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Question 1.3:
In the last decade, VSC technology has advanced considerably, and it has now become the predominant technology selected for new HVDC projects, especially to interconnect and transmit renewable energy. VSC is even starting to be evaluated as an alternative to the refurbishment of existing LCC HVDC links as the power rating of VSC converters trends up.

- **What are the main considerations on technology selection for new and refurbishment HVDC projects?**

EirGrid pursues a multi-condition techno-economic approach to technology selection, striking a balance between technical considerations as well as the environment and social impact associated with the project. For grid projects, candidate network locations are identified based on internal analysis of network needs including capacity requirements and potential grid reinforcements. Then consideration is given to whether a new installation or scaling/re-deployment of an existing installation is required. A Framework for Grid Development follows to allow stakeholders provide their feedback and insights. At this point, technology selection can occur on the basis of capability to meet system needs. On the one-hand, reliability, serviceability, security of supply and the power range defined by the voltage – current capabilities are considered, along with any dynamic characteristics or interactions with the wider electric system, which must be modelled and included in stability simulations, control & protection schemes. Concerns such as reliance on a single vendor for bespoke hardware or software support must also be considered against the entire project lifetime. On the other hand, this must be traded against compactness in line with potential visual and environmental impact.

Ireland is a synchronous island grid and any interconnection requires a HVDC scheme due to the distances and magnitudes of power transfer required for economic viability or social welfare. Therefore, key considerations are connecting to other synchronous grids, ideally with absolute power scheduling per market coupling arrangements. Another critical attribute is the capability to provide system services such as Fast Frequency Response and other forms of frequency damping to stabilise any oscillations. HVDC is able to compensate for sudden frequency decay occurring in a receiving system (due to an abrupt lack of generation) by increasing its power to compensate in a very fast timeframe in accordance with any Operating Protocol or Balancing and Ancillary Service Agreement, subject to appropriate telecommunications between converter stations. It is well documented that Ireland has ambitious targets for renewable sourced generation, with ambition of increasing from the current 40% RES-E generation annually to >80% by 2030. At times, significant exports from the all-island power system will be required to accommodate the high volumes of electrical energy without curtailment. With this influx of Inverter Based Resources (IBR), the dynamic nature of the grid is changing and voltage stiffness is reducing. This implies that any HVDC links suitable for exporting excess generation must be capable of riding through any faults and providing services such as Grid Forming or Blackstart capability in the event of power loss.

In the past, Line Commutated Converter (LCC) HVDC links have been integrated to enable longer transmission corridors with lower losses or to interconnect two distinct AC grids.

Traditionally, the AC grid(s) to which LCC links connected would have exhibited high inertia from rotating machines and “stiff” system strength on the basis of possessing higher Short Circuit Ratios (SCR). LCC schemes were also favoured due to their maturity, proven service lifetimes, relative simplicity to implement basic schemes with fewer components and ultimately, due to their ability to transfer higher active power capacity over longer distances and with lower conversion losses. However, LCC schemes require a synchronous voltage source supported by large reactive power compensation devices and harmonic filters to facilitate commutation, implying the converter stations have a large site footprint. Conversely, Voltage Source Converter (VSC) HVDC links were typically reserved for lower capacity (<1GW) projects since the ratings (including overload capability) of the IGBTs could not match those of thyristor based LCC schemes. VSC links were often confined to shorter, underground or submarine cable schemes arising from a technological limitation on its ability to handle dc line faults due to an existing permanent path for the current through the anti-parallel diodes at the valves.

However, once VSC links overcame the technological barrier (circa 2005) of reducing the fault current to zero at the DC line to enable a successful restarts, it is now considered for any project, OHL or UGC. Furthermore, the voltage and current capabilities of modern IGBTs have improved substantially, with manufacturers offering applications up to ± 525 kV and above 1,000 MW. A corresponding reduction in both price and IGBT losses has rendered VSC more economically viable and brings it into contention for projects traditionally reserved for thyristor-based LCC applications. VSC offer several benefits over LCC since they employ solid state switching devices whose power control speeds are within a sub-cycle mode, meaning: (i) very fast control of power transmission, especially for power reversals (which cannot be readily implemented by LCC) and (ii) very fast action towards reducing the voltage to zero and limiting the transmitted current during faults – an inherent circuit breaker effect. Advanced switching techniques (PWM or Multi-Level) at higher frequencies significantly reduce the need for large harmonic filters since the main frequency distortion components are significantly above the fundamental frequency.

