Module Development Points

<u>HVDC-LEARN</u>: Modular Education & Workforce Training in High Voltage Direct Current Electric Transmission

- Project website: home.engineering.iastate.edu/~jdm/hvdclearn/index.htm
- Repository: https://drive.google.com/drive/folders/1Hp72iszP8rgjQ4OuhH-wms_fySFEFBXY

Progress on module development (yr 1 modules only, as of 1/16/24)

Mod ID	Module title	Person/ school	Completion target	Status PLEASE E-MAIL ME YOUR MODULE STATUS (% COMPLETE) AS OF TODAY.
7a	Pt 2 pt onshore & offshore apps (Early completion is goal)	McCalley/ISU	Q1	100% complete.
1c	Intro to HVDC for offshore wind	Fang/MS	Q2	90% complete.
1b	Intro to HVDC for offshore wind	Li/UTK	Q2	75% complete.
1a	Intro to HVDC technology	Lof/Tufts	Q4	Developed structure 15% complete.
3d	Modular multilevel converter as HVDC cnvrtr interface and its control	Tolbert/UTK	Q3	Developed structure 75% complete.
3b	Power electronics 101: Fundamentals of switching pwr conv+EMT	Mehrizi-Sani/VT	Q3	Developed structure 15% complete.
5a	HVDC fault management & protection systems	Wallace/MS	Q4	Developed structure 20% complete.
2b	VSC-HVDC converter station technologies	Cui/NCSU	Q4	Developed structure 15% complete.
4d	Offshore HVDC cnvrtr grid forming controller design for black start capability	Nazir/Clemson	Q4	70% complete.

What is a module? Self-contained “mini-textbook”5-30 pages; can be more (Mod7a is 42 pages).

B-2: FRONT MATTER

7a Point to point HVDC systems

HVDC LEARN
Modules for Maturing HVDC Electric Transmission Knowledge

Primary Author	James McCalley, Iowa State University
Email Address:	jdm@iastate.edu
Co-author:	
Last Update:	January 4, 2025
Prerequisite Competencies:	1. Motivating needs for high-capacity electric transmission 2. Introductory HVDC as found in Modules 1a, 1b, 1c.
Module Objectives:	1. Identify features of point-to-point HVDC transmission 2. Distinguish from multi-terminal HVDC systems. 3. Identify point-to-point applications and describe unique implementations

Abstract

In contrast to multi-terminal HVDC systems, point-to-point (PTP) HVDC transmission connects only two converter terminals via a direct current transmission path. They may connect two asynchronous AC systems, or they may provide a DC transmission path within a single AC system. PTP is the oldest HVDC design, having seen application since the early 1950s, and with over 200 implementations worldwide, it is by far the most common design. Many new PTP HVDC projects are being planned or built today. The objective of this module is to characterize PTP HVDC designs and applications.

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Acronyms

AAC	All aluminum conductor
AC	Alternating current
ACSR	Aluminum conductor steel reinforced
AGC	Automatic generation control
BPS	Bypass switch
BTB	Back-to-back
CSC	Current source converter
DC	Direct current
ECC	Energy control center
ERTB	Earth return transfer breaker
HVDC	High voltage direct current
IFA	Interconnexion France Angleterre
IGBT	Insulated gate bipolar transistor
LCC	Line commutated converter
MI	Mass impregnated
MISO	Midcontinent Independent System Operator
MMC	Modular multilevel converter
MRTB	Metallic return transfer breaker
MVAR	Mega-volt-ampere-reactive
MW	Megawatt
NESC	National Electric Safety Code
PI	Proportional integral
PLL	Phase locked loop
POI	Point of interconnection
PTP	Point to point
ROW	Right of way
SGRS	Sylmar ground return system
SVC	Static var compensator
VSC	Voltage source converter
XLPE	Crosslinked polyethylene

Nomenclature

$i(t)$	current as function of time
t	time
L	inductance
$v(t)$	voltage as function of time
V_{Rated}	Rated DC voltage of HVDC pole
I_{Rated}	Rated DC current of HVDC line or cable
V_{ab}, V_{bc} , V_{ca}	Line-to-line voltages
$\angle V_{AB}$	Angle on a line-to-line voltage
$\bar{I}$	Current phasor
ω	frequency in radians per second
P_{ref}, I_{ref}	HVDC power and current references

Module Development Points (boxed items have example slides)

A. General comments:

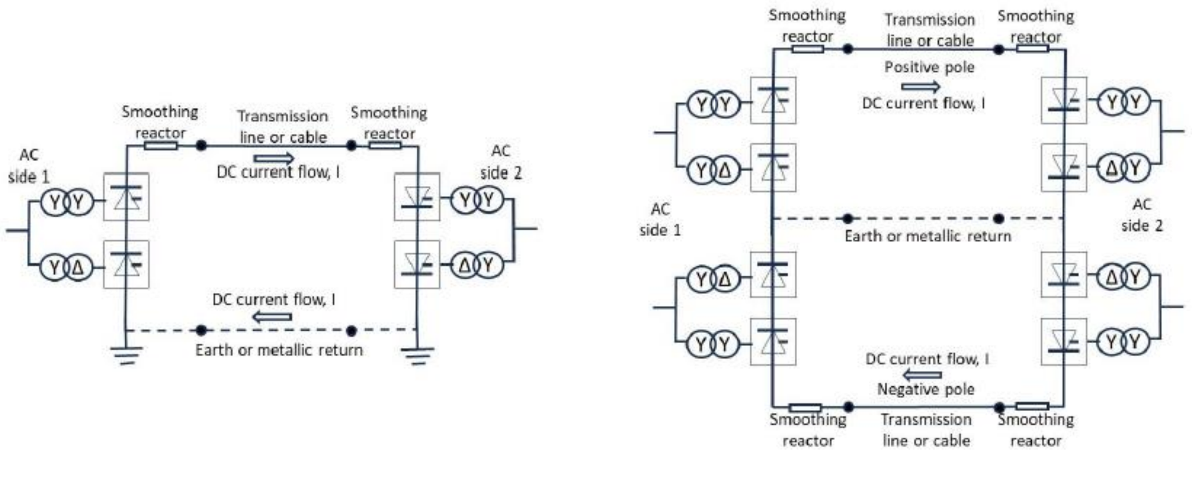
1. Like textbook development, takes longer than planned.
2. I find it hard to use graduate stdnts in developing modules
3. It requires much digging into other resources (texts, papers, internet, etc.).
4. Use existing textbooks but do not duplicate what is already in them; should add value to HVDC literature.
5. Original figures and simulation results take time to develop (student help is thinkable for these).
6. It is useful to review it yourself several times after completing it.
7. Look for ways to include visualizations, certainly figures but also photos, animations, videos (emphasized by DOE).
8. Look to include "Industry Insights," (ideas, methods, views from industry & relating to module content). See Mod7a for 4 examples (well-liked by DOE).
9. Point to references to facilitate reader follow-up.
10. Write (sectionally?) for multiple audiences: university engr courses; industry-short courses; community colleges; regulatory & policy groups; individual learning.

