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Department of EEE

UNIT- I

Basic Concepts & Necessity of HVDC systems

HVDC Transmission

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Topics:

- Necessity of HVDC systems
- Economics of HVDC transmission systems,
- Terminal equipment of HVDC transmission systems/ Apparatus required for HVDC Systems
- Types of HVDC Links
- Comparison of AC and DC Transmission
- Application of DC Transmission System
- Planning and Modern trends in D.C. Transmission
- Analysis of HVDC Converters
- Choice of Converter Configuration
- Analysis of Graetz circuit
- Characteristics of 6 Pulse converter
- 12 Pulse converters

Necessity of HVDC Systems

Why DC for Long Distance Bulk Power?

Alternating Current (AC) encounters structural transmission barriers over long distances that limit both capacity and performance. HVDC systematically bypasses these limits.

- ➢ . Elimination of Parasitic Losses: Completely avoids skin effect, charging currents, and continuous dielectric heating.
- ➢ . Pure Active Power Delivery: AC lines convey both active and reactive power. HVDC carries 100% active power, maximizing system utilization.
- ➢ . Submarine Capability: High capacitance renders long underwater AC transmission impossible due to huge charging currents. DC cables charge only once.

Economics of HVDC transmission systems

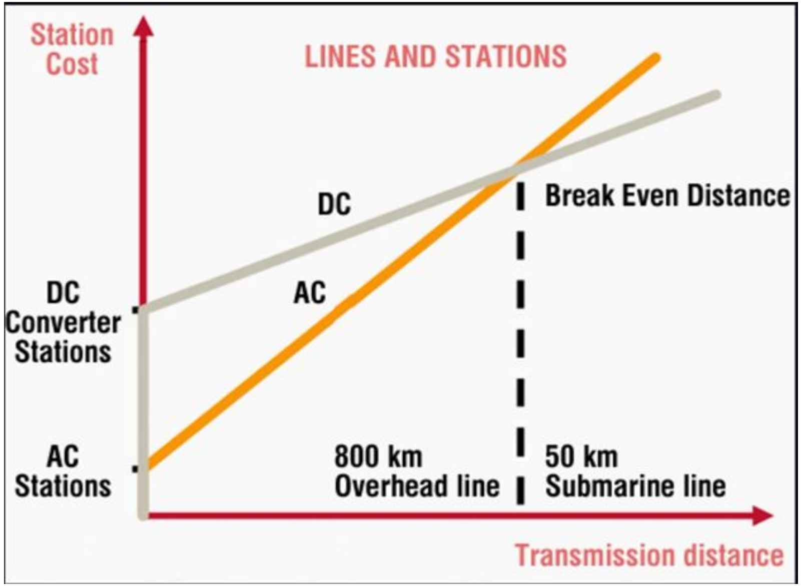
The Break-Even Distance Mechanism

Evaluating HVDC vs. HVAC involves balancing fixed initial terminal costs against ongoing per-kilometer line structural savings.

. High Terminal Investment: Converter substations require substantial initial layout costs for electronic valves, filters, and reactors.

. Lower Linear Infrastructure Cost: DC transmission uses fewer conductors (2 instead of 3), reducing tower sizing, insulation volume, and right-of-way width.

. Critical Thresholds: The capital expenditure curves cross at a designated break-even distance.



Standard Break-Even Values:

Overhead Overhead Lines: 500 - 800 km | Submarine Cables:~50 km

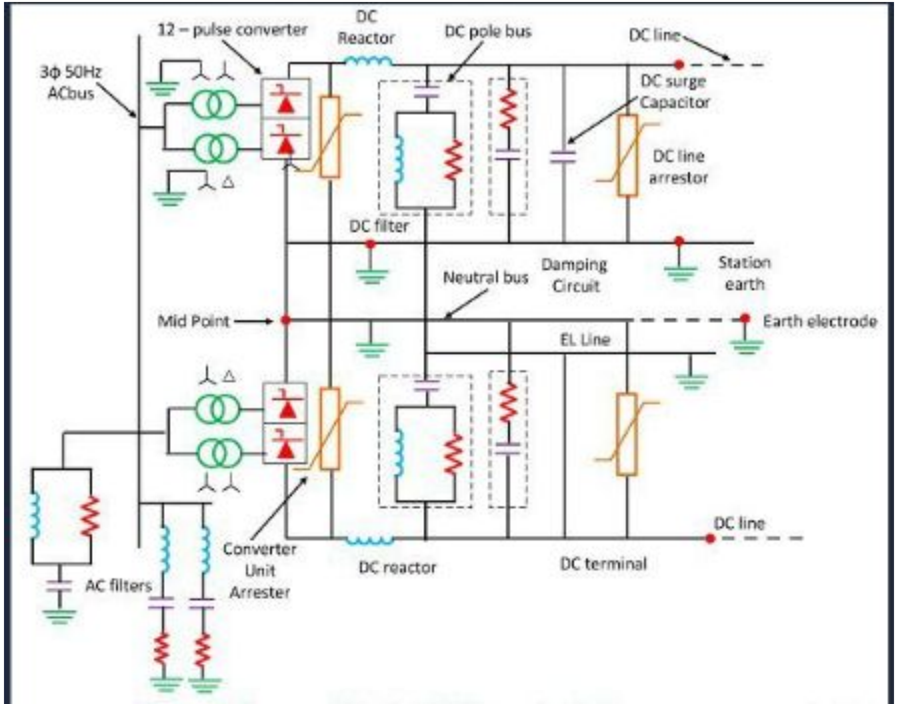
Apparatus required for HVDC Systems/ Terminal equipment of HVDC transmission systems

The HVDC system has the following main components.

- Converter Stations/ unit
- Converter valves
- Converter Transformers
- Filters
  - AC filter
  - DC filter
  - High-frequency filter
- Reactive Power compensation equipment
- Smoothing Reactor

For better understanding watch the below link

https://www.youtube.com/watch?v=UVtRG07ibj4



Schematic Diagram of A typical HVDCconverter Station

Converter Stations :

The core transformation between Alternating Current (AC) and Direct Current (DC) occurs within the **Converter Station**.

