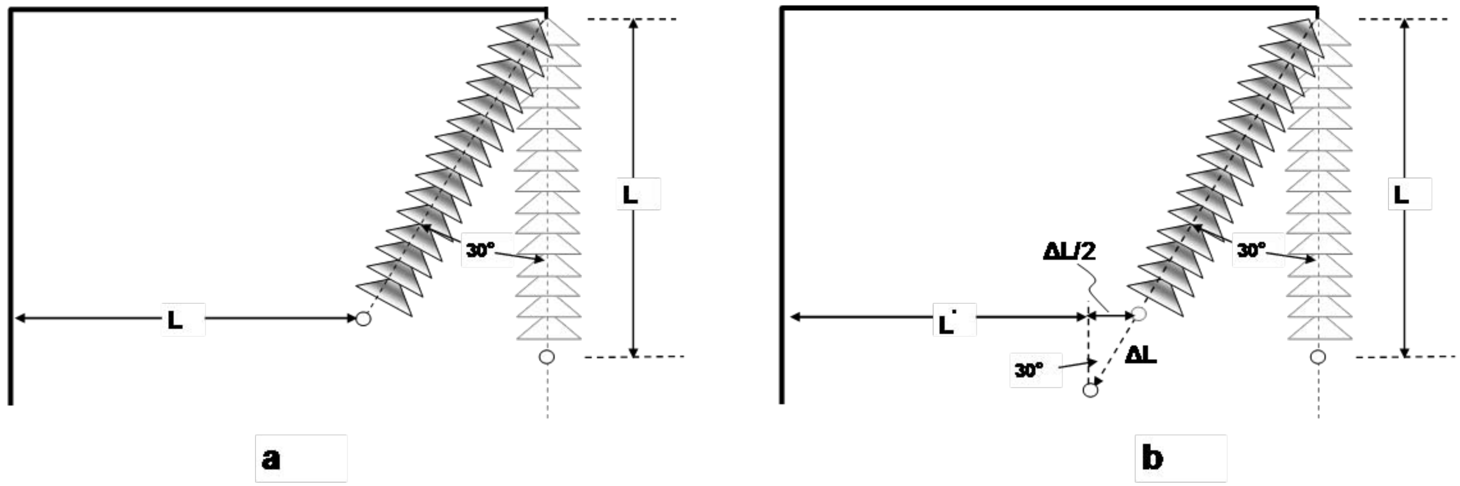
DC Operation

AC Operation





Does extension jeopardize clearance to tower?



- *At 30º swing, clearance reduction to tower is ½ clearance reduction to ground…normally not limiting*
- *Caution with long extensions and clearance to lower cross-arms on vertical configurations*

Example studies

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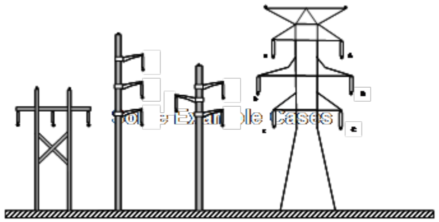
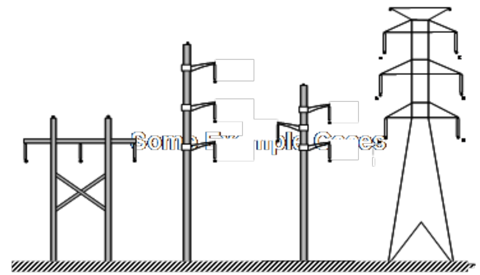
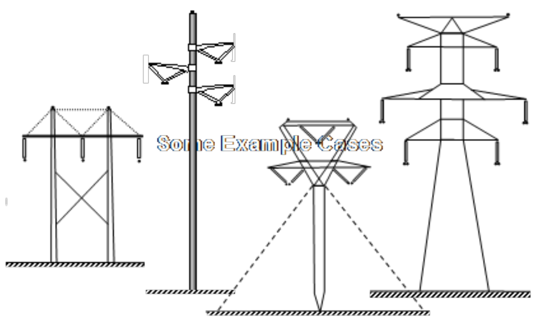
Towers considered:



