MVDC Use Case

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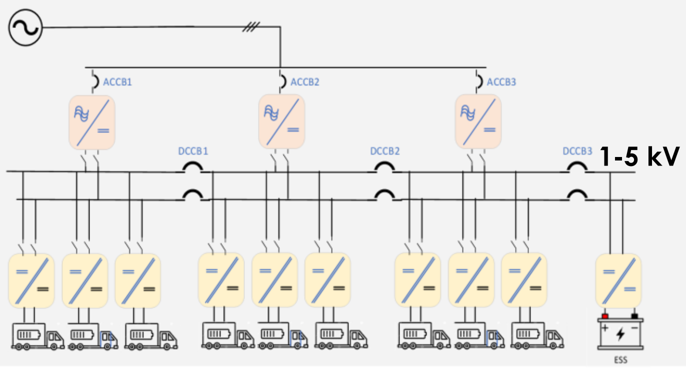
Project Summary

- MVDC driven by growth of DC load and DER/Storage integration
- The **objective** is to evaluate impact of MVDC technologies in distribution grid applications
    - Develop use cases and scenarios
    - Provide metrics

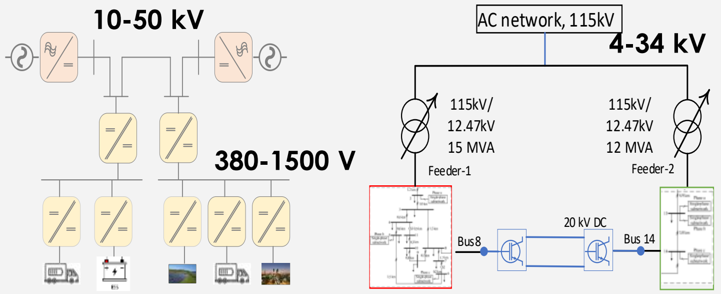
MV Power Electronics Applications

EVs- Megawatt Scale

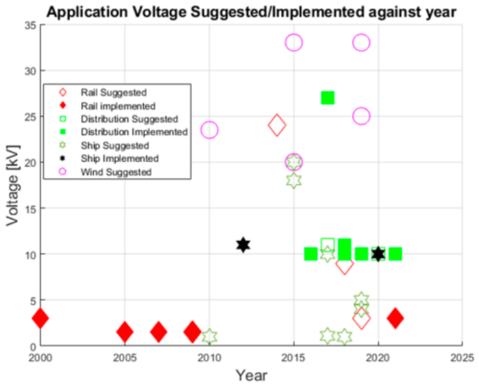


Grid-MV AC/DC Distribution

Grid-MVDC Link

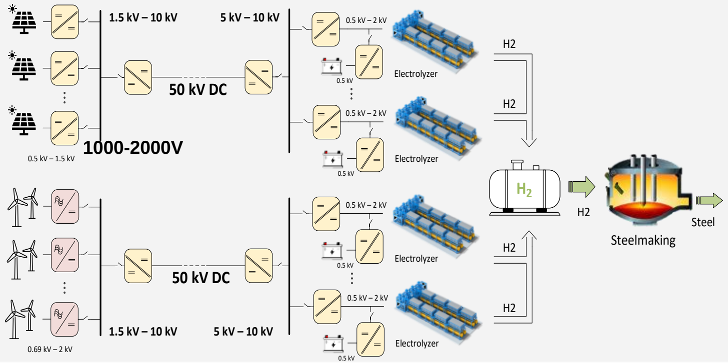


MV Power Electronic Projects Implemented in Asia/Europe

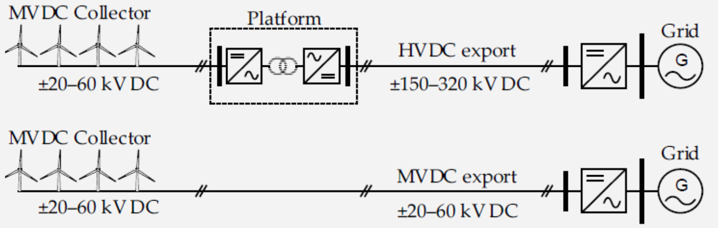


"Review of MVDC Applications, Technologies, and Future Prospects", Sophie Coffey, Energies, 2015

GW-Scale MVDC for Green Steel



Wind Collection and Distribution



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The Numbers

- DOE PROGRAM OFFICE:
  OE – Transformer Resilience and Advanced Components (TRAC)
- FUNDING OPPORTUNITY:
  AOP
- LOCATION:
  Knoxville, TN
- PROJECT TERM:
  10/01/2022 to 09/30/2023

PROJECT STATUS:
In-progress

AWARD AMOUNT (DOE CONTRIBUTION):
$300,000

AWARDEE CONTRIBUTION (COST SHARE):
$0

PARTNERS:
NA

Technical Approach

- Use fundamental advantages of MVDC and identify scenarios in distribution grid where such a technology can be beneficial

"Over the same cable, 1.57-1.88 x power can be transferred with DC compared to AC"

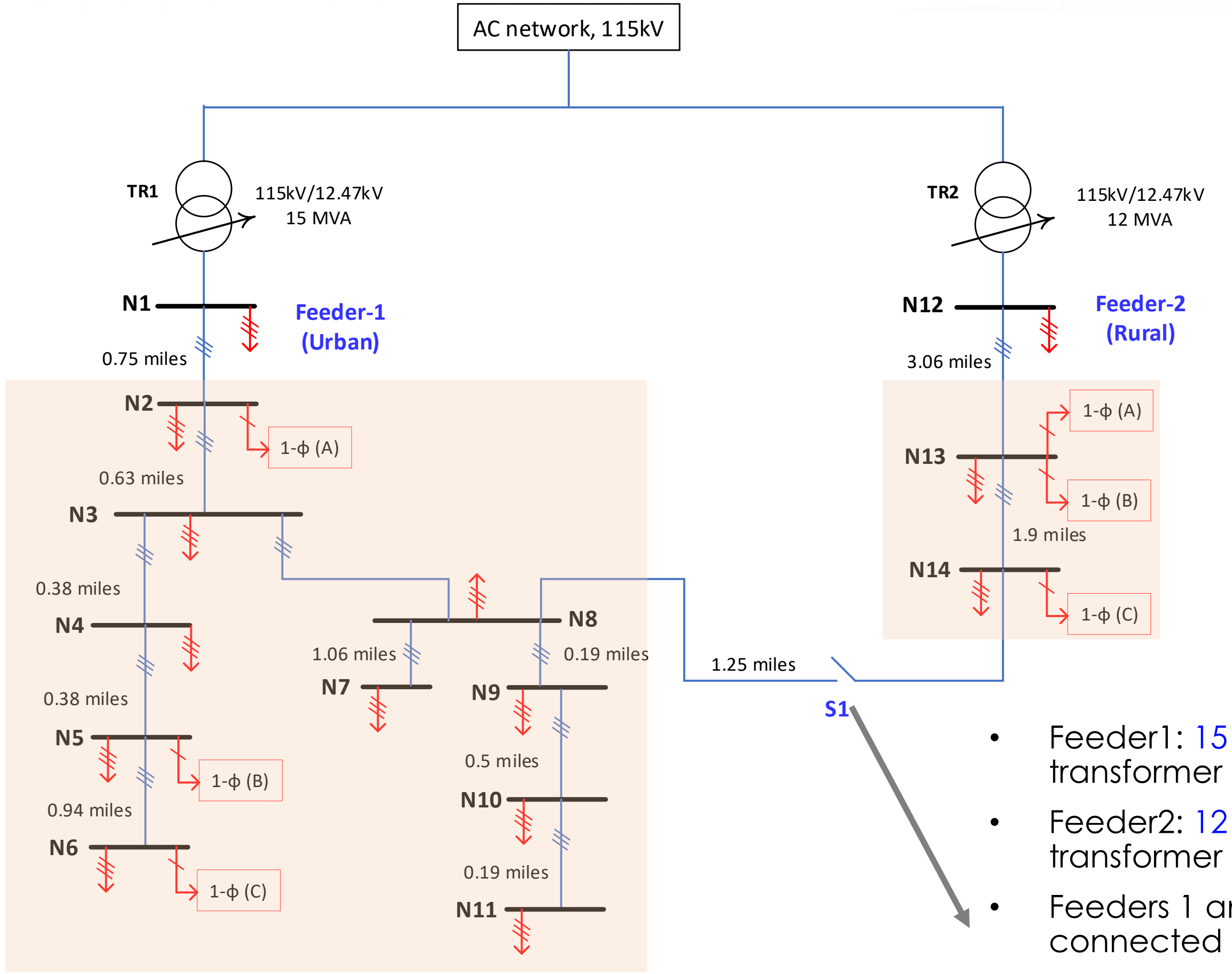
CIGRE WG C6/B4.37 "Medium Voltage DC Distribution Systems"