B. Module requirements:

1. Module should use our standard format (start from mod7a). This includes using "Styles" for headings and "References" for footnotes, endnotes, and "Crossreference" for auto-citing. See "Template.doc."
2. Front matter includes mod ID/title, logo, chart w/ learning objectives, 1-par abstract, tables of contents, figures, tables, acronyms, nomenclature, see previous slide.
3. Where appropriate, provide references to other modules, even if they do not yet exist. "Final 35-module product should be heavily interconnected."
4. Include a last section on "Energy equity issues related to *Module_Topic*." Spend time considering this. You may need to discuss with a person well-versed in energy equity issues*. See Mod7a for what was done there.
5. Treat your topic for both on & offshore issues, if appropriate.
6. Include "Summary of main learning points" at the end of text.
7. Put problems/question at end, with solutions.
8. Seek permission for borrowed figures; indicate "Source: XYZ, used with permission." Retain communications granting permission. What if figure creator & his/her organization/publisher no longer exists?

* 3 board members able to facilitate energy equity thinking. Sam Fried, Samantha.Fried@tufts.edu, (Tufts Program Manager for Science, Technology, Society and Civic Studies) has teaching/research experience on energy transition, civically-engaged STEM education, & environmental justice/equity. Betsy Frederick betsyfred@hotmail.com & Bonnie Bain bbain@salemsafe.org are with environmental justice advocacy group, "Salem Alliance for the Environment." (SAFE).

A-5: Examples of original figures that took time to develop



(a) Asymmetric monopolar configuration (b) Bipolar configuration

Figure 7a - 5: Electrical configurations for HVDC LCC-based PTP systems

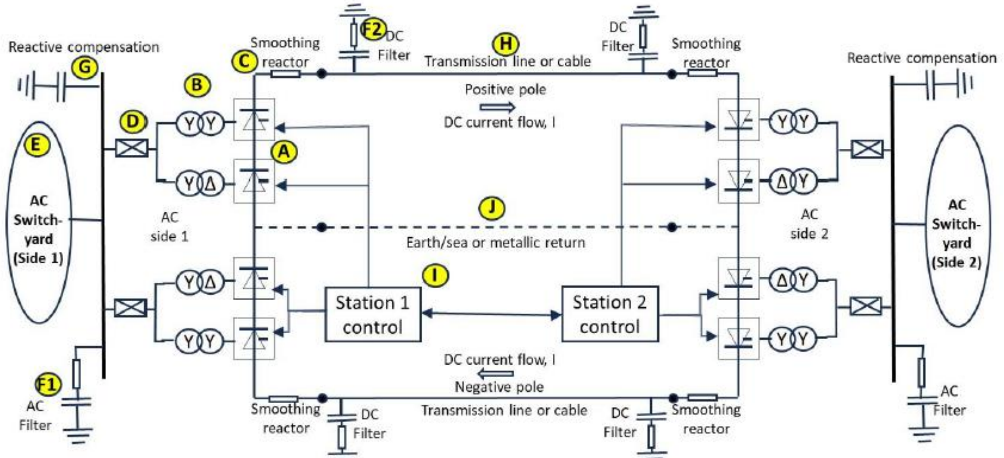


Figure 7a - 7: Components in a LCC PTP HVDC system

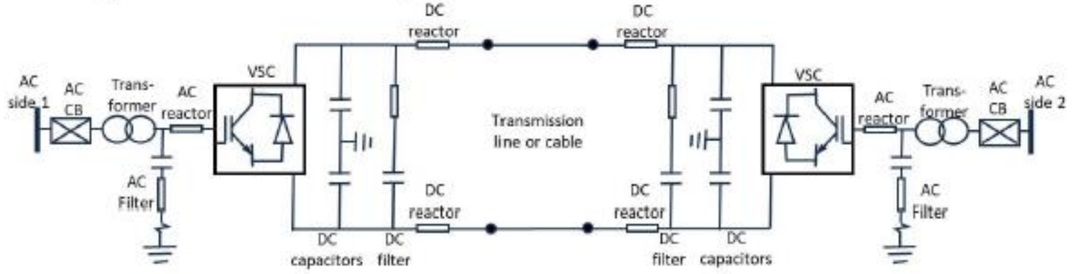


Figure 7a - 6: Symmetric monopolar configuration

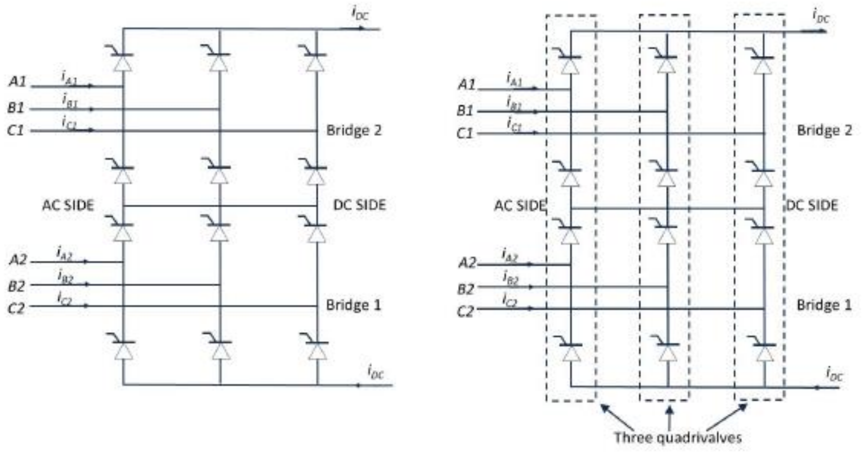


Figure 7a - 9: 12-pulse converter using single device package (left) and quadrivalves (right)

A-7: Visualization – ways to include photos, animations, videos

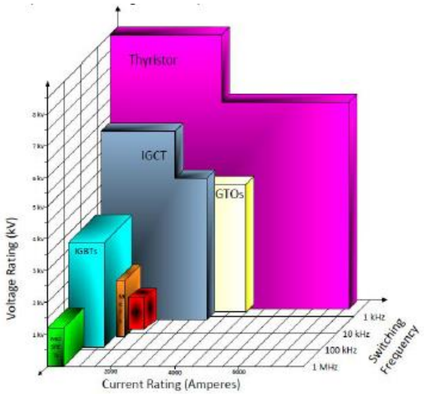


Figure 7a - 2: Comparison of device types in terms of power handling and switching speed [5]