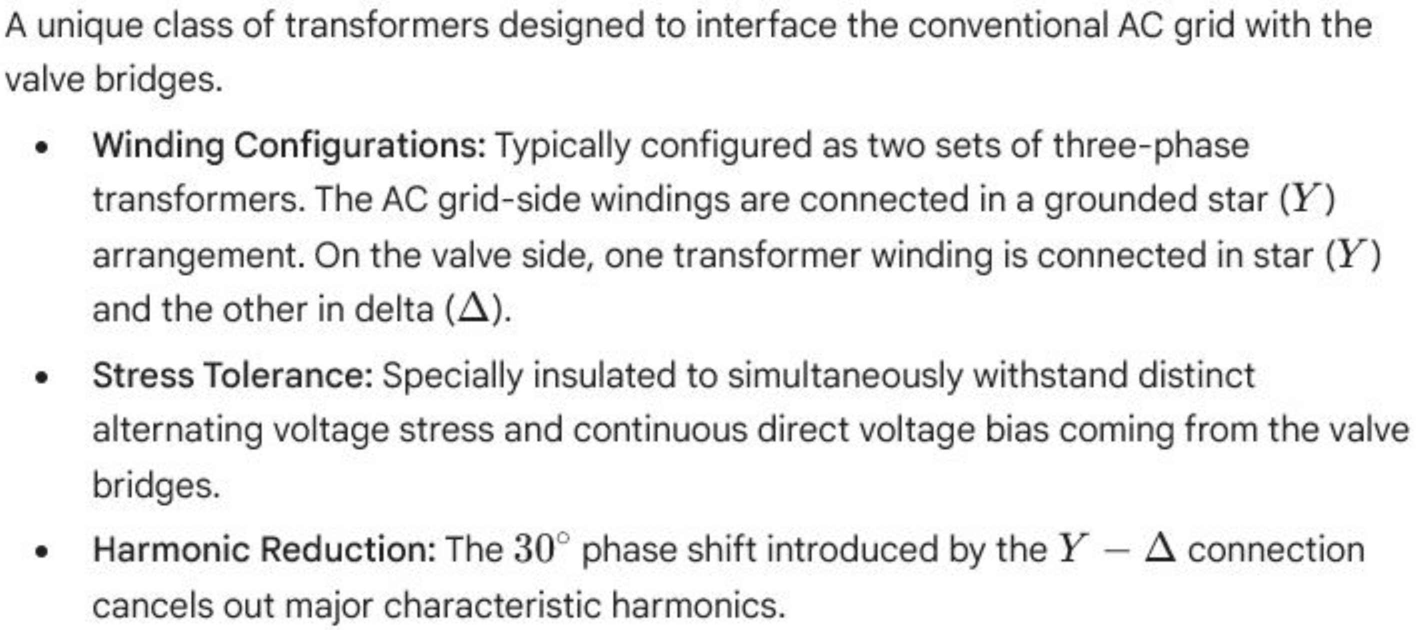
- **The Graetz Bridge:** Conversion relies on three-phase bridge circuits.
- **12-Pulse Configuration:** Modern HVDC systems standardly link two 6-pulse bridges in series. This specific configuration is paired with phase-shifting transformers to inherently eliminate lower-order harmonics (5th and 7th) significantly optimizing power quality.

Converter Valves:

Often called the "heart" of the HVDC terminal, these consist of high-power semiconductor assemblies (Thyristors or IGBTs) stacked to withstand massive operating voltages.

- **Installation:** Housed inside a heavily shielded **Valve Hall** to manage high-voltage clearances and electromagnetic interference.
- **Cooling Media:** High-load operations generate intense heat, necessitating advanced cooling systems utilizing air, oil, or deionized water.
- **Core Functions:** * High-speed switching and precise control of current.
  - Direct bidirectional power conversion (Rectification/Inversion).
  - Regulation of the overall DC output voltage.

Converter Transformers

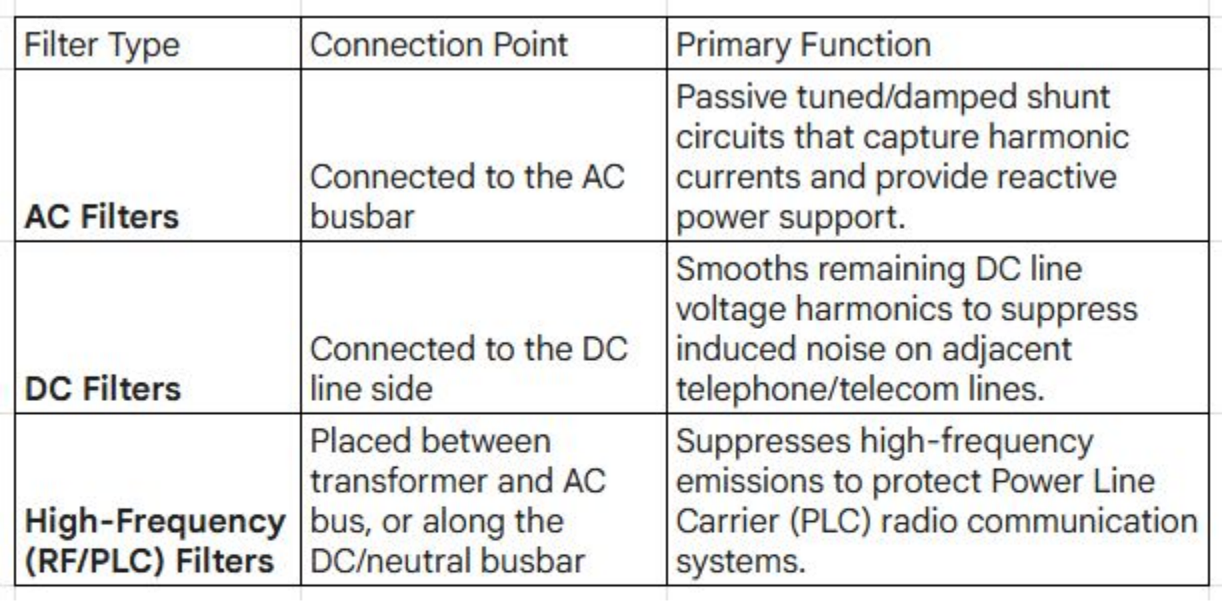


A unique class of transformers designed to interface the conventional AC grid with the valve bridges.