"In a system with predominant DC source and predominant DC load, implementing DC distribution may reduce conversion loss and also simplify integration issues"

- Use simulation platform to verify the use cases.
  - Interconnection of AC distribution systems
  - Supplying power for remote areas
  - DC load integration
  - Integration of DER and energy storage
  - Higher stability provided by DC systems

Accomplishments: Capacity Expansion Use Case

- Use case: Can MVDC be used for interconnection of AC systems and aid in capacity expansion while deferring infrastructure (feeder/transformer) development ?
- Model: Considered a typical CIGRE feeder model for North American distribution network
- Simulation Software: Implemented in PSCAD



- Feeder1: 15 MVA transformer
- Feeder2: 12 MVA transformer
- Feeders 1 and 2 can be connected by closing S1

Ref: Benchmark Systems for Network Integration of Renewable and Distributed Energy Resource, C6.04, Apr. 2014

Accomplishments: Capacity Expansion Use Case

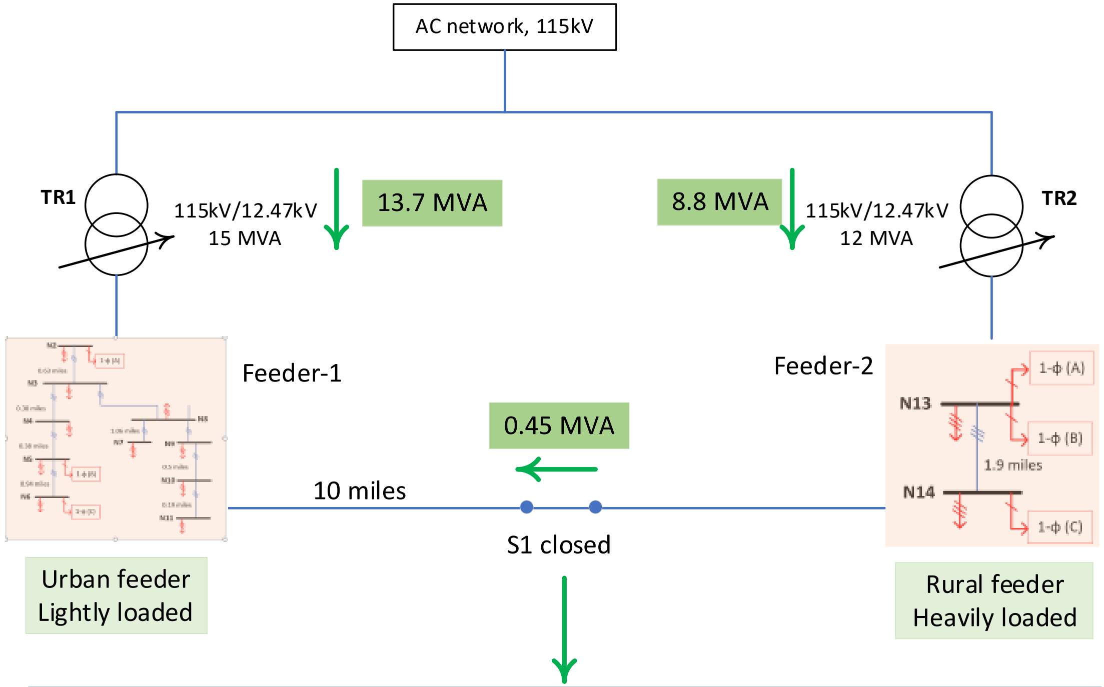
Can a heavily loaded feeder be supported by from lightly loaded feeder?

Scenario 1: Feeders Disconnected

- Loading - TR1: 14.1 MVA, TR2: 8.4 MVA
- Feeder-2 is lightly loaded
  - Feeder 1 is 94% loaded while Feeder 2 is 70% loaded

Scenario 2: Feeders Connected by closing S1

- Loading - TR1: 13.7 MVA, TR2: 8.8 MVA
- 0.45 MW power flows from Feeder-2 to Feeder-1
- Interconnecting the feeders passively will not aid heavily loaded feeder