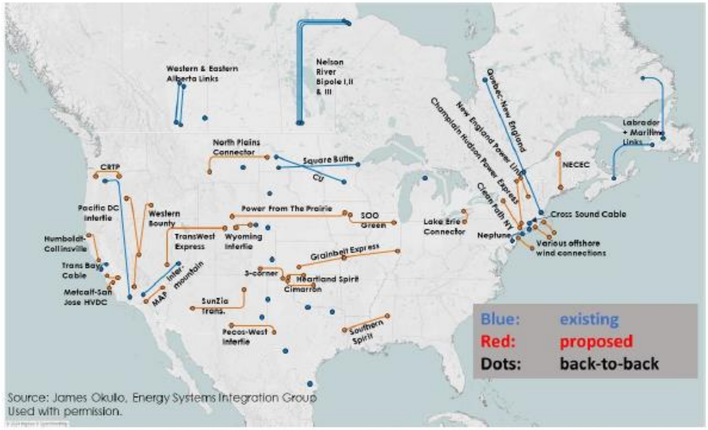


Figure 7a - 20: All existing and proposed HVDC projects

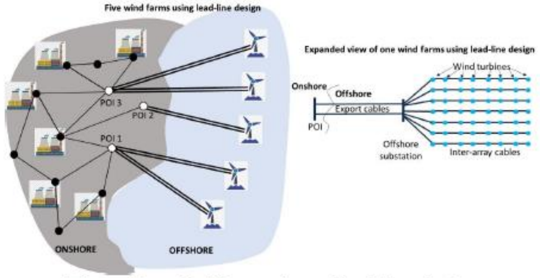


Figure 7a - 23: Illustration of lead-line design

Figure 7a - 17: A tower for the PDCI showing two conductors per pole

Figure 7a - 21: Comparison of Capacity-to-ROW requirement ratio

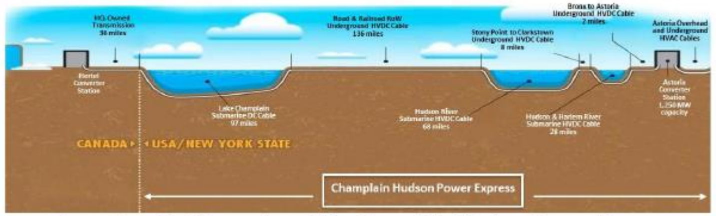
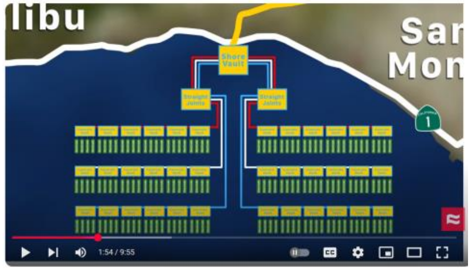


Figure 7a - 22: Illustration of the Champlain Hudson Power Express

INDUSTRY INSIGHT

The Sylmar Ground Return System (SGRS), completed in 2018, is comprised of two primary cables that are tied into the PDCI at the Los Angeles Department of Water and Power Sylmar converting station facility. It provides a ground return by sea for the PDCI. These cables run from the Sylmar converter station about 28 miles on overhead lines and then an additional 9 miles underground. The system then extends 2 miles offshore into Santa Monica Bay. At that point, the primary power cables tie into a large area electrode array that consists of 144 electrodes distributed through 36 large concrete vaults. The design of the array is such that it distributes the electrical discharge over a large area making it safe for marine life, divers, and the nearby infrastructures. The video at www.youtube.com/watch?v=9Ddi6sbSMwY (used with permission from the L3Harris company) describes the development of the SGRS.

Sylmar Cable Ground Return System Project



Sylmar Cable Ground Return System Project

A-8: Look to include "Industry Insight"

INDUSTRY INSIGHT

In 2023, the Midcontinent Independent System Operator (MISO) performed an extensive comparison of HVAC, EHVAC, and HVDC options in preparation for the second "tranche" of their Long-Range Transmission Planning study. Part of those efforts were presented to the MISO Planning Advisory Committee on March 8, 2023, and the presentation is publicly available [6]. A central part of the comparison involved identifying benefits of 765 kV AC transmission vs. ±640 kV HVDC transmission, the most important of which was that 765 kV AC is preferred for transmission distances below 250 miles, and HVDC is preferred for transmission distances exceeding 400 miles. Transmission distances between 250 and 400 miles are in the "interchangeable design region" and require further analysis. These perspectives are illustrated in Figure 7a - 4.

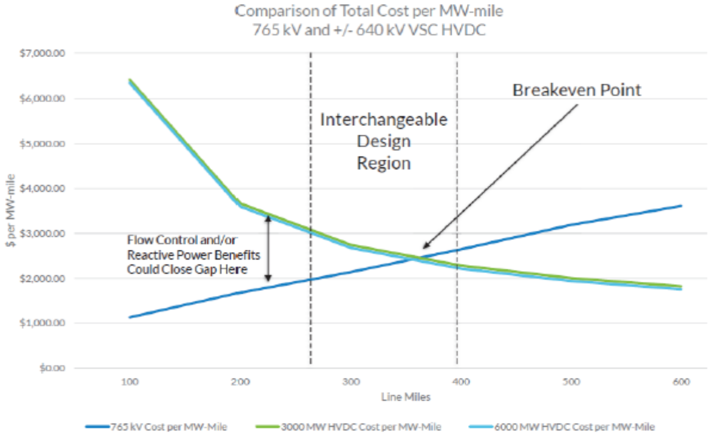


Figure 7a - 4: 765 kV AC vs ±640 kV HVDC - comparison of $/MW-mile

INDUSTRY INSIGHT

The Pacific DC Intertie (PDCI) is a PTP HVDC system from the Celilo converter terminal in Oregon to the Sylmar converter terminal in Los Angeles; it was commissioned in 1970. On February 9, 1971, at 6:01am PST, the San Fernando earthquake struck Los Angeles with 6.6 magnitude and epicenter six miles northeast of Sylmar. It resulted in extensive damage to the Sylmar converter terminal and the shutdown of the PDCI. Immediate effort was made to repair one pole, and the system was operated in monopolar metallic return mode while work on the other pole continued. The effort was coordinated among engineers from the Bonneville Power Administration in Portland, Oregon, the Los Angeles Department of Water and Power, the Electric Power Research Institute in Palo Alto, California, and the Westinghouse Research and Development Center in Pittsburg, Pennsylvania. This was the first case of bipolar DC system design adapted to facilitate monopolar metallic return operation and led to a 1982 paper published in the IEEE Transactions on Power Apparatus and Systems [18]. The abstract of that paper reads as follows:

> "When a bipolar HVDC transmission system is operating monopolar using the earth as a return path, it is often desired to divert the return current from the earth to the line from the unused pole. To do so requires either that the system be shut down temporarily or that a dc circuit breaker be used. This paper describes the development of such a new dc circuit breaker, and its application on the Pacific Intertie as a Metallic Return Transfer Breaker (MRTB)."

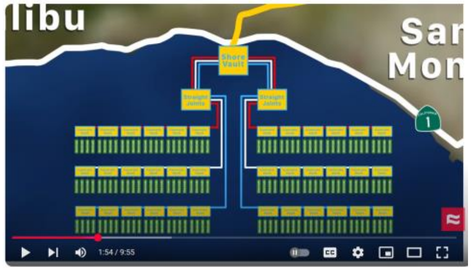
INDUSTRY INSIGHT

With respect to VSC-based HVDC controls, the following vendor-specific systems are of interest:

- Referring to its eLumina™ control system, GE-Vernova "provides a fully digital, highly redundant control platform for both Voltage Source Converter and Line Commutated Converter HVDC schemes" that is "…compact, flexible and designed with standard building blocks that are easily configured for point-to-point, multi-terminal, or back-to-back converter arrangements with most functions remaining common" [36].
- Siemens states, "HVDC PLUS® is completely appropriate for steady state and dynamic AC voltage control, independently on each station. Its typical advantages are apparent when weak AC networks are being connected" [37].
- Hitachi writes, "Thanks to the modularity and high performance of the MACH equipment, the type of hardware and system software used for a VSC-HVDC control system are the same as in an LCC-HVDC or a FACTS control system. In fact, only the application software and the valve control differ" [38].
- Mitsubishi states, "HVDC-Diamond® is Mitsubishi Electric's latest offering in the field of HVDC. Our converter uses the well-proven Modular Multi-level Converter (MMC) topology, which gives a flexible solution in terms of scaling of power output, from 50 MW to 1000 MW and more. Being a Voltage Source Converter (VSC), the system has significant ancillary benefits to the operator, such as reactive-power support, black-start capability, fast power-flow reversal, improved grid accessibility for weak systems, low harmonic distortion, etc." [39].
- With respect to its Honshu-Hokkaido HVDC line, Toshiba writes, "The VSC HVDC system ensures more flexible grid operations than the LCC HVDC system due to its capability for black-start operations to assist grid restoration by transmitting power from Honshu to Hokkaido during a blackout situation in Hokkaido. Furthermore, it can also control reactive power output independently from active power transmission. The VSC HVDC system contributes to lowering the initial investment amount as it does not need harmonic filters or reactive power plants which LCC HVDC systems normally require" [40].