- **Winding Configurations:** Typically configured as two sets of three-phase transformers. The AC grid-side windings are connected in a grounded star (Y) arrangement. On the valve side, one transformer winding is connected in star (Y) and the other in delta (Δ).
- **Stress Tolerance:** Specially insulated to simultaneously withstand distinct alternating voltage stress and continuous direct voltage bias coming from the valve bridges.
- **Harmonic Reduction:** The 30° phase shift introduced by the $Y - \Delta$ connection cancels out major characteristic harmonics.

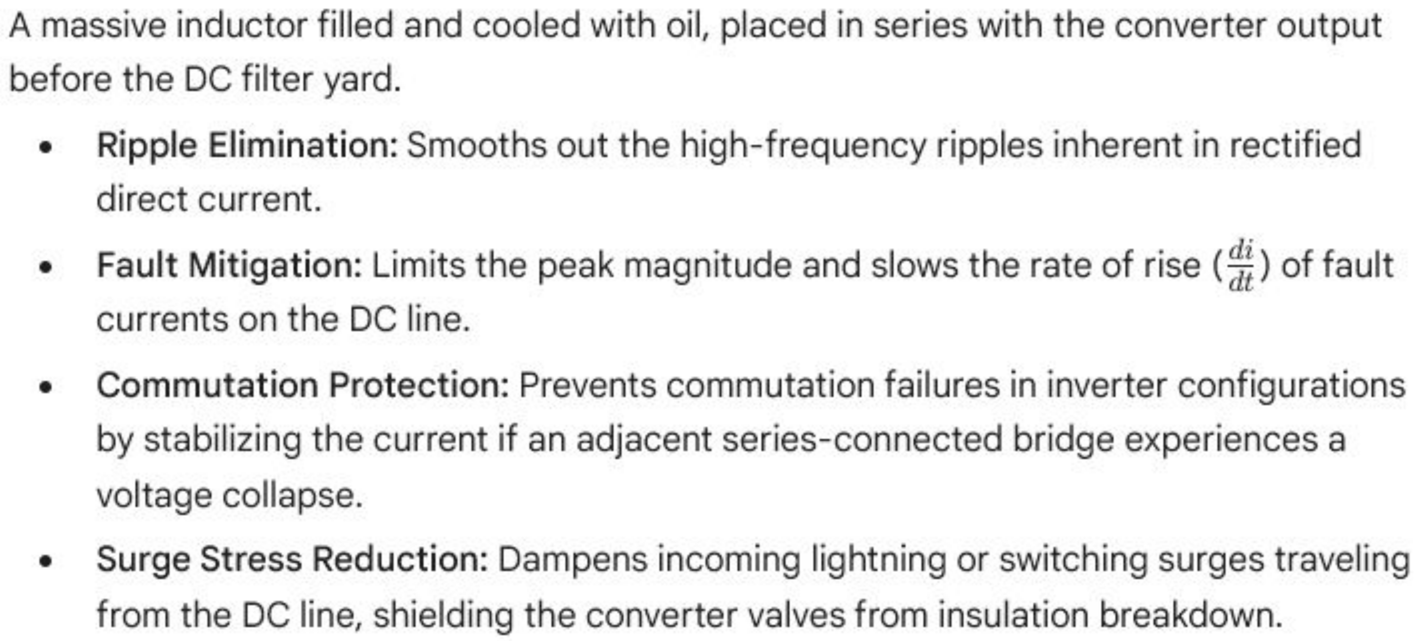
Filters:

Converters generate substantial harmonic distortions that can lead to control instability, extreme overvoltages via resonance, and localized heating in nearby machinery. Terminal stations deploy three distinct filter systems to neutralize these risks:



Filter Type	Connection Point	Primary Function
AC Filters	Connected to the AC busbar	Passive tuned/damped shunt circuits that capture harmonic currents and provide reactive power support.
DC Filters	Connected to the DC line side	Smooths remaining DC line voltage harmonics to suppress induced noise on adjacent telephone/telecom lines.
High-Frequency (RF/PLC) Filters	Placed between transformer and AC bus, or along the DC/neutral busbar	Suppresses high-frequency emissions to protect Power Line Carrier (PLC) radio communication systems.

Smoothing Reactors:



A massive inductor filled and cooled with oil, placed in series with the converter output before the DC filter yard.

- **Ripple Elimination:** Smooths out the high-frequency ripples inherent in rectified direct current.
- **Fault Mitigation:** Limits the peak magnitude and slows the rate of rise ($\frac{di}{dt}$) of fault currents on the DC line.
- **Commutation Protection:** Prevents commutation failures in inverter configurations by stabilizing the current if an adjacent series-connected bridge experiences a voltage collapse.
- **Surge Stress Reduction:** Dampens incoming lightning or switching surges traveling from the DC line, shielding the converter valves from insulation breakdown.

Reactive Power Compensation Equipment:

LCC (Line Commutated Converter) stations draw substantial reactive power proportional to their active power load. While AC filters supply a baseline portion of this demand, supplemental systems are integrated to ensure dynamic stability:

- Shunt Capacitors: Provide fixed or stepped reactive blocks.
- Synchronous Condensers: Supply spinning reactive reserves and boost short-circuit ratios.
- Static VAR Systems (SVC/STATCOM): Deliver ultra-fast, continuously variable reactive compensation.

Circuit Breakers: These are used to interrupt DC fault currents.

- Protect the HVDC system during faults
- Isolate faulty sections

Breaking DC current is difficult because DC has no natural current zero.