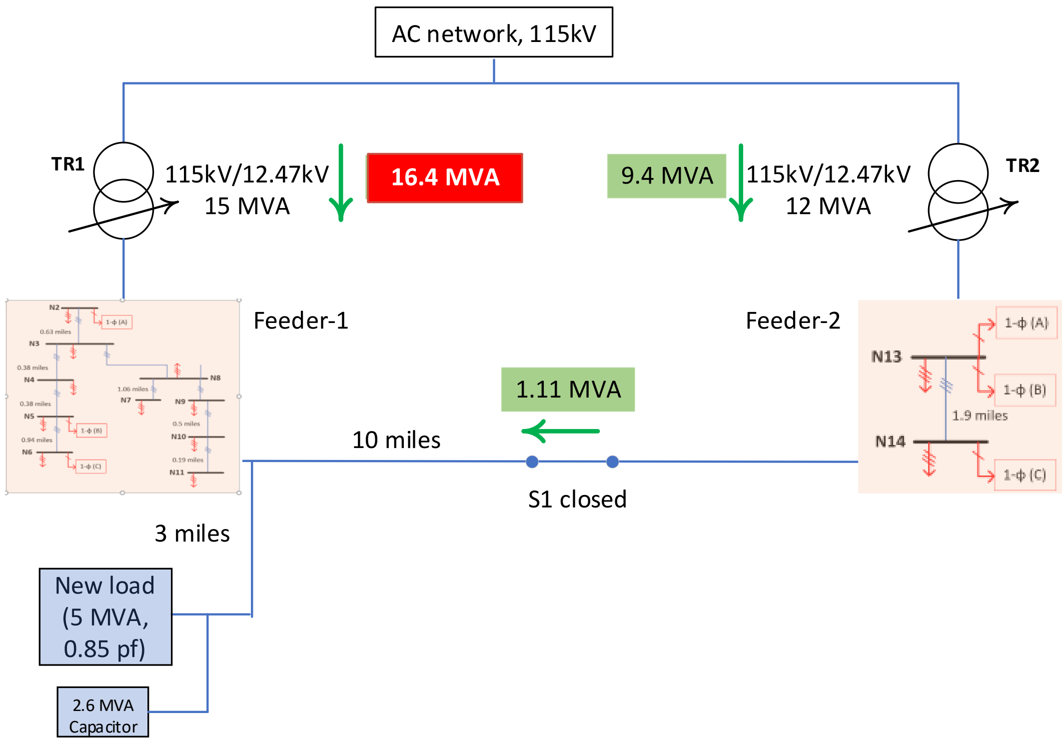
S1 closed but not much power flows from lightly loaded Feeder 2 to heavily loaded Feeder 1

Accomplishments: Capacity Expansion Use Case

Scenario 3: A new load of 5MVA, 0.85 pf at Bus 8 in Feeder 1 through an OHL of length 3 miles

- Not enough power flow from Feeder 2 to Feeder 1, resulting in Transformer 1 being overloaded

Passive Interconnection of feeders



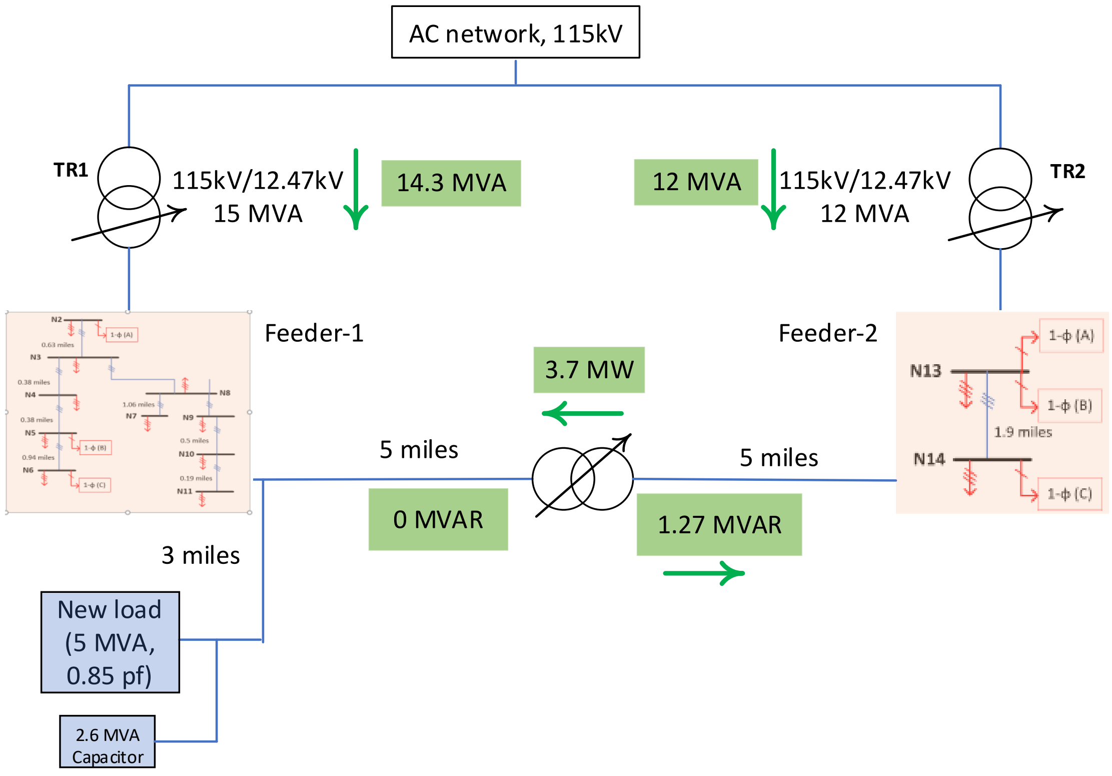
Load expansion cannot be handled with the existing infrastructure (TR1 and Feeder1 upgrade)

Accomplishments: Capacity Expansion Use Case

Scenario 4: 5 MVA power flow controller (back-to-back converter) between buses 8 and 14

- Q is supplied by power flow controller to improve the voltage profile as per IEEE 1547 requirements
- 3.70 MW of active power is transferred through the dc link from Feeder-2 to Feeder-1
- 1.27 MVAR of Reactive power is supplied to Feeder-2
- Possible to cater the load expansion

Interconnection of feeders with active control



With power flow control, more power is transferred from lightly loaded Feeder 2 to heavily loaded Feeder 1 , thereby serving new additional load on Feeder 1

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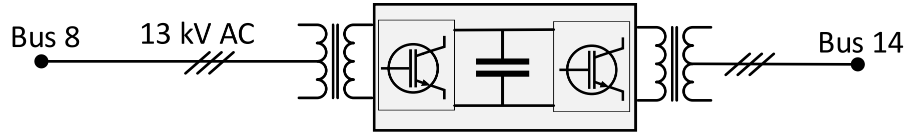
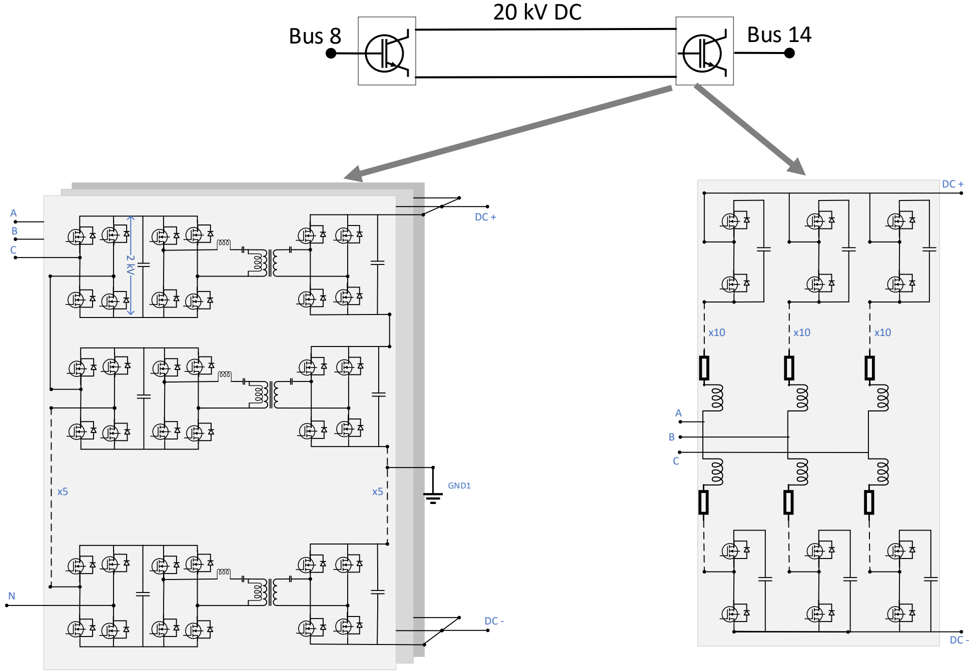
Accomplishments: Capacity Expansion Use Case