INDUSTRY INSIGHT

The Sylmar Ground Return System (SGRS), completed in 2018, is comprised of two primary cables that are tied into the PDCI at the Los Angeles Department of Water and Power Sylmar converting station facility. It provides a ground return by sea for the PDCI. These cables run from the Sylmar converter station about 28 miles on overhead lines and then an additional 9 miles underground. The system then extends 2 miles offshore into Santa Monica Bay. At that point, the primary power cables tie into a large area electrode array that consists of 144 electrodes distributed through 36 large concrete vaults. The design of the array is such that it distributes the electrical discharge over a large area making it safe for marine life, divers, and the nearby infrastructures. The video at www.youtube.com/watch?v=9Ddi6sbSMwY (used with permission from the L3Harris company) describes the development of the SGRS.



Sylmar Cable Ground Return System Project

A-9: Point to references to enable reader follow-up

p. 4

Reference [4] provides an extensive and up-to-date list of all HVDC projects around the world. Of the 233 projects listed, which include projects that are decommissioned, existing, or under construction, 226 of them are PTP HVDC configurations and only seven are not. Furthermore, of the 33 planned HVDC projects listed at [4], all are PTP configurations. Therefore, although interest in other HVDC designs is certainly growing (five of the seven non-PTP lines were built after 2013), PTP configurations have and will for the immediate future continue to comprise a large percentage of HVDC projects.

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Because salt water is highly conductive, sea electrodes may be attractive when an HVDC terminal is close to the ocean. In this approach, current flows from the electrode to the seawater; however, the terminal to electrode connection must be provided by a cable, a connection that may be costly since it spans the distance from the terminal to the shoreline and from the shoreline undersea to the electrode. References [30, 32] provide excellent summaries of design and operational issues related to HVDC electrodes.

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Do three things:

1. Existing modules: Scan the table of contents of existing modules to see if there is a section in an existing module that addresses a topic touched on in your module.
   ➔Add reference to "Section k, Module XYZ" accordingly.
2. Planned modules: Page through the module abstracts (or at least scan the module list to the right) to identify modules addressing a topic touched on in your module.
   ➔Add reference to "Module XYZ" accordingly.
3. In your module, reference other modules using singular form "module" to make such references easy to find if we add links later, i.e., use "Module 2a and Module 2b" rather than "Modules 2a and 2b."

"Final 35-module product should be heavily interconnected !!!"

B-3: Reference other modules

(yellow to be completed year 1; blue in year 2; white in year 3)

Mod #	Lead-auth /Lead-rvwr	Module title	# of 1-h lectures	Comp date
1. INTRODUCTORY/OVERVIEW COVERAGE, Li				
1a	T2/UT1	Intro to HVDC technology	3	Q4
1b	UT1/T2	Application Guide for HVDC Transmission	3	Q2
1c	M1/T1	Intro to HVDC for offshore wind	3	Q2
1d	T1/C1	HVDC for executives	2	Q9
2. STATION COMPONENTS, Cui				
2a	V1/O1	HVDC reactive power, EMI, and filter design	4	Q3
2b	O1/C1	VSC-HVDC converter station technologies	3	Q4
3. CONVERTERS, Enslin				
3a	C2/C1	Interoperability between different HVDC converter technologies/vendors	3	Q12
3b	V1/M1	Power electronics 101: Fundamentals of switching pwr conv+EMT	3	Q5
3c	M1/UT2	Operation of thyristors & IGBTs in converters	4	Q7
3d	UT2/M1	Modular multilevel converter as HVDC cnvrtr interface and its control	3	Q3
4. CONTROL, Mehrizi-Sani				
4a	UT2/O1	Cnvtr cntrl fundamentals	4	Q6
4b	V1/C2	Dynamic modeling/cntrl of HVDC converters and grid-forming functions	4	Q8
4c	O1/V1	Control of multiterminal HVDC networks	4	Q8
4d	C2/C1	Offshore HVDC cnvrtr grid forming controller design for black start capability	3	Q4
5. HVDC PROTECTION, Nazir				
5a	M2/UT2	HVDC fault management & protection systems	6	Q4
5b	V1/UT1	HVDC measurements, faults, and misoperation	3	Q9
5c	C1/C2	Protection for multi-terminal HVDC networks	3	Q7
5d	UT2/M2	Protection: ability to ride through faults in HVDC	3	Q9
5e	V1/UT1	Cybersecurity in HVDC systems	3	Q11
6. HVDC LINE & CABLE TECHNOLOGIES, Wallace				
6a	M2/C1	Insulation - HVDC cables	5	Q10
7. POINT-TO-POINT HVDC CONFIGURATIONS, McCalley				
7a	I1/UT1	Onshore & offshore apps	2	Q3
8. MULTI-TERMINAL HVDC NETWORKS, Tolbert				
8a	UT2/O1	Design/operation of multiterminal HVDC grids	3	Q12
9. PLANNING AND DESIGN, McCalley				
9a	T2/O1	HVDC in pwr sys.; meshed HVDC systems	3	Q8
9b	I1/T1	Processes for planning & building offshore HVDC	3	Q2
9c	I1/T1	Expansion planning for offshore HVDC, topology/ capacity design for HVDC interregional transmission	5	Q6
9d	I1/M1	Macrogrid & HVDC offshore networks	4	Q8
9f	UT1/T2	A long-term planning study of offshore HVDC	4	Q8
10. HVDC SYSTEM SIMULATION & ANALYSIS, Fang				
10a	O1/C2	Hardware-in-the-loop electromag transient sim	3	Q12
10b	I1/T3	Large-sys analysis of multiterminal HVDC grids	4	Q10
10c	V1/M1	Frequency-dependent representation of AC syst	4	Q12
10d	M1/O1	Modeling of HVDC grids	6	Q11
10e	T3/I1	Reactive power & harmonics	6	Q8
11. REGULATORY/PERMITTING PROCESSES & PROC, McCalley				
11a	T1/T2	Offshore transmission development processes	3	Q5
11b	I1/UT1	HVDC right-of-way	3	Q12
12. ENERGY EQUITY & ENVIRONMENTAL JUSTICE, Hines				
12a	T1/V1	Effects of HVDC on enrgy equity & env. justice.	3	Q11

B-4: Section on Energy Equity Issues

7a-6 Energy equity issues related to PTP HVDC

In Section 7a-6.1 we address energy equity issues for PTP HVDC as used for onshore systems; energy equity issues for PTP HVDC as used for offshore systems is addressed in Section 7a-6.2.