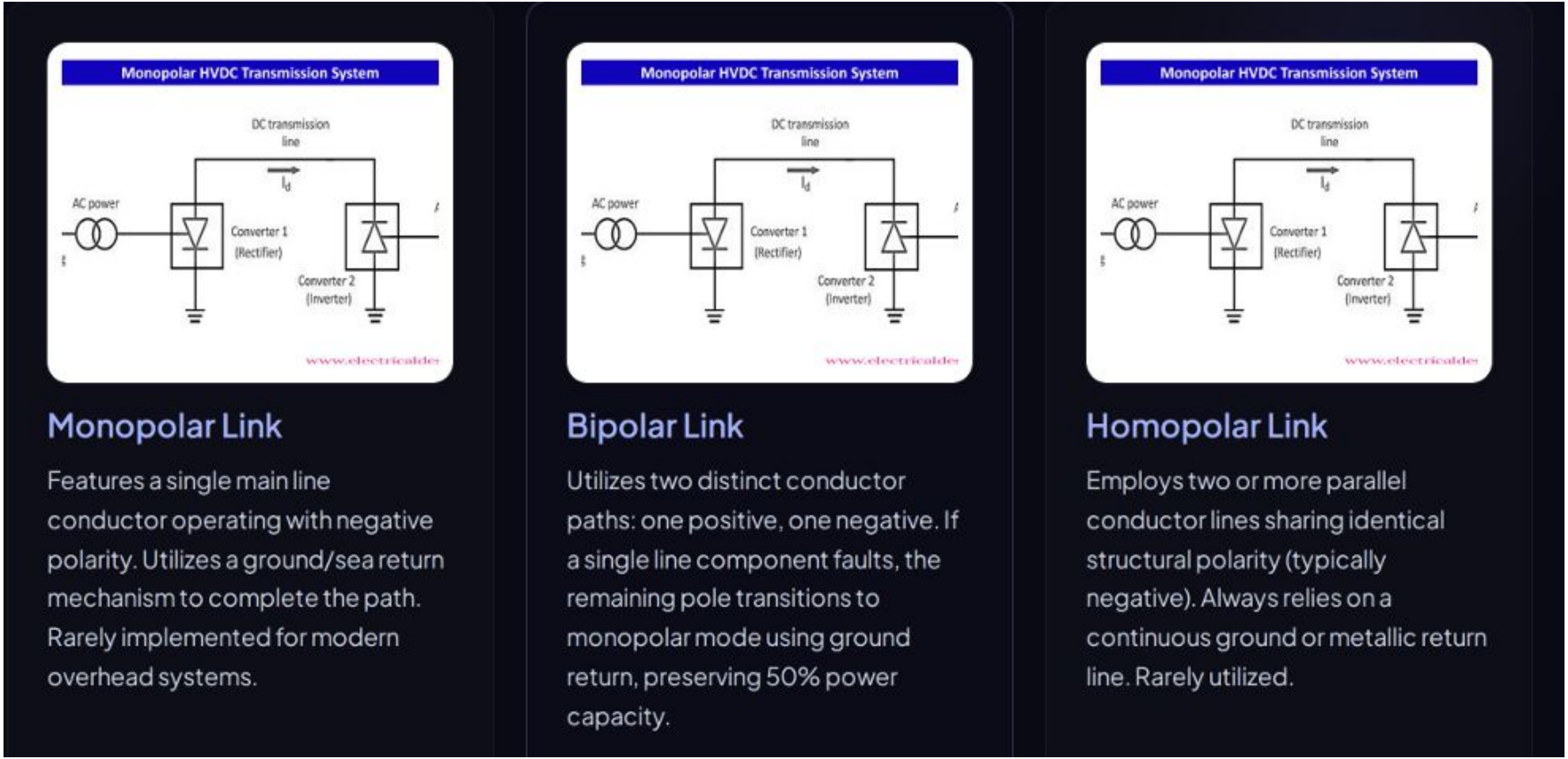
Surge Arresters: These protect equipment from overvoltages caused by Lightning, Switching surges and also

- Divert surge energy safely to ground
- Protect converter valves and insulation

Ground Electrodes: Used in monopolar and homopolar HVDC systems

- Provide return current path through earth
- Maintain system continuity

Types of HVDC Links



Monopolar Link

Features a single main line conductor operating with negative polarity. Utilizes a ground/sea return mechanism to complete the path. Rarely implemented for modern overhead systems.

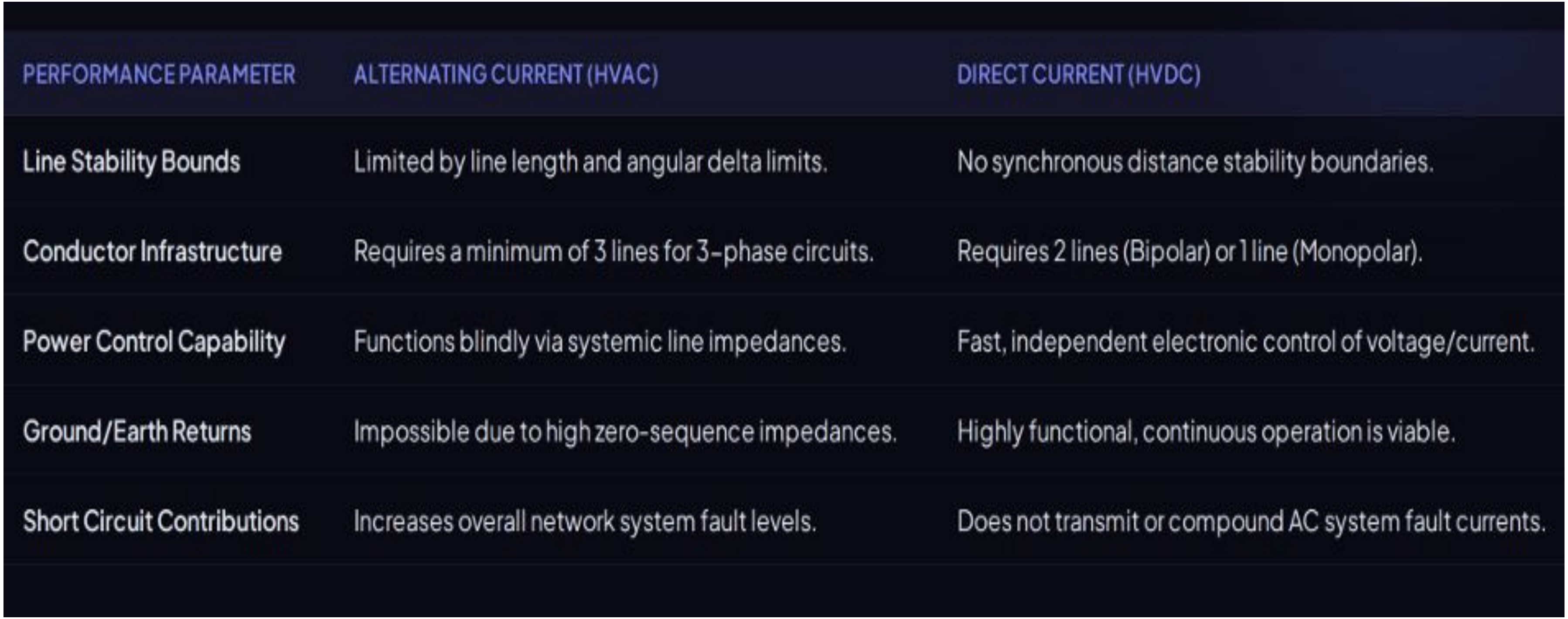
Bipolar Link

Utilizes two distinct conductor paths: one positive, one negative. If a single line component faults, the remaining pole transitions to monopolar mode using ground return, preserving 50% power capacity.