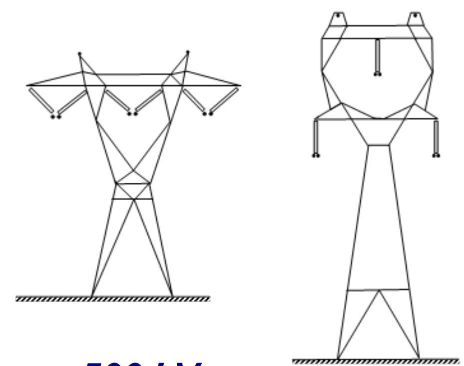
138 kV



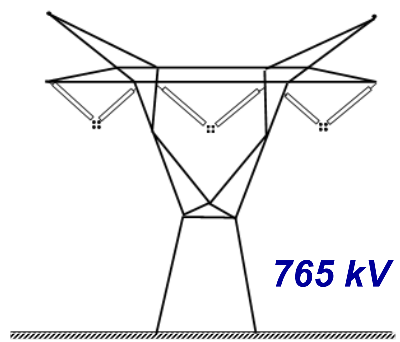
230 kV



345 kV



500 kV



765 kV

Conclusions:

1. V_{dc} may be as high as $2xV_{l\text{-}g\ ac}$ at lower voltages, less than $V_{l\text{-}g\ ac}$ 1.0 at the highest. V_{bipole} will generally exceed $V_{tripole}$
2. Conductor gradient usually limits V_{dc} for lower voltage; Earth field for highest voltages or lines with very large bundles
3. Tripole conversion gets larger MW gains than the bipole except when converting a double circuit ac line to all dc
4. Where insulation is limiting, there are work-arounds
5. Bipole and tripole have different effests on allowable flow on parallel ac
6. Conversion can increase a circuit's contribution to path flow by as much as 2:1… the largest gains at the lowest transmission voltages.

Is ac to dc conversion economically justified?