7a-6.1 Energy equity issues for onshore HVDC systems

Building onshore HVDC transmission has two different kinds of impacts: terminal impacts and line impacts. There are three kinds of terminal impacts: land use, economic development, and energy cost.

Land use: The terminal requires some amount of land for the converter. LCC stations can vary in size, but a reasonable range is 5-10 acres, including indoor and outdoor equipment [68, 69]. This level of land requirement can have significant influence on displacing other usages, including farmland, dwellings, or businesses.

Local economic development: Operation and maintenance of the HVDC terminal motivate some employment opportunities local to the community. However, the largest impact on local jobs occurs from the power generating resources constructed that will use the HVDC transmission system. This impact is a positive one if the terminal is primarily an exporting terminal; indeed, in this case, the local community benefits from increased property tax revenues (usually paid by the generation plant developer) and land lease payments as well. On the other hand, this impact can be a negative one if the terminal is primarily an importing terminal, assuming the power import results in reduction of local generating sources.

Energy costs: Extraction of resources from an area for export to another area generally increases energy cost for the sending area and decreases energy cost for the receiving area.

The last two impacts are generally conflicting, i.e., exporting areas see economic development in the form of job creation for the local economy but increased energy cost. Importing areas see little job creation, perhaps even job loss if local generation resources are retired, but simultaneously they see energy cost reduction. In both cases, one needs to quantify these effects and make decisions based on their compositive influence.

The line impacts (distinct from terminal impacts addressed above) of onshore HVDC PTP transmission are not large in terms of local economic development; they are almost zero in terms of the influence on local energy costs. However, line impacts are significant in terms of land use when new ROW is required. As a result, so-called "flyover" regions, i.e., those where HVDC transmission is routed but no terminals are sited, are often rejected by local communities. There are three ways to address this. The first way is to compensate local landowners with tangible benefits that balance the loss of land use. Such benefits can be ongoing monetary payments and/or additional infrastructure currently unavailable in the community, e.g., broadband communication systems or public parks and bike paths. The second way is to reduce ROW requirements by re-using existing transmission ROW, co-locating the new HVDC lines in existing ROW of other infrastructure (e.g., see description of the SOO-Green HVDC line in Section 7a-4.3), or utilizing submarine HVDC cables in river beds (e.g., see description of the Champlain-Hudson Power Express in Section 7a-4.4). The third way to address line impacts is to install terminals along the HVDC transmission route to enable energy injection by local generators and energy withdrawals by local loads. However, doing so changes the design from PTP to multiterminal and requires use of VSC-based HVDC, as it is not technically feasible with LCC-based HVDC.

7a-6.2 Energy equity issues for offshore HVDC systems

Equity issues for offshore HVDC systems that bring offshore energy to shore include the same two categories as identified for onshore HVDC systems in Section 7a-6.1, terminal impacts and line impacts, but their nature is different. One of the main reasons for this difference is that there is significant human impact only at the receiving terminal as the sending-end terminal is offshore. At the receiving end terminal, there are also land-use issues and uniquely so since the land often includes coastal regions involving sensitive marine life and areas of human recreation. The economic development influence can be significant, since the local economy benefits from the development at both terminals, and the wind generating resources at the (offshore) sending end terminal can be significant. And for the same reason, the impact on local energy cost can be highly desirable relative to energy costs associated with existing local generating resources. Of course, any offshore energy development must address the visual impact of the wind turbines and the impact of the undersea cabling on marine life, shipping, and other subsea infrastructure, but these impacts are not unique to HVDC transmission.

B-5: Treat both onshore & offshore systems

Table of Contents

7a-5 PTP for offshore wind

Power from an offshore wind farm, i.e., an array of offshore turbines, is collected through an AC network of submarine inter-array cables that transfers power from the wind turbines to an offshore collection substation. Array cables also provide auxiliary power to turbines when they are not generating electricity, and normally, they are coupled with a fiber optic line to enable communication with each turbine. If the objective is to connect one or a limited number of wind farms to shore, then the so-called lead-line design (also called radial design) is generally least-cost. The lead-line design is a PTP system that interconnects the offshore substation to the onshore point of interconnection (POI). Figure 7a - 23 shows, on the left, five wind farms interconnected to shore via a lead-line design, and on the right, an expanded view of a single lead-line design.

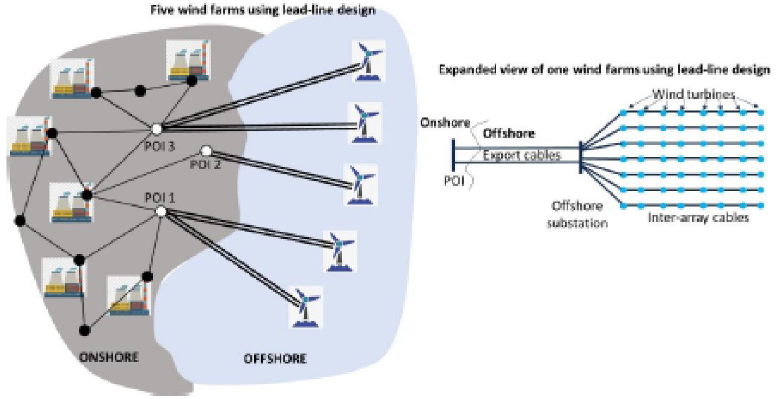

Figure 7a - 23: Illustration of lead-line design

The export cable may use either AC or DC transmission. AC may be preferred if the transmission distance from offshore substation to POI is less than about 40 miles, whereas HVDC is usually the best choice if this transmission distance exceeds about 60 miles. This is in part due to the high charging currents generated by AC cables (also mentioned in Section 7a-4.3). It is also influenced by the fact that lengths of AC cables are expensive to joint offshore [66]. On-site jointing is almost always required for export cables because of their longer transmission length, and doing so at sea is a complex and time-consuming process requiring, for each joint, from one [67] to seven days [58]. AC cable jointing is more difficult than DC cable jointing because AC cables utilize stranded conductors to minimize the skin effect, and the stranding increases the time required for on-site jointing. In contrast, DC cables utilize solid conductors. Power transfer requirements may also play a role as capacity for a single DC cable can be significantly higher than the capacity for a single AC cable. For example, the highest voltage HVAC export cables that are currently available are 420 kV with a capacity of approximately 400 MW per three-phase installation, whereas the highest voltage HVDC export cable that will be available soon is ±525 kV with a capacity of approximately 2000 MW in a bipole configuration [66].

B-6: Summary of main learning points

7a-7 Summary of main learning points

We summarize the main learning points of HVDC PTP transmission addressed in this module.