Homopolar Link

Employs two or more parallel conductor lines sharing identical structural polarity (typically negative). Always relies on a continuous ground or metallic return line. Rarely utilized.

Comparison of AC and DC Transmission

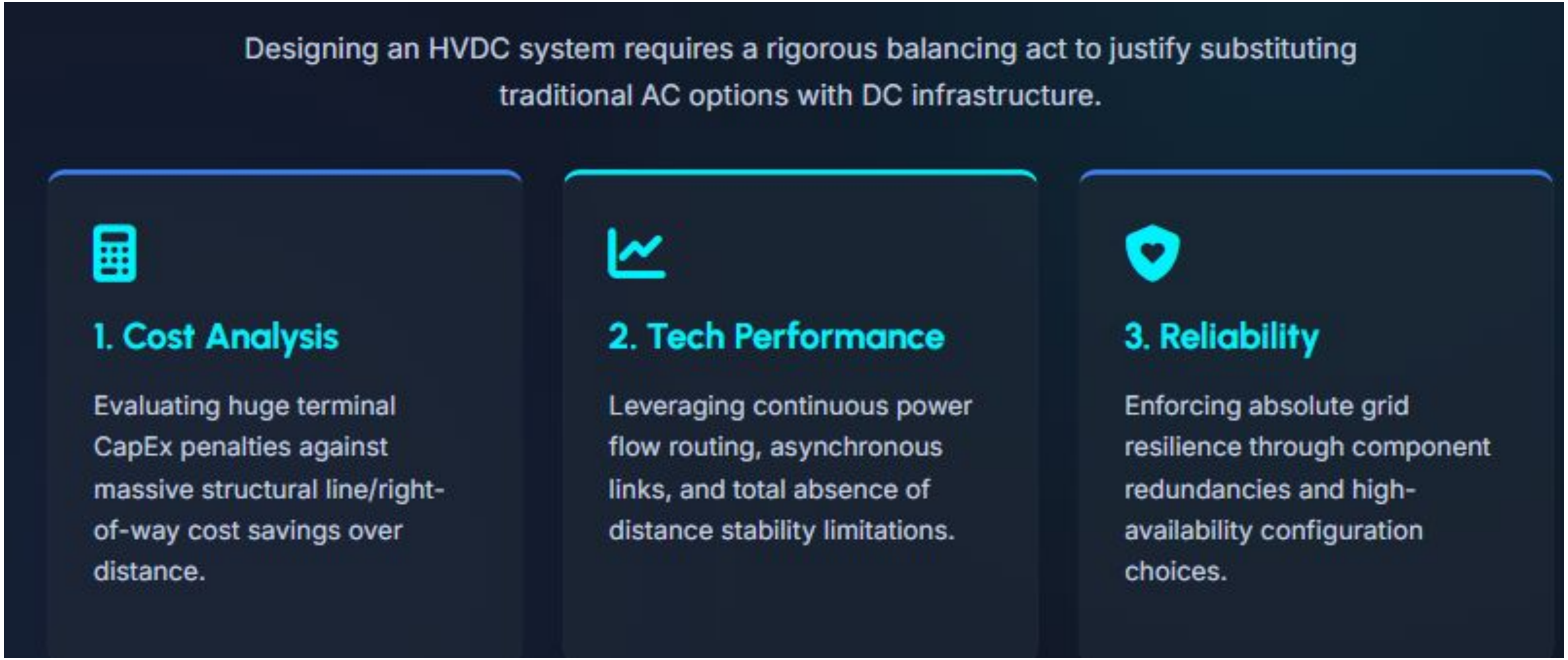


PERFORMANCE PARAMETER	ALTERNATING CURRENT (HVAC)	DIRECT CURRENT (HVDC)
Line Stability Bounds	Limited by line length and angular delta limits.	No synchronous distance stability boundaries.
Conductor Infrastructure	Requires a minimum of 3 lines for 3-phase circuits.	Requires 2 lines (Bipolar) or 1 line (Monopolar).
Power Control Capability	Functions blindly via systemic line impedances.	Fast, independent electronic control of voltage/current.
Ground/Earth Returns	Impossible due to high zero-sequence impedances.	Highly functional, continuous operation is viable.
Short Circuit Contributions	Increases overall network system fault levels.	Does not transmit or compound AC system fault currents.

Applications of HVDC transmission:

- Long distance bulk power transmission: Used for transmitting large power over long distances with low losses
- Underground or underwater cables: Suitable for submarine and underground cable transmission, especially across seas, oceans, and densely populated cities where overhead lines are not possible.
- Asynchronous interconnection of AC systems operating at different frequencies or where independent control of systems is desired
- Control and stabilization of power flows in AC ties in an integrated power system.

Planning HVDC Transmission



Designing an HVDC system requires a rigorous balancing act to justify substituting traditional AC options with DC infrastructure.

1. Cost Analysis

Evaluating huge terminal CapEx penalties against massive structural line/right-of-way cost savings over distance.

2. Tech Performance

Leveraging continuous power flow routing, asynchronous links, and total absence of distance stability limitations.

3. Reliability

Enforcing absolute grid resilience through component redundancies and high-availability configuration choices.

COST DYNAMICS & BREAK-EVEN POINT:

The Capital Trade-Off

HVDC projects carry an asymmetric financial profile compared to AC transmission alternatives:

- → **Terminals:** Exceptionally high capital expenditure (CapEx) for converters, filters, and valvehalls.
- → **Lines:** Significantly cheaper per kilometer. Requires fewer conductors and smaller support towers.
- → **Right-of-Way:** Greatly reduced physical land footprint compared to multi-circuit AC lines.