Approaches to implement power flow control

- MVAC line with fractionally-rated power electronics
  - May not be feasible if the control range required is large (example: long interconnecting line or feeders supplied from different transmission lines)
- MVAC line with Back-to-back low voltage power electronics (1000-1500 V DC bus)
  - Interconnecting feeder needs an upgrade if it is not rated for handling additional power
- MV power electronics with MVDC interconnecting line
  - 60-80% additional power can be transferred over the same line compared to MVAC solution which means **interconnecting feeder upgrade can be deferred**

MVAC solution Based on Back-To-Back 480 V Converter





MVDC solution Based on Cascaded H-Bridge Converter with HF Isolation

MVDC solution Based on MMC

Accomplishments: Capacity Expansion Use Case

Comparison of MVAC with LV PE and MVDC solution

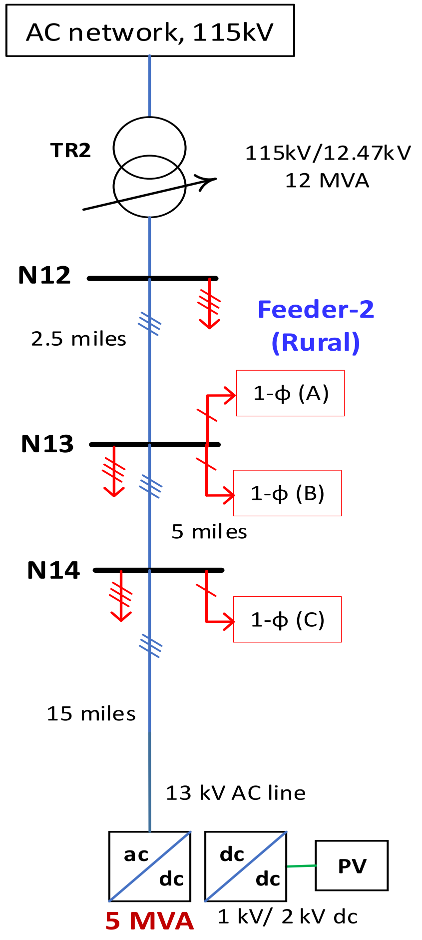
BTB Converter with MVAC Distribution	MVDC Distribution with MMC	MVDC Distribution with CHB
	Cost points and Targets	
Commercial solution: $120-$150/KVA	Cost point not available at MVDC level	BOM Target for MVDC solution to be cost comparable to MVAC solution: $100/kVA
	BOM Comparison (semiconductors, capacitors and transformers only)	
SiC based solution: $30-$40/kVA IGBT based solution: $20-$30/kVA	IGBT based solution: $35-45/kVA	MV SiC solution: $40-$50/kVA Not a significant cost increase compared to LV power electronics
	Other Factors	
Protection: Well understood with MVAC breakers and fuses	Protection: Well understood with MVAC breakers and fuses	AC side protection (solid state circuit breaker) cost unknown
Standard 60 Hz transformers	Standard 60 Hz transformers	Reliability of HF magnetics at MV
Capacitor requirement: Low	Capacitor requirement - High	Capacitor requirement: Medium but can be further reduced
Commercially available	Commercially available	Solution at research level

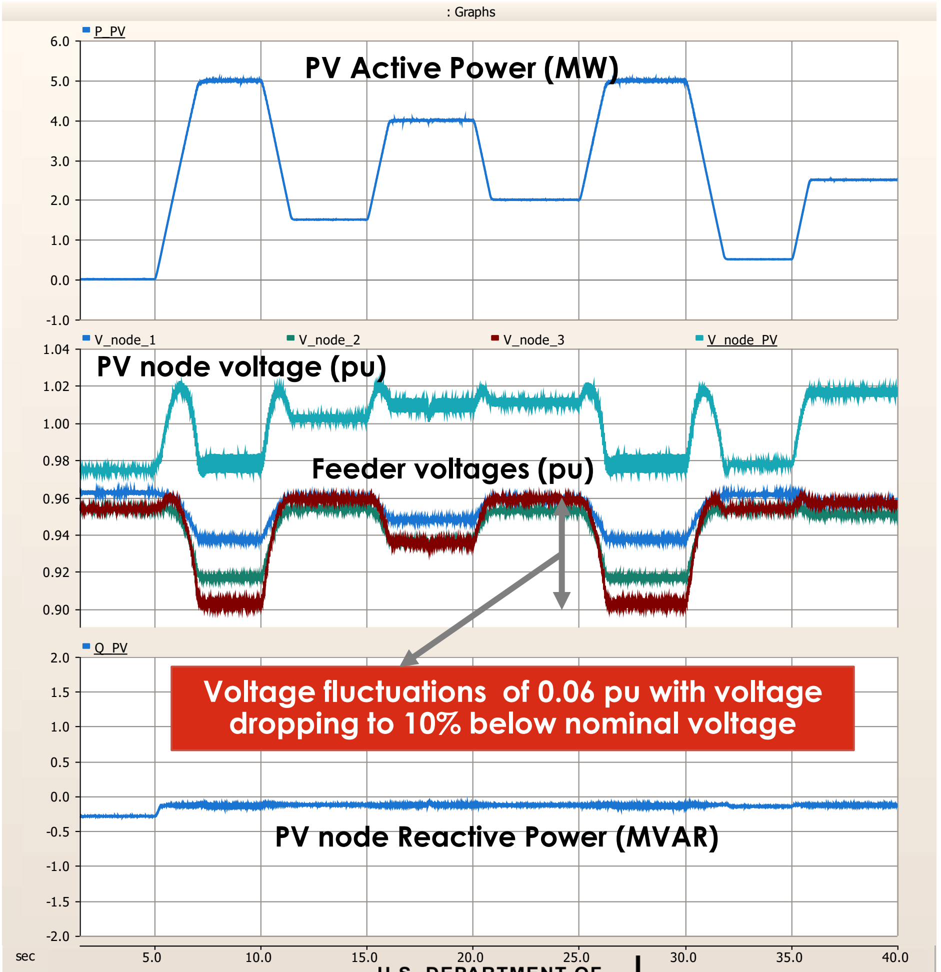
MV power electronics is cost comparable with LV power electronics – driven by lowering cost of 3.3 kV SiC MOSFETs. Complexity, protection, and reliability are still an issue to be addressed

Accomplishments: Remote DER Integration Use Case

- A PV generation of 5 MW is connected to the network through a 15-mile OHL
- 5 MW is the upper limit of DER connected at distribution grid level – ex. community solar.
- Q is supplied by PV inverter to improve the voltage profile as per IEEE 1547 requirements
- With variation in solar irradiance, P changes, resulting in unacceptable fluctuations in load bus voltages
- The magnitude of voltage variation depends on DER size, line length, and feeder size – to be studied.