Example costs for transmitting electric power

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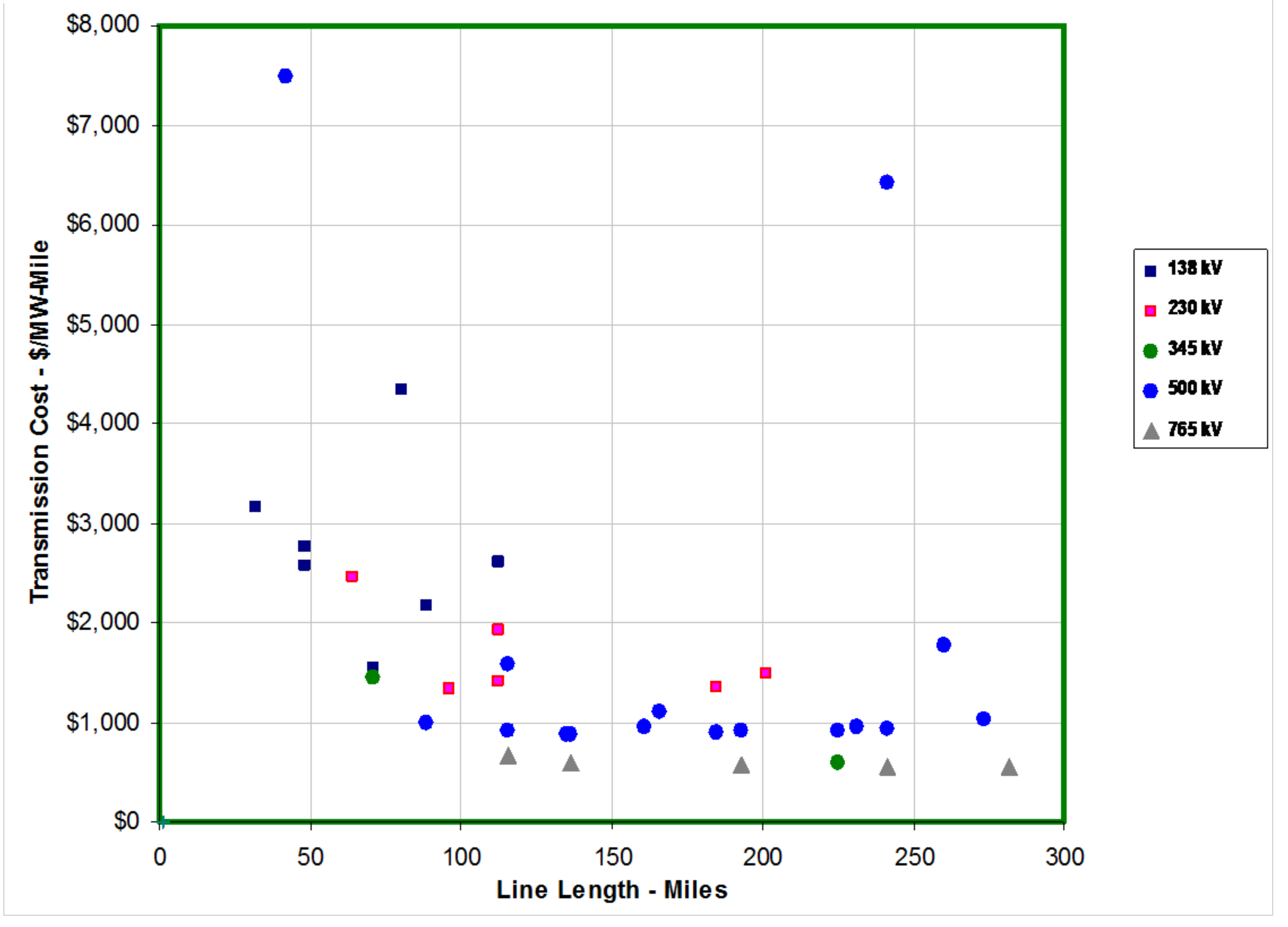
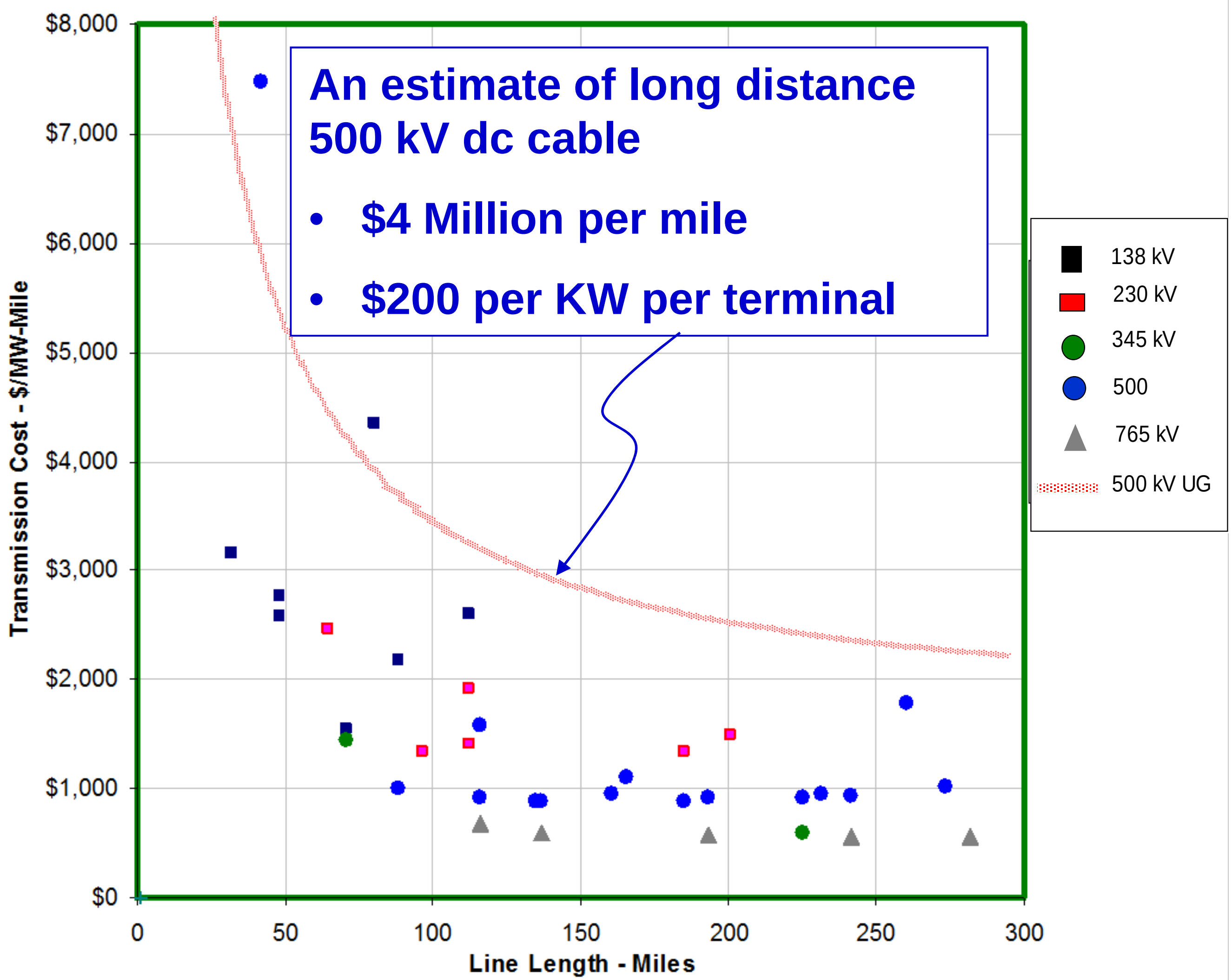
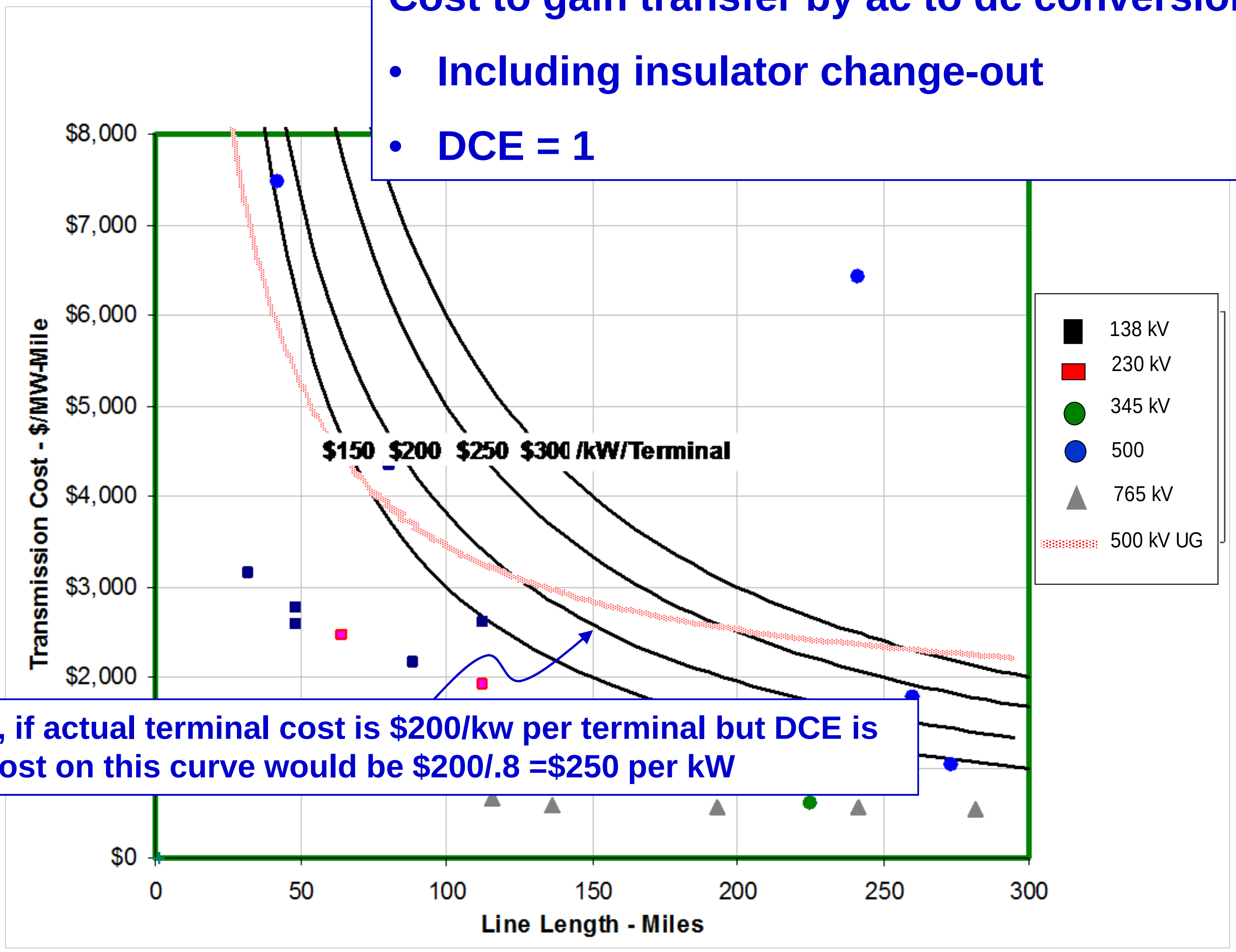