1. *HVDC designs:* There are three main HVDC designs: PTP, multiterminal, and DC grid. This module focuses on only the PTP design.
2. *Two basic technologies*: There are two basic technologies used for HVDC PTP transmission, depending on the converter type. LCC-based HVDC uses the thyristor; VSC-based HVDC uses the IGBT. Whereas for LCC-based HVDC, power handling capability is higher and cost per unit power-handling capability is lower, VSC-based HVDC tends to require smaller land areas and has greater control capabilities.
3. *Electrical configurations*: There are two main electrical configurations used for LCC-based PTP transmission – the asymmetrical monopolar configuration and the bipolar configuration, with the bipolar configuration being the most common. VSC-based PTP transmission may also be configured in either of these two ways; in addition, VSC-based PTP often uses the symmetrical monopolar configuration.
4. *HVDC PTP components*: The main components of any HVDC system include the converters, converter transformers, smoothing reactors, circuit breakers and switches, filters, reactive power compensation devices (LCC-based HVDC only), conductor systems, control and communication systems, and electrodes and return circuits. With the exception of only the reactive power compensation devices, both LCC-based and VSC-based systems have all of these components, although their design and specific attributes are somewhat different.
5. *Applications*: Almost all PTP applications in service today are LCC-based, and most of these systems will remain in operation for at least several decades to come. As a result, it is important to maintain LCC-based HVDC expertise. However, because of the faster and broader control capabilities of VSC-based HVDC, including their ability to be used in HVDC grids, it is likely that most HVDC transmission systems implemented in the future will be VSC-based.
6. *Energy equity*: Unlike AC transmission, PTP HVDC systems are capable of bridging attractive low-carbon/low-cost generation resources across long distances to major load centers, at affordable costs. This makes PTP HVDC to be a socially attractive technology. However, it is important when designing such systems to identify and communicate impacts on land, energy cost, and economic development, to ensure energy equity for local populations.

B-7: Problems/questions at the end, w/solutions

Problems

Problem 1: An HVDC developer in the Midwest has settled on building an overhead HVDC VSC ±640 kV PTP line, and current plans have one terminal in Davenport, Iowa, using right-of-way along I-74 to reach the other terminal in Indianapolis, Indiana, a distance of 311 miles. But this plan makes Illinois a "flyover" (see Section 7a-6.1) state, and the Illinois Commerce Commission is uncomfortable as a result. In response, the developer is considering moving the eastern terminal of the line to Danville, an Illinois town just west of the Illinois-Indiana state border, which would be a line of 219 miles. (a) Considering Figure 7a - 4, explain why the economics of this change might not favor use of HVDC as a solution and what alternatives you would recommend be considered. (b) Related to this same figure, note the statement that "flow control and/or reactive power benefits could close gap here" – what does this mean?

Solution: (a) Figure 7a - 4 shows that, at 219 miles, a 765 kV AC transmission line may cost significantly less than the proposed HVDC VSC line, and so a 765 kV line should be considered instead of an HVDC line. The reason for the difference is that, at 219 miles, relative to 765 kV AC transmission, the extra cost of HVDC converter stations is not outweighed by the savings from the simpler and shorter towers and less ROW associated with the HVDC line. (b) The economic valuation of the figure, apparently, did not account for flow control and reactive power benefits provided by VSC, as compared to the 765 kV AC transmission approach. A PTP HVDC line is a MW flow-controllable branch in the network, and that controllability can be used to relieve AC transmission congestion elsewhere. In addition, a VSC-based HVDC line provides voltage control via the ability to absorb or produce reactive power. A 765 kV AC transmission line provides neither of these benefits.

Problem 2: From Section 7a-3.2 we read that "It is this smoothing reactor that makes the DC-side of the converter appear as a current source (i.e., a constant current supply). This happens because the change in inductor current *di/dt* must be limited to maintain finite voltages if *L* is large, as indicated by *di(t)dt=(1/L) v(t)*, where *i(t)* and *v(t)* are the time-domain expressions for, respectively, the current through and the voltage across the smoothing reactor." Assume the voltage across the smoothing reactor is *v(t)*=100*u(t)* volts, where *u(t)* is the unit step function. Express the rate of change of current and the current for (i) *L*=1 henry and (ii) *L*=0.001 henry. In both cases, assume *i*(*t*=0)=0.

Solution:

i. $\frac{di(t)}{dt}=\frac{1}{1}100u(t)=100u(t)\rightarrow i(t)=\int_0^t 100u(\tau)d\tau=100tu(t)$amperes

ii. $\frac{di(t)}{dt}=\frac{1}{0.001}100u(t)=100{,}000u(t)\rightarrow i(t)=\int_0^t 100{,}000u(\tau)d\tau=100{,}000tu(t)$amperes

Problem 3: As indicated in Section 7a-3.2.1, the National Electric Safety Code (NESC), Paragraph 314-C, states that "supply circuits shall not be designed to use the earth normally as the sole conductor for any part of the circuit," but that "monopolar operation of a bipolar HVDC system is permissible for emergencies and limited periods for maintenance."

a. Why does the NESC restrict use of the earth as a conductor (i.e., use of earth electrodes)? Hint: See Section 7a-3.4.9.
b. Under what conditions would it be desirable to operate a bipolar HVDC system as a monopolar HVDC system?
c. What changes are necessary to operate a bipolar HVDC system as a monopolar HVDC system?

Solution:

a. As implied in Section 7a-3.4.9, use of earth electrodes poses risk to human safety due to step potential (the voltage difference across a step) and touch potential (the voltage between the ground surface and any object such as a fence that might be touched by a person standing close to the object.
b. From Section 7a-3.2.1, it may be desirable to operate a bipolar system in the monopolar configuration in the initial stage before bipolar operation begins, and as a reduced-capacity (50%) operating state when one pole of a bipolar configuration is out of service.
c. From Section 7a-3.2.2, under the condition that a pole experiences a permanent fault, the faulted pole can be isolated, and the system operated in the monopolar configuration with the earth or metallic return carrying full current but at zero voltage.

Problem 4: How do VSC-based HVDC systems achieve pole-to-pole voltages twice that of the cable ratings used for each pole? Hint: see Section 7a-3.3.

Solution: VSC-based HVDC systems built to-date have almost always been underground or submarine systems and as a result have deployed the symmetric monopolar configuration. This configuration uses both positive and negative high voltage conductors as in a bipolar configuration, where, unlike the bipolar configuration, the system is operated as a single unit.

Problem 5: Describe the difference between a thyristor, a valve, and a converter unit.

Solution: A thyristor is the basic element in a converter unit; it is a power electronic device that has controllable (via a gate pulse) turn-on (conducting) capability, but turn-off capability occurs only when the device is reverse bias (and thus it is called a "line commutated" device). A valve is a package of thyristors (and may be just a single thyristor). A converter unit is an arrangement of valves in a topology together with a control scheme to provide conversion between an AC and a DC system.

Problem 6 [10, p. 123]: At full power, the AC current for a six-pulse converter bridge connected through a Y-Y transformer can be expressed using Fourier series (neglecting commutation overlap) as:

$$I_{YY}=2\frac{\sqrt{3}}{\pi}I_{DC}\left[sin\omega t-\frac{1}{5}sin5\omega t-\frac{1}{7}sin7\omega t-\frac{1}{11}sin11\omega t+\frac{1}{13}sin13\omega t+\cdots\right]$$

Likewise, the AC current for a six-pulse converter bridge connected through a Y-Δ transformer can be expressed using Fourier series (neglecting commutation overlap) as:

$$I_{Y\Delta}=2\frac{\sqrt{3}}{\pi}I_{DC}\left[sin\omega t+\frac{1}{5}sin5\omega t+\frac{1}{7}sin7\omega t-\frac{1}{11}sin11\omega t+\frac{1}{13}sin13\omega t+\cdots\right]$$

Show that the total AC current is given as indicated in Section 7a-3.4.5.