COST: THRESHOLD DISTANCES

Overhead Overhead Lines

600–800 km

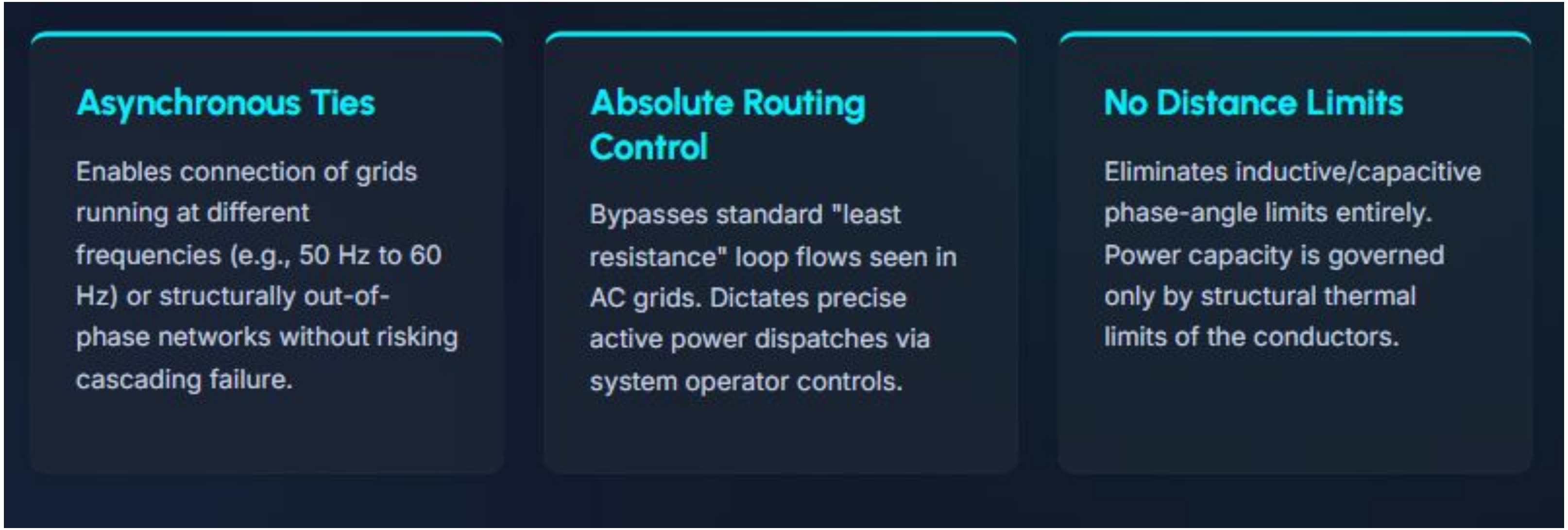
Beyond this range, line-saving costs surpass initial back-to-back station expenses, making HVDC highly optimal.

Submarine Cables

~50 km

AC charging current losses render long underwater AC cables physically impossible, lowering the break-even line sharply.

Technical Performance



Asynchronous Ties

Enables connection of grids running at different frequencies (e.g., 50 Hz to 60 Hz) or structurally out-of-phase networks without risking cascading failure.

Absolute Routing Control

Bypasses standard "least resistance" loop flows seen in AC grids. Dictates precise active power dispatches via system operator controls.

No Distance Limits

Eliminates inductive/capacitive phase-angle limits entirely. Power capacity is governed only by structural thermal limits of the conductors.

TECHNICAL PERFORMANCE: GRID SUPPORT

Dynamic System Enhancements

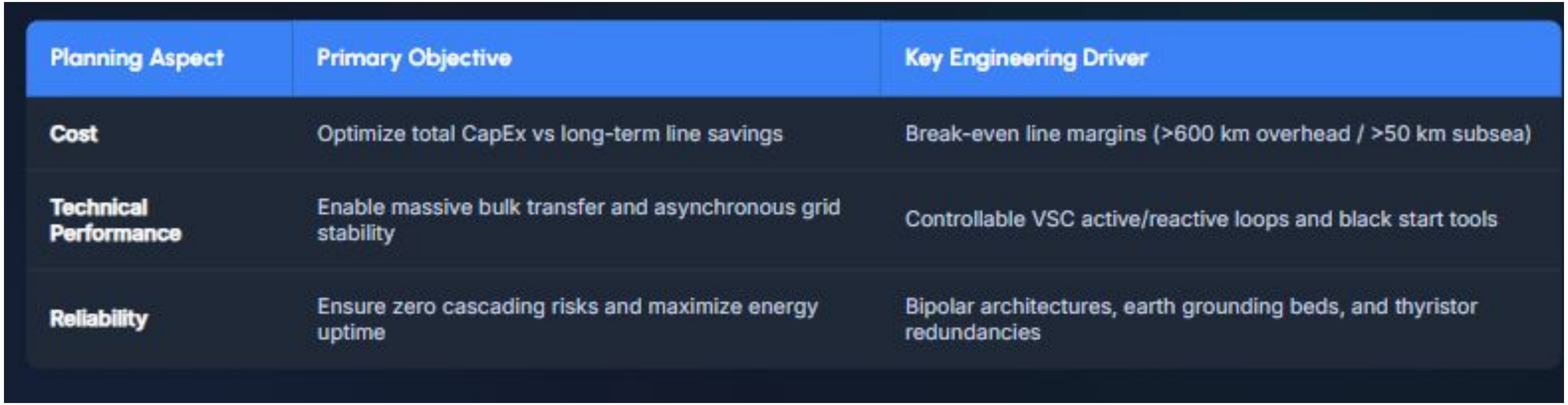
Modern Voltage Source Converter (VSC) terminals operate as highly versatile stability tools for surrounding AC grids:

→ **Reactive Power Injection:** Supplies or absorbs VARs dynamically to regulate local grid voltages during remote faults.

→ **Black Start Capability:** Provides an energized voltage source to restart completely blacked-out networks.

→ **Damping Oscillations:** Fast power adjustment modulations quickly damp out electromechanical grid oscillations.