Fast VSC based switching means that fault ride through is more easily achievable to avoid commutation faults. Unlike LCC, VSC schemes are self-commutated, operable in 4-quadrants, and do not depend on local voltages, instead relying on external voltage control signals for commutation. This implies that a Blackstart capability to restore voltage can be provided by VSC HVDC links to the host AC network(s) post fault. Similarly, Grid Forming may be specified. It also allows for independent rapid control of both active and reactive power, which is critical for evolving power grids. In fact, individual converter stations may act as a STATCOM providing reactive power support during DC circuit outages. VSCs maintain a constant polarity of the DC voltage for their building blocks. The change of power flow direction is achieved by reversing the direction of the current. LCCs do not have this capability as reversing power flow direction at any connected station requires reversing the voltage polarity for all other connected DC stations. Therefore, VSCs are more suitable for DC grid implementation, since they may be integrated in multi-terminal DC systems. This will be a key enabler for the integration of offshore IBR to the Irish power system, where >10GW of future capacity is expected to connect.

The considerations of VSC vs LCC are given in the table below:

Aspect	Consideration	LCC	VSC
Active Power Transfer	Can the realisable capacity be matched against system needs? (Consider Largest single infeed / outfeed)	Can be tailored (max achievable = 12GW, ±1,100kV)	Can be tailored (max achievable = 2GW, ±525kV)
	Are active power losses minimised?	Converter losses ≈ 0.6 - 0.8% *Cable losses dependent on length/topology*	Converter losses ≈ 1% for PWM Converter losses ≈ 0.8% for Multi-Level *Cable losses dependent on length/topology*
	Is Power flow reversal practical? (To enable import and export)	Voltage Polarity Reversal, Slow	Current direction reversal, Very fast
Reactive Power Compensation	Are there Reactive power requirements?	50-60% of rated MW	None
	Is there inherent VAR control or Grid support?	No	Can provide Mvar to AC grid
Power Quality	How significant are AC and DC harmonic levels? (any AC cables may promote resonances and exacerbate)	Higher harmonic distortion	Lower harmonic emissions for PWM schemes Negligble harmonic emissions for Multi-level schemes
	Are Harmonic filters required?	Large filter equipement requirements	Low or no filter equipment required
Performance	Can Active and Reactive Power be controlled independently?	No, inherently linked	Yes, P and Q are independent Reactive power also independent of other terminals Can provide continuous AC voltage regulation
	Is there a dependency on the Grid frequency?	Line dependent for commutation (50/60 Hz)	Frequency independent, Self-commutated (up to ≈2 kHz)
	Is it prone to commutation failure or internal faults?	Can turn on only, Transient AC voltage disturbances (amplitude or phase shift) result in internal dc temporal over-current, Slower fault recovery (<0.3s), Suffers commutation failures	Can turn on and off Immune to any voltage dips or transient AC disturbance, Faster fault recovery (<0.2s), Does not suffer commutation failure
	Can overloads be tolerated?	Good overload capability (≈20%)	Poor overload capability for PWM based schemes (≈10%) Improved overload capability for Multi-level schemes (>15%)
	How are DC side faults handled?	Controlling the firing angle of the thyristors valves stops the increase of DC fault current during short circuit events, reducing the impact. During overhead line faults, power transmission is stopped for arc de-ionization, then resumes promptly.	Continuous conduction in the IGBT causes increased DC fault current even when the IGBTs are turned off. The AC circuit breakers at both VSC HVDC terminals must be opened to stop diode conduction. The HVDC link must be re-started / de-blocked after fault removal.
System Services	Can it provide Blackstart in the event of a power interruption?	No	Yes, assuming other terminal has a power source available
	Can the technology provide any ancillary services for frequency or voltage control	Power Oscillation Damping Sub-synchronous Damping Emergency Power Control Frequency Containment Reserves (depending on operating point)	Power Oscillation Damping Sub-synchronous Damping Emergency Power Control Frequency Containment Reserves Synthetic Inertia AC line emulation Reactive power boost
	Can it support Grid Forming in low inertial grids?	No	Yes, assuming specified appropriately
Interactions	Are there any potential interactions with the wider electric system? (Dynamic stability simulations, control & protection schemes)	Controller dependent Typically improves transient behaviours Requires bespoke studies to identify interactions	Controller dependent Dampens transient migrations Requires bespoke studies to identify interactions (complex)