Results for PV plant connected to distribution feeder over a long line

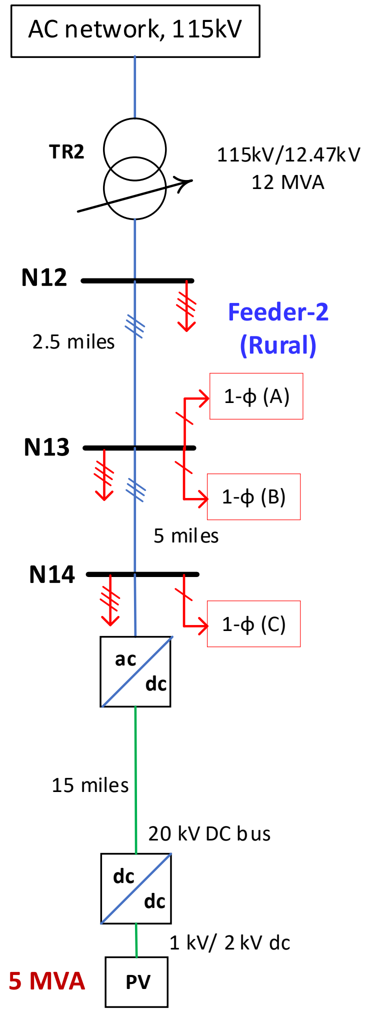


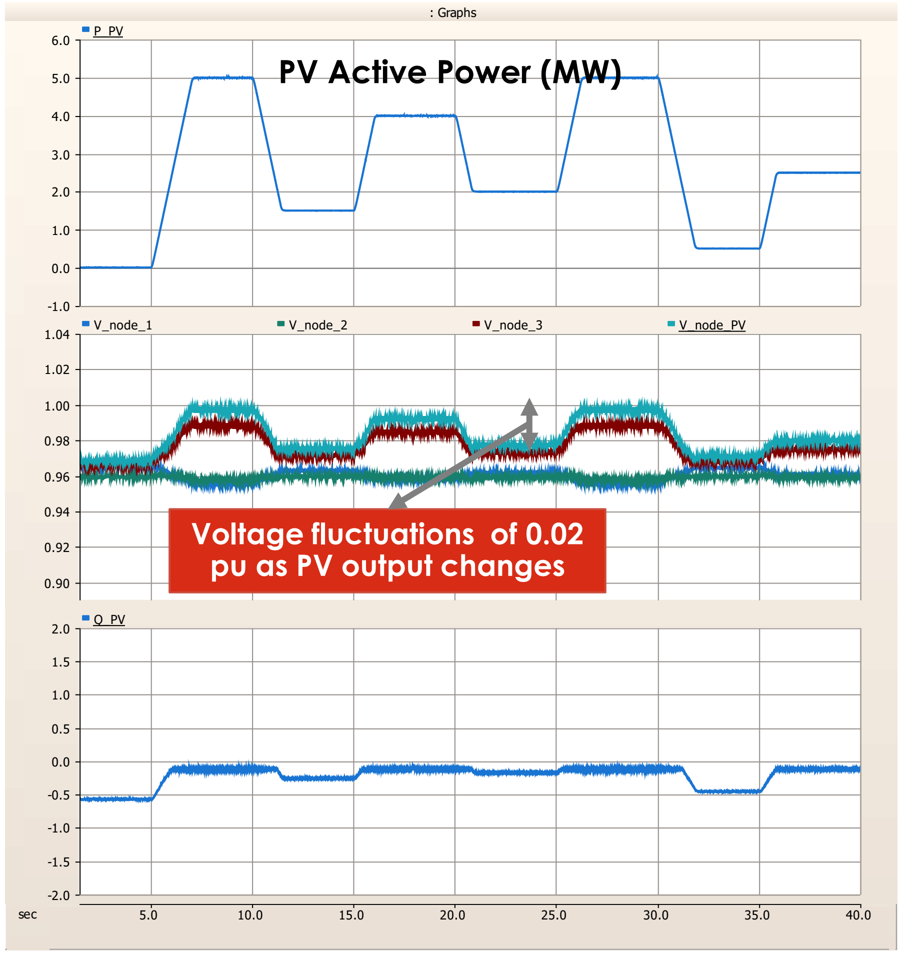


Accomplishments: Remote DER Integration Use Case

- Converting the PV-Grid interconnecting line from MVAC to MVDC negates the need for line impedance compensation
- Voltage fluctuations reduced from 0.06 pu to 0.02 pu
- The cost of conversion to MVDC needs to be considered.
- The additional cost of MVDC conversion may be justified if combined with other advantages.

Results for PV connected to distribution feeder over a long line using MVDC



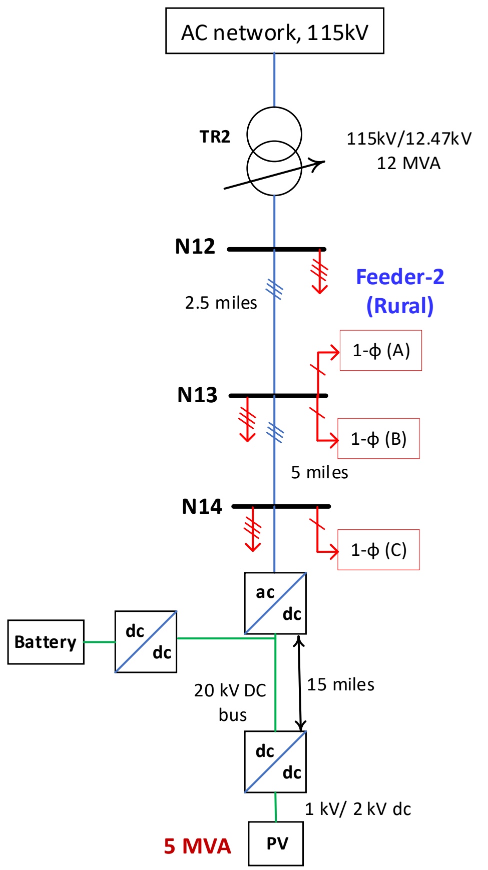


Voltage fluctuations as PV output changes

Accomplishments: Remote DER Integration Use Case

- Storage is typically coupled with PV for a firm source
- **Resiliency with storage sited close to load:** Battery storage at N14 on MVDC line improves the power availability in case of loss of MVDC line
- The increase in cost with MVDC conversion may be justified with increase in resiliency
- Again, MVDC is straightforward if an overhead AC line cannot be built. If underground cable is considered,
  - about 40% smaller cable is required with MVDC compared to MVAC
  - MVAC has capacitive current issues especially at long lines
- Similar argument can be made for remote load connections