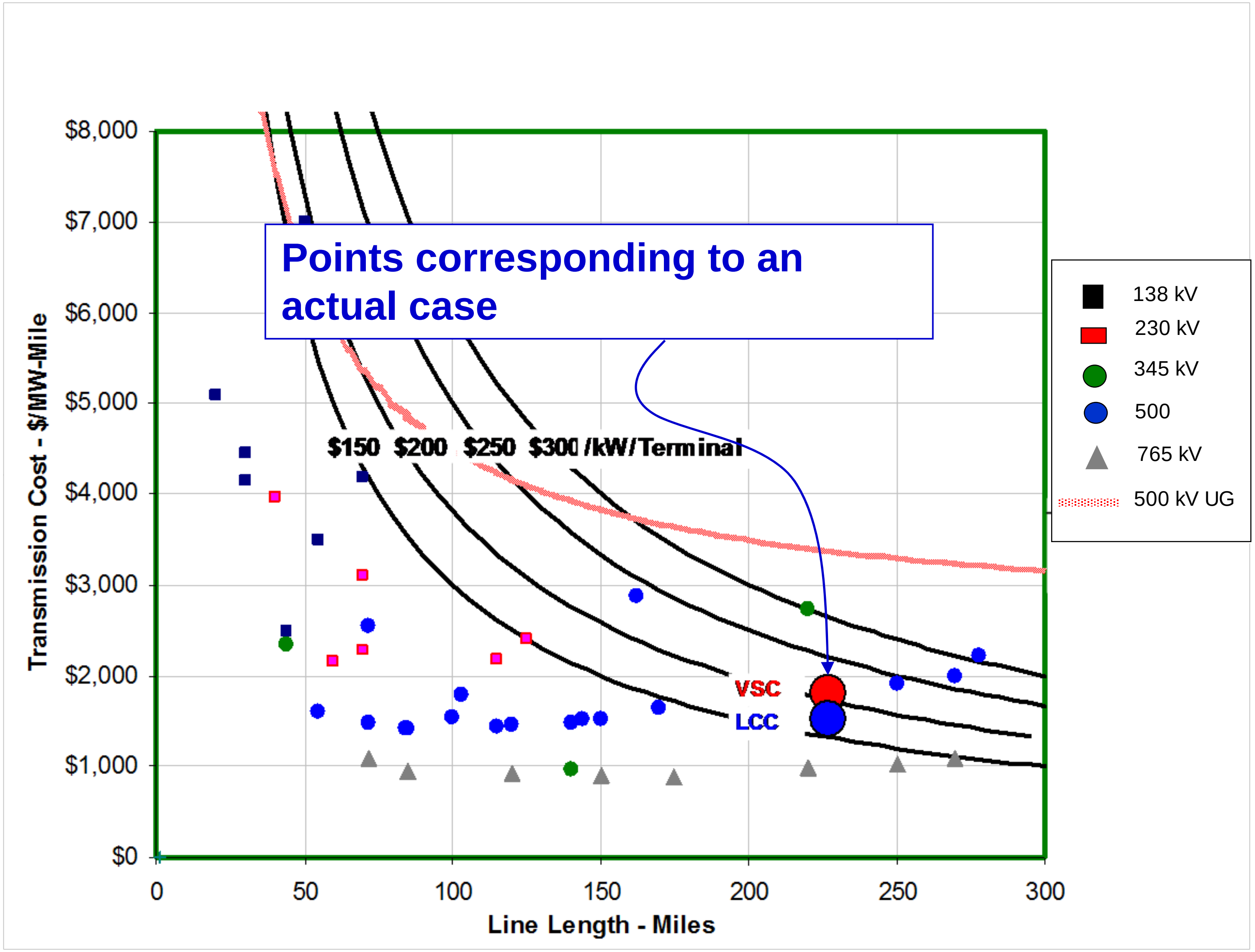

An estimate of long distance 500 kV dc cable
• $4 Million per mile
• $200 per KW per terminal
$8,000
$7,000
$6,000
$5,000
$4,000
$3,000
$2,000
$1,000
$0
Transmission Cost - $/MW-Mile
0
50
100
150
200
250
300
Line Length - Miles
138 kV
230 kV
345 kV
500
765 kV
500 kV UG

Cost to gain transfer by ac to dc conversion:

- Including insulator change-out
- DCE = 1



For example, if actual terminal cost is $200/kw per terminal but DCE is .8, *effective* cost on this curve would be $200/.8 =$250 per kW



Points corresponding to an actual case
$8,000
$7,000
$6,000
$5,000
$4,000
$3,000
$2,000
$1,000
$0
Transmission Cost - $/MW-Mile
0
50
100
150
200
250
300
Line Length - Miles
$150 $200 $250 $300 /kW/Terminal
VSC
LCC
138 kV
230 kV
345 kV
500
765 kV
500 kV UG

Current Industry Needs?

Industry Needs?

1. Demonstration projects
2. Example studies which integrate system issue
3. DC Voltage limitations of converted lines
4. Better definition of ground-level field requirements
5. Better definition of system influence on choice of conversion option