	Is there a threshold for operation?	Minimum active power transmission, must be OFF at 0 MW	No minimum active power transmisison, may be ON at 0 MW
Maintenance	Is the technology proven with a reliable track record?	Thyristor based Available since 1970	IGBT based PWM since 1999 Multi-level since 2010
	Are Spare parts readily available? (off the shelf or OEM only?) Are there vendor-dependent components / IP to consider?	Yes, most reactive & thyristor components have multiple vendors Control scheme dependency on OEM (Less Complex than VSC)	More limited availability of IGBTs depending on OEM Control scheme dependency on OEM (More Complex than LCC)
	What number of components to achieve desired rating? (impact on number of spares required, more parts to maintain, outage duration)	Fewer thyristors (≈ 40-50% of VSC IGBTs for PWM) More reactive compensation and filtering devices	More IGBT components than LCC thyristors Fewer or no reactive compensation and filtering devices Multi-level requires significantly more electronics than PWM
	What is the cost of components to achieve desired rating?	Cheaper	Collectively more expensive
	Are there any special transformer considerations?	Requires bespoke Converter transformer specification: > On-Load Tap Changers > Tailored winding configuration for x-pulse converter > More expensive Transformer stresses will be higher (greater harmonic emissions, DC stresses)	Conventional Power transformer specification Transformer stresses will be lower (reduced harmonic emissions, DC stresses)
	Are there any special cable considerations?	Depends on topology and circuit length (resistance)	Depends on topology and circuit length (resistance)
	Is DC smoothing required?	Requires DC smoothing reactors	Requires DC smoothing capacitors
Future-proofing	Are appropriate models available to address future compatibility? (control schemes, real time simulator, digital twin)	Vendor specific	Vendor specific
	Can it operate in low system strength conditions? (i.e. reduced voltage stiffness)	No ($SCR_{min} > 2$)	Yes ($SCR_{min} = 0$)
	Is it suitable for connecting Inverter Based Resources?	Limited conditions	Yes
	Can it accommodate more than 2 terminals? (Consider multi-terminal / mesh expandability)	Limited conditions	Yes
	Can more than one vendor be integrated into the solution?	Limited conditions	Limited conditions
Installation	What is the expected delivery time for the project? (can it meet application timelines, e.g. IBR connection)	Project specific, cables are typically the longest lead time ≈ 3 years	Project specific, cables are typically the longest lead time ≈ 4 years
Control	Is it possible for the scheme to be automated or is remote control required?	Full automation is possible Manual control may be necessary for reactive power control Power flows can be scheduled	Full automation is possible Power flows can be scheduled
	Are inter-station communication links required? (provide fast system services, monitoring and control)	Can operate manually without optical channels but preferred for power reversal and limited frequency containment services	Can operate manually without optical channels but preferred for faster frequency containment services
	What is the projected lifetime of the control system? (Built in redundancy, feasibility of replacement mid lifespan)	Project specific (typically 20-25 years) Typically controlled by Master-Slave configuration Replacement control schemes typically possible)	Project specific (typically 20-25 years) Typically controlled by Master-Slave configuration Replacement control schemes typically possible)
	Is it possible to keep non-proprietary elements out of the control scheme? (Avoid vendor lock-in)	Non-core components (switches, firewalls, AC relays and switchgear) can be replaced by parties other than the original vendor	Non-core components (switches, firewalls, AC relays) can be replaced by parties other than the original vendor
Environmental	What is the size of the Site footprint? (visual impact and blending with surrounding environment)	LCC sites are significantly larger than VSC due to the higher levels of reactive compensation and harmonic filtering required	VSC links are typically 40-50% more compact than LCC PWM schemes are taller, slimmer and have potential harmonic filters Multi-level schemes have lower but broader profiles with few filters.
	Are there audible emissions? (Loud sounds, sporadic or consistent)?	Continuous hum from reactive compensation, transformers & filters Occasional blast sound from shunt operation	Quieter than LCC Continuous hum from transformers (and any small filters)
	Are there any special shielding requirements? (electromagnetic interference)	Yes (particularly for reactors)	Yes (particularly for PWM schemes)
Cost	What is the overall cost of the project delivery?	Cheaper	Becoming competitive