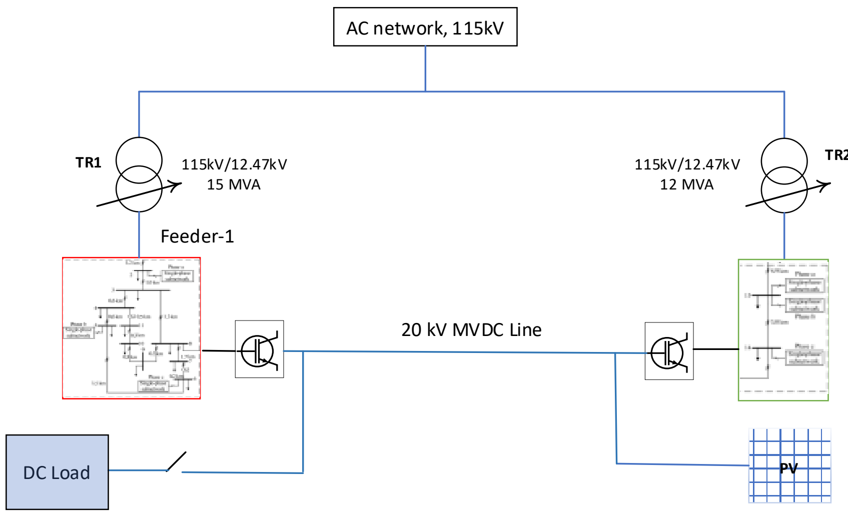
Remove PV interconnection with storage sited close to load center to improve resiliency



Accomplishments: Summary

- Capacity expansion through interconnection of feeders with MVDC helps defer infrastructure (transformer, feeder) build
- Remote source/load integration though MVDC may be beneficial with reduced reactive power compensation requirement
- In addition, by enabling the option of siting storage close to the load center, resiliency can be improved
- MVDC has typically been used in cases where there is no other choice, ex. an existing AC line cannot be upgraded
- MVDC may appear more attractive if it can meet more than one of the following typical advantages
    - Interconnection of AC systems
    - DC source/load integration
    - Resiliency improvement
    - Remote source/load interconnection
- Future cases will evaluate if the same multi-terminal MVDC system with multiple DC sources and loads

Future test case: Multi-terminal MVDC system



Timeline

- Milestone update

	Q1	Q2	Q3	Q4	Status
Use case 1 development: Capacity expansion use case	■	■			Completed
Use case2 development: Remote source integration			■		Completed
Use case3 development			■	■	In-progress
Metrics development				■	In-progress

- Summarize the risks and mitigation strategy
  - NA

THANK YOU

This project was supported by the Department of Energy (DOE) - Office of Electricity's (OE), Transformer Resilience and Advanced Components (TRAC) program led by the program manager Andre Pereira

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Acronyms

DER: Distributed Energy Resources

MVDC: Medium voltage DC

MV: Medium Voltage

Backup Slides

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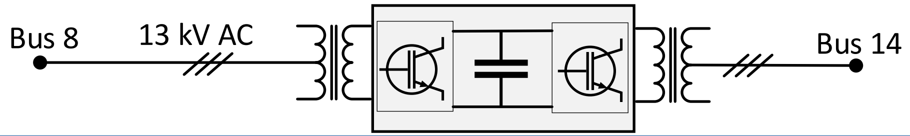
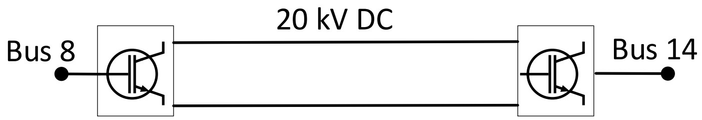
Accomplishments: Capacity Expansion Use Case

Approaches to implement power flow control

MVAC solution Based on Back-To-Back 480 V Converter	**MVDC solution Based on Cascaded H-Bridge Converter**





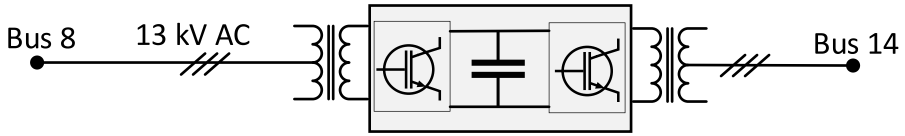
BTB Converter with MVAC Distribution	**MVDC Distribution w/ Converter At Each End**
Comparison method 1 (Including everything)	
Commercial solution: $140/KVA • PV central converter $50/KVA, Transformers @$20/KVA, Two transformers and converters	BOM Target : $100/kVA
Comparison method 2 (semiconductors and transformers only)	
Total SiC based solution: $174k ($35/kVA) Total IGBT based solution: $125k ($25/kVA)	Total MV SiC solution: $225k ($45/kVA)
Semiconductor cost (SiC) = 6*4440*2.5 = $67k Remove numbers Semiconductor cost (IGBT) = 6*6000*0.5 = $18k • 1100 V DC Bus, 1700 V MOSFET modules, 6 HB modules rated at 4440 A • **1700 V SiC HB modules: 2-3 $/A** • **1200 V IGBT: $0.5 /A**	Semiconductor VA = 60 *222*4 +120*166*4 = $132k • 2000 V DC Bus – 5 modules stacked in series • 60 HB modules rated at 222 A, 120 HB modules rated at 166 A • **3300 V SiC HB modules: 4 $/A**
Capacitors = (50000/500)*65 = = $6.5k	• Capacitors: 5*3*2*(11000/500)*65 = $43k
60 Hz Transformer cost @ 20$/KVA: $100k	MF Transformer cost @ 5$/KVA: $50k

MV power electronics is cost comparable with LV power electronics – driven by lowering cost of 3.3 kV SiC MOSFETs.

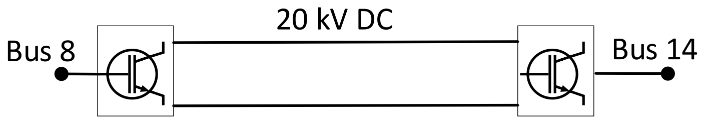
Accomplishments: Capacity Expansion Use Case