Planning summary



Planning Aspect	Primary Objective	Key Engineering Driver
Cost	Optimize total CapEx vs long-term line savings	Break-even line margins (>600 km overhead / >50 km subsea)
Technical Performance	Enable massive bulk transfer and asynchronous grid stability	Controllable VSC active/reactive loops and black start tools
Reliability	Ensure zero cascading risks and maximize energy uptime	Bipolar architectures, earth grounding beds, and thyristor redundancies

Modern trends in D.C. Transmission :

The recent developments are expected to improve reliability and reduce the cost of HVDC valves. These are mainly :

- Development in high power semiconductor devices - these include direct light triggered thyristors (LTT) and metal- oxide semiconductor controlled thyristors(MCT)
- Better cooling techniques such as forced vaporization (two phase flow) as a means of reducing thermal resistance between the heat sink and the ambient.
- Suspension of quadrivalve assembly from ceiling to withstand seismic forces.

Analysis of the Graetz Circuit (6-Pulse Bridge)

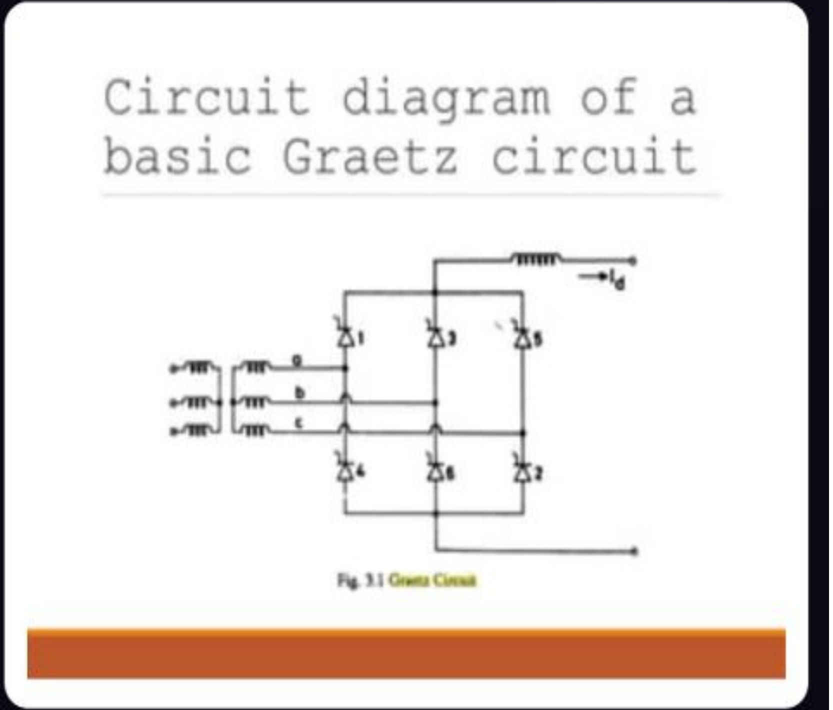
Operational Mechanisms

The standard 6-pulse bridge forms the foundational building block of classical HVDC conversion systems.

- Comprises 6 controlled valves arranged into positive and negative commutation pairings.
- Each valve handles conduction for a 120° window following a defined sequence: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6$.
- Produces a characteristic DC output ripple frequency of $6f$ (e.g., 300 Hz for a 50 Hz line).

Average No-Load Voltage:

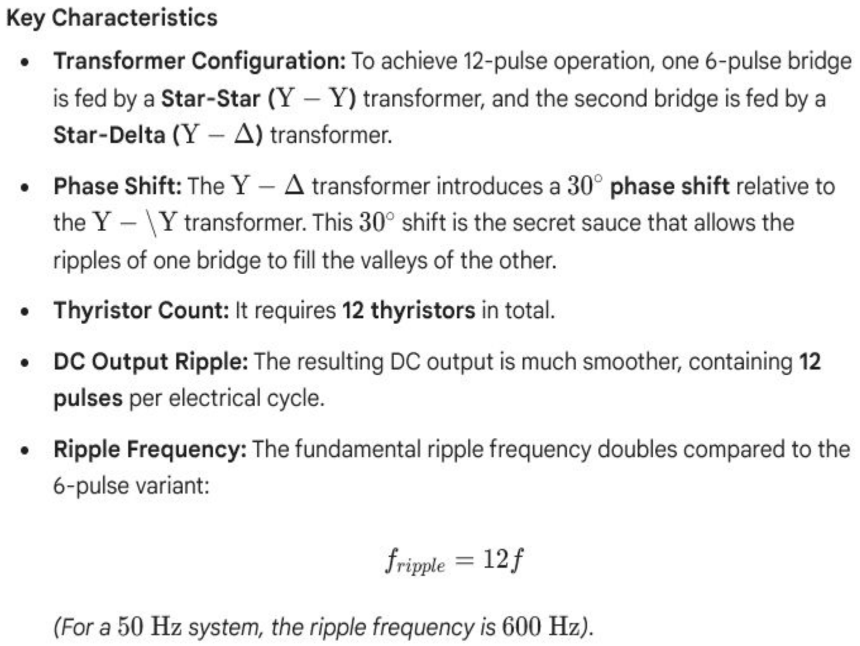
$$V_{d0} = \frac{3\sqrt{2}}{\pi}E_{LL} \approx 1.35E_{LL}$$