Solution: The current in a 12 pulse converter is the sum of the current from the Y-Y transformer and the current from the ΔΔ transformer, which is

$$I=I_{YY}+I_{Y\Delta}=2\frac{\sqrt{3}}{\pi}I_{DC}\left[sin\omega t-\frac{1}{5}sin5\omega t-\frac{1}{7}sin7\omega t-\frac{1}{11}sin11\omega t+\frac{1}{13}sin13\omega t+\cdots\right]$$
$$+2\frac{\sqrt{3}}{\pi}I_{DC}\left[sin\omega t+\frac{1}{5}sin5\omega t+\frac{1}{7}sin7\omega t-\frac{1}{11}sin11\omega t+\frac{1}{13}sin13\omega t+\cdots\right]$$

$$=2\frac{\sqrt{3}}{\pi}I_{DC}\left[2sin\omega t-\frac{2}{11}sin11\omega t+\frac{2}{13}sin13\omega t+\cdots\right]$$
$$=4\frac{\sqrt{3}}{\pi}I_{DC}\left[sin\omega t-\frac{1}{11}sin11\omega t+\frac{1}{13}sin13\omega t+\cdots\right]$$

Problem 7: (a) Referring to Section 7a-3.4.7, show that, for equal power transfers and equal nominal voltages (line to line for AC and pole to ground for DC), the AC rms current is about 1.15 times the DC current. (b) Using $P_{Loss,DC}=2R_{DC}[I_{DC}]^2$, $P_{Loss,AC}=3R_{AC}[I_{rms}]^2$, and I_{rms}/I_{DC}=1.15, show that for equal power transfers and equal nominal voltage levels, the HVAC losses are about 2.2 times greater than the HVDC losses. (c) Section 7a-3.4.7 indicates that AC losses being about 2.2 times greater than the HVDC losses is driven by the number of poles vs phases, their relative current density, and the difference in resistances. Explain each one of these effects.

Solution: (a) Given the relations from Section 7a-3.4.7,

$$P_{DC}=2V_{P-G}I_{DC}$$
$$P_{AC}=\sqrt{3}V_{LL}I_{rms}$$

and under the conditions of the problem, which are $P_{DC}=P_{AC}$, and $V_{P-G}=V_{LL}$, the above two equations may be equated as

$$2V_{P-G}I_{DC}=\sqrt{3}V_{LL}I_{rms}\rightarrow 2I_{DC}=\sqrt{3}I_{rms}\rightarrow\frac{I_{rms}}{I_{DC}}=\frac{2}{\sqrt{3}}=1.1547$$

(b) With $P_{Loss,DC}=2R_{DC}[I_{DC}]^2$, $P_{Loss,AC}=3R_{AC}[I_{rms}]^2$, we can write that $\frac{P_{Loss,AC}}{P_{Loss,DC}}=\frac{3}{2}\left(\frac{I_{rms}}{I_{DC}}\right)^2\frac{R_{AC}}{R_{DC}}$, and using $\frac{I_{rms}}{I_{DC}}$=1.15$\rightarrow\left(\frac{I_{rms}}{I_{DC}}\right)^2=1.15^2=4/3$, we have that $\frac{P_{Loss,AC}}{P_{Loss,DC}}=\frac{3}{2}\,\frac{4}{3}\frac{R_{AC}}{R_{DC}}\rightarrow\frac{P_{Loss,AC}}{P_{Loss,DC}}=2\frac{R_{AC}}{R_{DC}}$. Then, with $\frac{R_{AC}}{R_{DC}}=1.1$, we have that $\frac{P_{Loss,AC}}{P_{Loss,DC}}=2.2$.

(c) For HVDC, assuming a bipole configuration, the number of poles is two, whereas in AC transmission, the number of phases is three; relative current density refers to the fact that AC rms current is about 1.15 times the DC current; the difference in DC and AC resistance is due to the skin effect which makes a conductor use for AC have a higher effective resistance.

Problem 8: Section 7a-3.4.7 indicates that converter transformers used in LCC-based HVDC systems must provide tap changing, whereas Section 7a-3.5 indicates this is unnecessary for converter transformers used in VSC-based HVDC systems. Why is this the case?

Solution: Tap changing is a voltage control method. Because LCC-based HVDC converters always absorb reactive power (i.e., they cannot supply reactive power), they do not have inherent voltage control capabilities. VSC-based HVDC converters, on the other hand, absorb and supply reactive power and therefore can effectively control AC-side voltages without tap changing.

Problem 9: Referring to the discussion of underground conductor systems in Section 7a-3.4.7 and in Section 7a-3.5, why do bidirectional LCC-based underground HVDC use MI paper-insulated cables, yet, any VSC-based underground HVDC uses XLPE cables?

Solution: XLPE cables are less expensive and so are preferred where they can be used. They cannot be used with bidirectional LCC-based underground HVDC because, with LCC-based HVDC, bidirectionality can only be achieved via polarity reversal, and polarity reversal cannot be performed with XLPE cables because frequent polarity reversal can lead to the formation of voids within the insulation due to the different thermal expansion coefficients of the paper and impregnating

Some last items

1. I need to know whether you have hired anyone on HVDC-Learn, position (1/2-time RA?), and whether they are female or minority.
2. Yr 1 modules need to be well-underway – please email me status of your module as of today (table on right gives 11/18 status).
3. We have decided to have yr 1 short course in Boston, hosted by Tufts, since focus is on OSW & there is significant OSW interest/ activities in Boston area. See slides 16-19. Give input on dates:
   - Week of 3/10-3/14
   - Week of 3/17-21 (Spring break at ISU)
   - Week of 3/24-28
   - Week of 3/31-4/4
   - Week of 5/5-5/9
   - Week of 5/12-5/16 (latter part of week not good for JDM)
   - Week of 5/19-5/23
   - Week of 5/26-5/30
   - Week of 6/2-6/6
   - Week of 6/9-6/13 (not good for PAL)
   - Week of 6/16-6/20 (not good for PAL)
4. Multischool senior design projects: Who can do this Sp '2025?
5. If you don't have a yr 1 module, consider to get an early start working on your yr 2 or yr 3 modules.
6. There is a module review/dissemination process that will be provided by ISU library at no cost – see slide 15 (next slide).

Mod ID	Module title	Person/ school	Completion target	Status PLEASE E-MAIL ME YOUR MODULE STATUS (% COMPLETE) AS OF TODAY.
7a	Pt 2 pt onshore & offshore apps (Early completion is goal)	McCalley/ISU	Q1	98% complete.
1c	Intro to HVDC for offshore wind	Fang/MS	Q2	90% complete.
1b	Intro to HVDC for offshore wind	Li/UTK	Q2	75% complete.
1a	Intro to HVDC technology	Lof/Tufts	Q4	Developed structure 15% complete.
3d	Modular multilevel converter as HVDC cnvrtr interface and its control	Tolbert/UTK	Q3	Developed structure 10% complete.
3b	Power electronics 101: Fundamentals of switching pwr conv+EMT	Mehrizi-Sani/VT	Q3	Developed structure 10% complete.
5a	HVDC fault management & protection systems	Wallace/MS	Q4	Developed structure 20% complete.
2b	VSC-HVDC converter station technologies	Cui/NCSU	Q4	Developed structure 10% complete.
4d	Offshore HVDC cnvrtr grid forming controller design for black start capability	Nazir/Clemson	Q4	35% complete.