Approaches to implement power flow control

MVAC solution Based on Back-To-Back 480 V Converter



MVDC solution Based on Cascaded H-Bridge Converter



BTB Converter with MVAC Distribution	**MMC**
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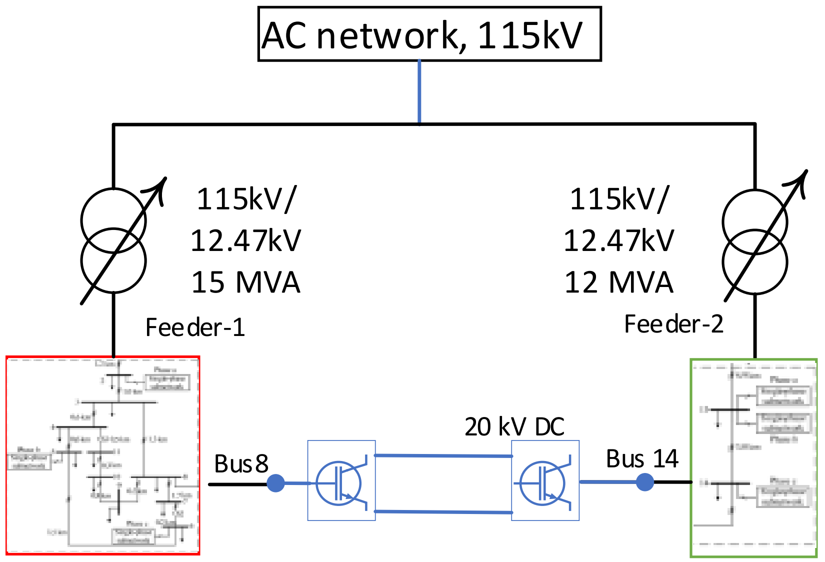
• Capacitors = (50000/500)*65 = = \$6.5k	• Capacitors = 24*12*(1800/500)*65= \$67k
60 Hz Transformer cost @ 20\$/KVA: \$100k	60 Hz Transformer cost @ 20\$/KVA: \$100k

MV power electronics is cost comparable with LV power electronics – driven by lowering cost of 3.3 kV SiC MOSFETs.

Accomplishments: Capacity Expansion Use Case Summary

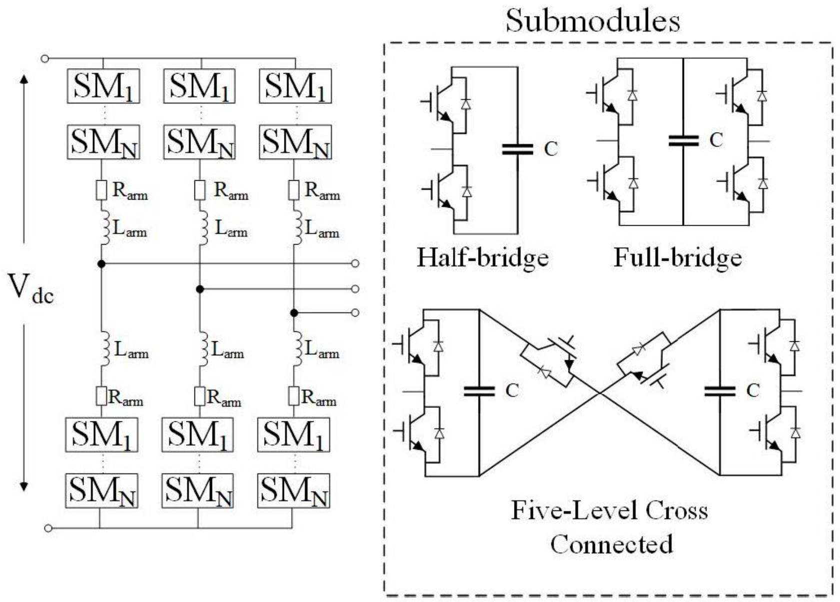
- Capacity expansion through interconnection of feeders helps defer infrastructure build
- MVDC seems to be cost comparable to MVAC solution in the case of Capacity expansion.
- Protection and reliability of MVDC based solution have to be addressed.
- The MVDC approach is straightforward if
    - A new AC line cannot be built
    - An existing AC line can not be upgraded
- Miles of interconnection line

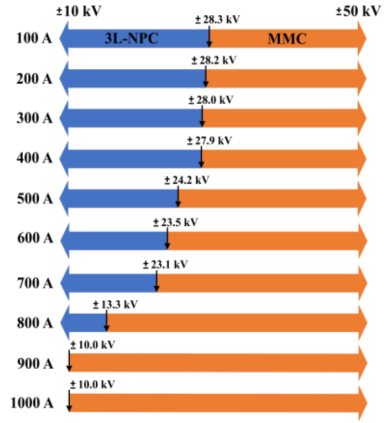
Interconnection of AC systems using MVDC



Accomplishments: Capacity Expansion Use Case Summary

- MMCs are usually considered above 10 kV
  - scalability
  - voltage balancing across switches,
  - reduced harmonics,
  - lower switching frequencies
  - improved fault ride through capability
  - and active redundancy
  - cost that is introduced by sub-module redundancy
  - Significant losses in the full-bridge (FB) configuration
- Typically, HB at MVDC
- FB has better fault blocking capability





ig. 14. Variation of voltage crossover points with the change of rated currents.

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9321748

Accomplishments: Capacity Expansion Use Case Summary

- Standard MVAC v/s MVDC transmission crossover point is <10 km @10 kV, from loss point of view.
- However, in the current use case power electronics is present in both MVAC and MVDC
- MVDC will always be efficient compared to MVAC in case of capacity expansion through interconnection of feeders.

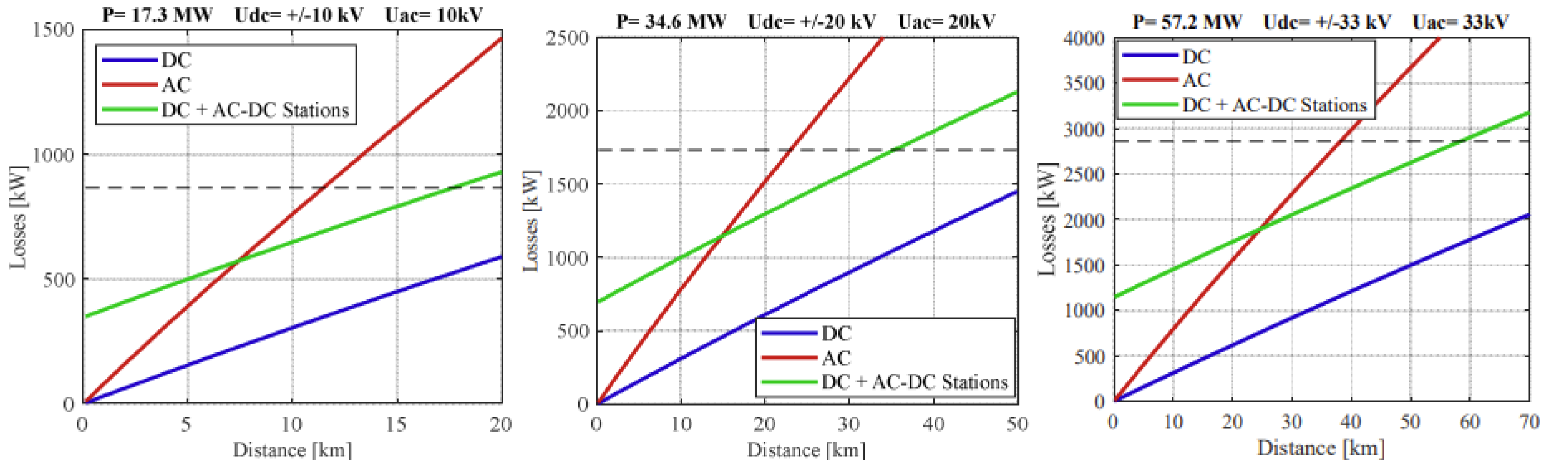


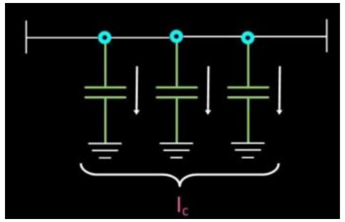
Fig. 2 – Power losses in function of the distance for the point-to-point transmission at 3 different voltages. The dashed black line represents 5% of losses related to the nominal power.