Circuit diagram of a basic Graetz circuit

Fig. 3.1 Graetz Circuit

12-Pulse Converter

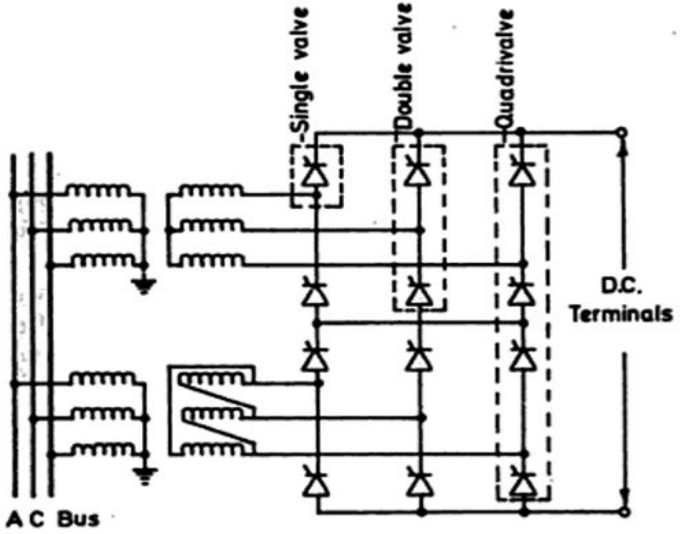


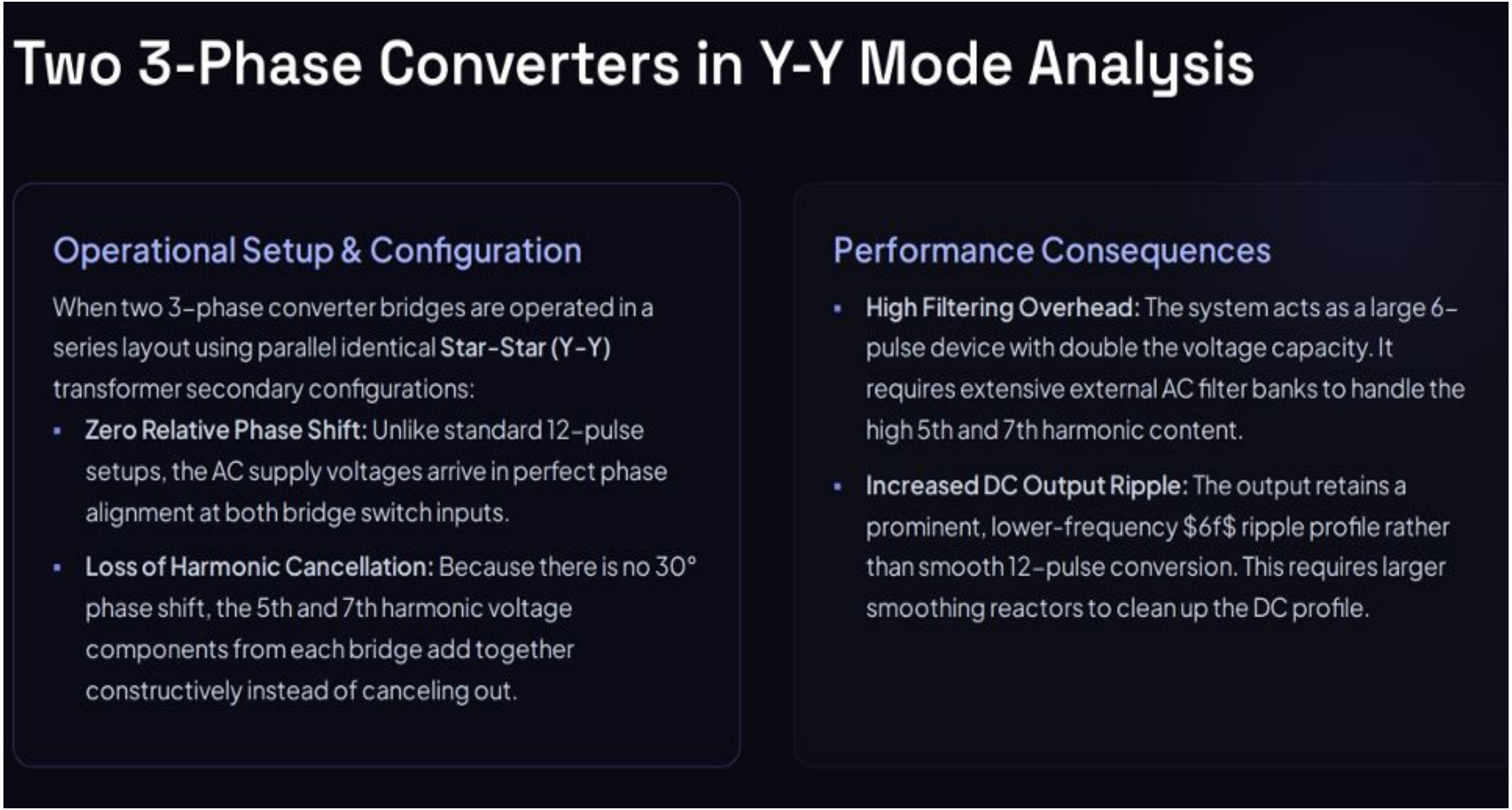
Key Characteristics

- **Transformer Configuration:** To achieve 12-pulse operation, one 6-pulse bridge is fed by a **Star-Star ($\mathrm{Y}-\mathrm{Y}$)** transformer, and the second bridge is fed by a **Star-Delta ($\mathrm{Y}-\Delta$)** transformer.
- **Phase Shift:** The $\mathrm{Y}-\Delta$ transformer introduces a 30° **phase shift** relative to the $\mathrm{Y}-\backslash\mathrm{Y}$ transformer. This 30° shift is the secret sauce that allows the ripples of one bridge to fill the valleys of the other.
- **Thyristor Count:** It requires **12 thyristors** in total.
- **DC Output Ripple:** The resulting DC output is much smoother, containing **12 pulses** per electrical cycle.
- **Ripple Frequency:** The fundamental ripple frequency doubles compared to the 6-pulse variant:

$$f_{ripple} = 12f$$

(For a $50\ \mathrm{Hz}$ system, the ripple frequency is $600\ \mathrm{Hz}$).





Two 3-Phase Converters in Y-Y Mode Analysis

Operational Setup & Configuration

When two 3-phase converter bridges are operated in a series layout using parallel identical **Star-Star (Y-Y)** transformer secondary configurations:

- **Zero Relative Phase Shift:** Unlike standard 12-pulse setups, the AC supply voltages arrive in perfect phase alignment at both bridge switch inputs.
- **Loss of Harmonic Cancellation:** Because there is no 30° phase shift, the 5th and 7th harmonic voltage components from each bridge add together constructively instead of canceling out.

Performance Consequences

- **High Filtering Overhead:** The system acts as a large 6-pulse device with double the voltage capacity. It requires extensive external AC filter banks to handle the high 5th and 7th harmonic content.
- **Increased DC Output Ripple:** The output retains a prominent, lower-frequency $6f$ ripple profile rather than smooth 12-pulse conversion. This requires larger smoothing reactors to clean up the DC profile.

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Thank you