Weeks Leon is available:

- **Week of 3/24-28**
- **Week of 3/31-4/4**
- **Week of 5/5-5/9**
- **Week of 5/12-5/16**
- **Week of 5/19-5/23**
- **Week of 5/26-5/30**

Module review/dissemination process

- **Logistics led by Hantao Cui of NC State University and J. McCalley of Iowa State University**
- **Original approach was that Hantao would create module conversion process: Word to Jupyter**
- **Jupyter was attractive because it facilitates interlinkage, web deployment, and animation/videos.**
- **We are considering to shift from developing our own process using Jupyter to using Iowa State Library Services, *which are available at no cost*. These services include the following:**
  - Software for coordinating module review
  - Conversion of module to Pressbooks (https://pressbooks.com/) which has capabilities similar to Jupyter
  - Facilitate DOI assignment, market to peer institutions for adoption, catalogue to enhance findability, facilitate dissemination, and support re-use and repackaging, all without restricting where and how authors can disseminate their modules;
  - Authors receive credit towards a peer-reviewed library-available work;
- **Module development workflow, with ISU Library Services, will be as follows:**

1. All modules written in Word.
2. Appropriate permissions for reuse of figures, videos, animations obtained by author.
3. Module reviewed using ISU Digital Press journal management software. Project faculty coordinate review process.
4. Final module converted to Pressbook form to facilitate (i) interlinkage between modules; (ii) use of videos & animations.
5. Module is published.

Short-course on HVDC

- **3 short courses developed over 3 yrs of project. Each 8-hr short-course delivered by end of each project year. Logistics led by Xin Fang of Mississippi State Unvrsty.**
- **Year 1 short course "Introduction of HVDC for offshore wind"**

This short course, "Introduction of HVDC for Offshore Wind," provides a comprehensive overview of high voltage direct current (HVDC) technology and its application in offshore wind power integration. The course is structured into six key subtopics, each delivered by experts in the field over a total of approximately 8 hours.

1. **Introduction of HVDC technology, 1.5 hour Lof/Tufts, Module 1a**
2. **Application Guide for HVDC transmission, 1 hour Li/UTK, Module 1b**
3. **Point to Point HVDC and offshore grids, 1.5 hour McCalley/ISU, Module 7a**
4. **HVDC application in offshore wind power integration, 1 hour Fang/MSU, Module 1c**
5. **Modular multilevel converter design, 1.5 hour Tolbert/UTK, Module 3d**
6. **VSC-HVDC Converter station technologies, 1.5 hour Cui/NCSU, Module 2b**

- **Logistics:**

Date: Two days between 3/25 and 6/25.

Time: Day 1, 1-5pm; Day 2, 8-noon.

Location: Boston, hosted by Tufts.

Mode: Live and virtual; Professional development hours (PDHs) provided.

Materials: Six (of our nine) year 1 textual modules, each with accompanying powerpoint slides

Year 2 topic: Onshore HVDC design, operation, protection & control.
Year 3 topic: Multiterminal HVDC.

Short-course on HVDC

Course outcomes:

This course equips professionals with essential knowledge to navigate the complexities of integrating offshore wind power using HVDC technology. It addresses both the theoretical and practical aspects, preparing participants to tackle current challenges and to leverage future opportunities in the evolving landscape of power transmission and renewable energy integration. By completing this course, participants will:

- **Gain a foundational understanding of HVDC technology and its historical context.**
- **Understand technical and economic advantages of HVDC transmission, especially in offshore wind applications.**
- **Learn the design and operation of P2P HVDC systems and their components.**
- **Acquire knowledge on integrating offshore wind power plants using HVDC, including equipment sizing and economic considerations.**
- **Understand design principles of MMCs and their role in HVDC systems.**
- **Familiarize with VSC-HVDC converter station technologies and their integration with AC grids.**

Short-courses on HVDC – topical summary

1. Introduction of HVDC technology (1.5 hours, Lof/Tufts)

The course begins with an introduction to HVDC technology, tracing its historical evolution from the late 19th-century "war of the currents" between DC and AC systems. It covers the resurgence of HVDC interest post-World War I, the development of mercury valves and thyristors, and the establishment of the first commercial HVDC interconnection in 1954. This section sets the foundation by explaining how HVDC systems enable efficient long-distance power transmission, particularly advantageous for underwater cables and interconnecting non-synchronous power grids.

2. Application Guide for HVDC Transmission (1 hour, Li/UTK)

The second segment provides an application guide for HVDC transmission, exploring current applications and future potentials. It discusses the technical and economic advantages of HVDC over HVAC systems, such as reduced transmission losses and improved grid stability. Real-world examples illustrate how HVDC is implemented in various scenarios, including long-distance transmission and back-to-back systems for network interconnection and power flow control.

3. Point-to-point HVDC and offshore grids (1.5 hours, McCalley/ISU)

This part focuses on Point-to-Point (P2P) HVDC systems, the most common HVDC design connecting two converter terminals via a direct current transmission path. It covers the basics of P2P design, including components such as converters, protection systems, filters, and conductors. The session examines different configurations—monopolar and bipolar—and describes applications such as overhead lines, back-to-back stations, underground cables, and submarine links, supplemented with descriptive examples. Offshore designs for both point-to-point will be described and compared to offshore backbone/meshed designs.

Short-courses on HVDC – topical summary (continued)

4. HVDC Application in Offshore Wind Power Integration (1 hr, Fang/MSU)

The fourth segment delves into the application of HVDC in the integration of offshore wind power. As offshore wind farms increase in size and are located further from shore, HVDC becomes a more efficient solution compared to traditional AC connections. This section discusses offshore wind power plant topologies, equipment sizing, and compares the economics of offshore AC and DC transmission options. It highlights how HVDC technology addresses challenges related to distance and grid connection, enhancing the reliability and efficiency of power delivery from offshore installations.

5. Modular multilevel converter design (1.5 hr, Tolbert/UTK)

This section explores the design of Modular Multilevel Converters (MMC), which are critical in HVDC systems for handling high voltage levels using low-voltage power electronic devices like Insulated Gate Bipolar Transistors (IGBTs). Topics include the structure and operation of MMCs, submodule functions, equivalent circuit derivation, and operation principles. Various modulation methods are covered, such as nearest level control and different Pulse Width Modulation (PWM) techniques. The session also addresses design challenges such as circulating current control, capacitor balancing, and arm inductance design.

6. VSC-HVDC Converter Station Technologies (1.5 hours, Cui/NC State)

This section provides an overview of Voltage Source Converter (VSC) HVDC converter station technologies, essential for asynchronously connecting DC systems like offshore wind farms to AC grids. It covers the historical development of VSC HVDC technology and compares it with Line Commutated Converter (LCC) HVDC systems. Key components such as power electronic devices (IGBTs, capacitors, reactors), converter transformers, and AC/DC switchgear are discussed. The operational principles, control strategies, modulation techniques (including PWM and Space Vector Modulation) and design considerations like station layout, cooling systems, and redundancy practices are also examined. The session concludes with discussions on integrating VSC-HVDC systems with AC grids, focusing on grid stability and power quality impacts.