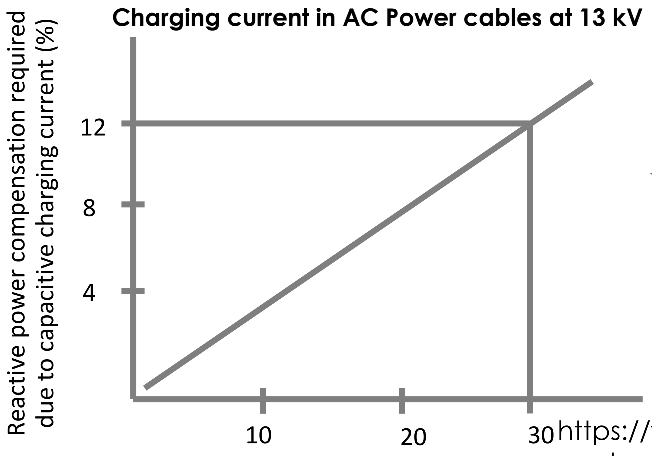
Pierre Le Métayer "Break-even distance for MVDC electricity networks according to power loss criteria"

Accomplishments: Capacity Expansion Use Case Summary

- Underground cables have charging current issue.
- Charging current is 1 A/mile for a 270 A cable
- In 13 kV class systems, additional compensation to address capacitive charging current is an issue only above 25 miles
- For a 35 kV line, the compensation goes higher than 10% at 10 miles – a bigger issue at sub transmission lines
- However, the impact of inrush current to charge the capacitance on the breakers must be considered.

Charging current representation in power cables





Voltage 8.7/15 (17.5) kV Single Core armoured copper conductors

Typical technical data

Design Standards:
BS 6622
BS 7835

Nominal cross-sectional area	mm²	70	95	120	150	185	240	300	400	500	630	800	1000
Diameter over conductor	mm	9.8	11.5	12.8	14.3	15.9	18.4	20.5	23.2	26.2	30.3	34.7	38
Approximate diameter over insulation	mm	20	21.7	23	24.5	26.1	28.6	31.1	34.2	37.2	41.3	45.7	49.4
Approximate overall diameter	mm	35	37	39	41	42	45	47	52	55	59	66	71
Approximate weight of cable	kg/m	1800	2200	2550	2850	3300	3950	4650	5800	6950	8500	10500	12800
Minimum bending radius (static)	mm	650	700	750	800	800	850	900	1000	1050	1150	1250	1400
Maximum pulling tension on cable	kg	350	475	600	750	925	1200	1500	2000	2500	3150	4000	5000
Maximum DC resistance @20°C	Ω/km	0.2680	0.1930	0.1530	0.1240	0.0991	0.0754	0.0601	0.0470	0.0366	0.0283	0.0221	0.0178
Maximum AC resistance@ 90°C	Ω/km	0.3420	0.2470	0.1960	0.1590	0.1270	0.0976	0.0786	0.0625	0.0500	0.0404	0.0338	0.0290
Inductance	mH/km	0.436	0.420	0.403	0.389	0.380	0.363	0.347	0.341	0.329	0.319	0.303	0.295
Reactance@50Hz	Ω/km	0.137	0.132	0.126	0.122	0.119	0.114	0.109	0.107	0.103	0.100	0.095	0.093
Impedance @ 50Hz @ 90°C	Ω/km	0.369	0.28	0.233	0.201	0.175	0.15	0.135	0.124	0.115	0.108	0.101	0.097
Maximum capacitance (C)	µF/km	0.232	0.259	0.282	0.303	0.323	0.359	0.401	0.442	0.486	0.539	0.632	0.699
Maximum charging current	A/km	0.63	0.71	0.77	0.83	0.88	0.98	1.09	1.2	1.32	1.47	1.72	1.9
Short circuit ratings													
1 second short circuit-rating of conductor (90 to 250°C)	kA	9.7	13.5	17.1	21	26.3	34.6	43.4	55.6	>60	>60	>60	>60
1 second short circuit-rating of metallic screen (80 to 200°C)	kA	8.3	10.9	11.4	11.7	12.2	13.3	14.1	19.1	20.8	22.5	25.4	27.5
Continuous current carrying capacity (as per conditions detailed below)													
Direct buried	Amps	270	320	360	410	455	520	580	650	710	760	810	860

https://www.powerandcables.com/wp-content/uploads/2016/12/Nexans-6-33kV-Medium-High-Voltage-Underground-Power-Cables.pdf

Accomplishments: Capacity Expansion Use Case

Comparison of MVAC with LV PE and MVDC solution

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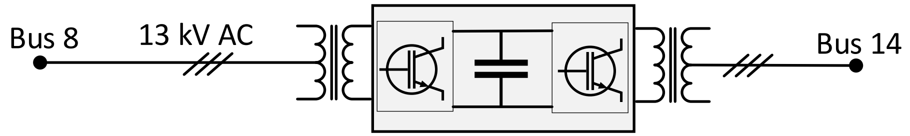
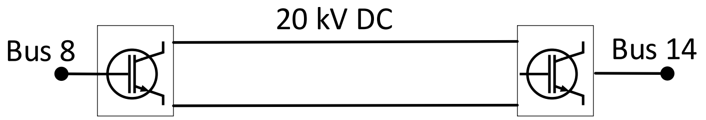


MVDC solution Based on Cascaded H-Bridge Converter with HF Isolation



BTB Converter with MVAC Distribution	MVDC Distribution w/ Converter At Each End
Comparison method 1 (Including everything)	
Commercial solution: $140/KVA • PV central converter $50/KVA, Transformers @$20/KVA, Two transformers and converters	BOM Target for MVDC solution to be cost comparable to MVAC solution: $100/kVA
Comparison method 2 (semiconductors, capacitors and transformers only)	
Total SiC based solution: $174k ($35/kVA) Total IGBT based solution: $125k ($25/kVA)	Total MV SiC solution: $225k ($45/kVA) Not a significant cost increase compared to LV power electronics
Other Factors	
Protection: Well understood with MVAC breakers and fuses	AC side protection (solid state circuit breaker) cost unknown
Standard 60 Hz transformers	Reliability of HF magnetics at medium voltage
Commercially available	Solution at research level

MV power electronics is cost comparable with LV power electronics – driven by lowering cost of 3.3 kV SiC MOSFETs. Complexity, protection, and reliability are still an issue to be addressed