



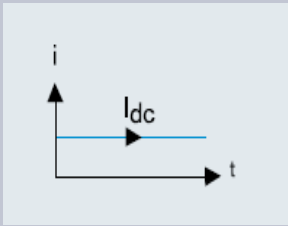
Basic Principles of HVDC



Manikandan S
Dy.Mgr, HVDC KOLAR

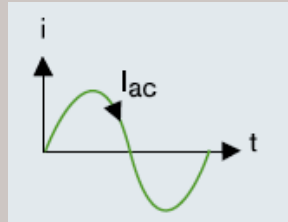
The War of the Currents

Direct Current DC



- **Thomas Edison**

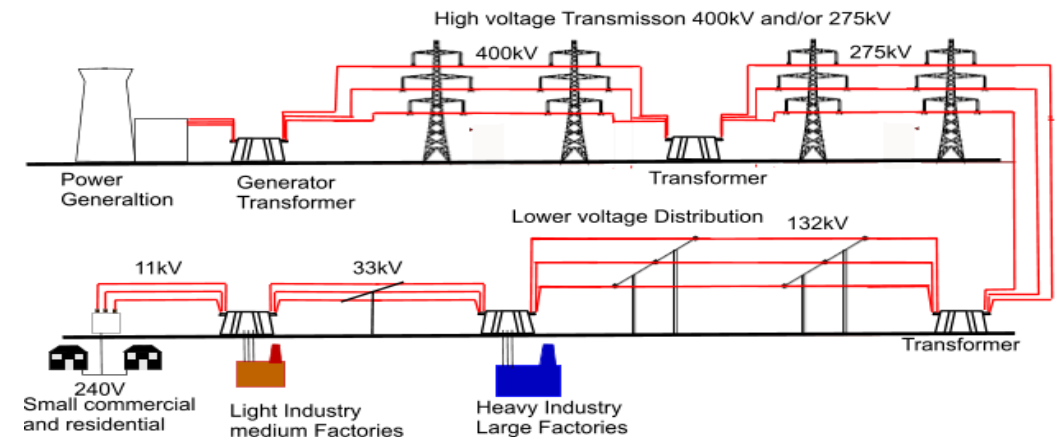
Alternating Current AC



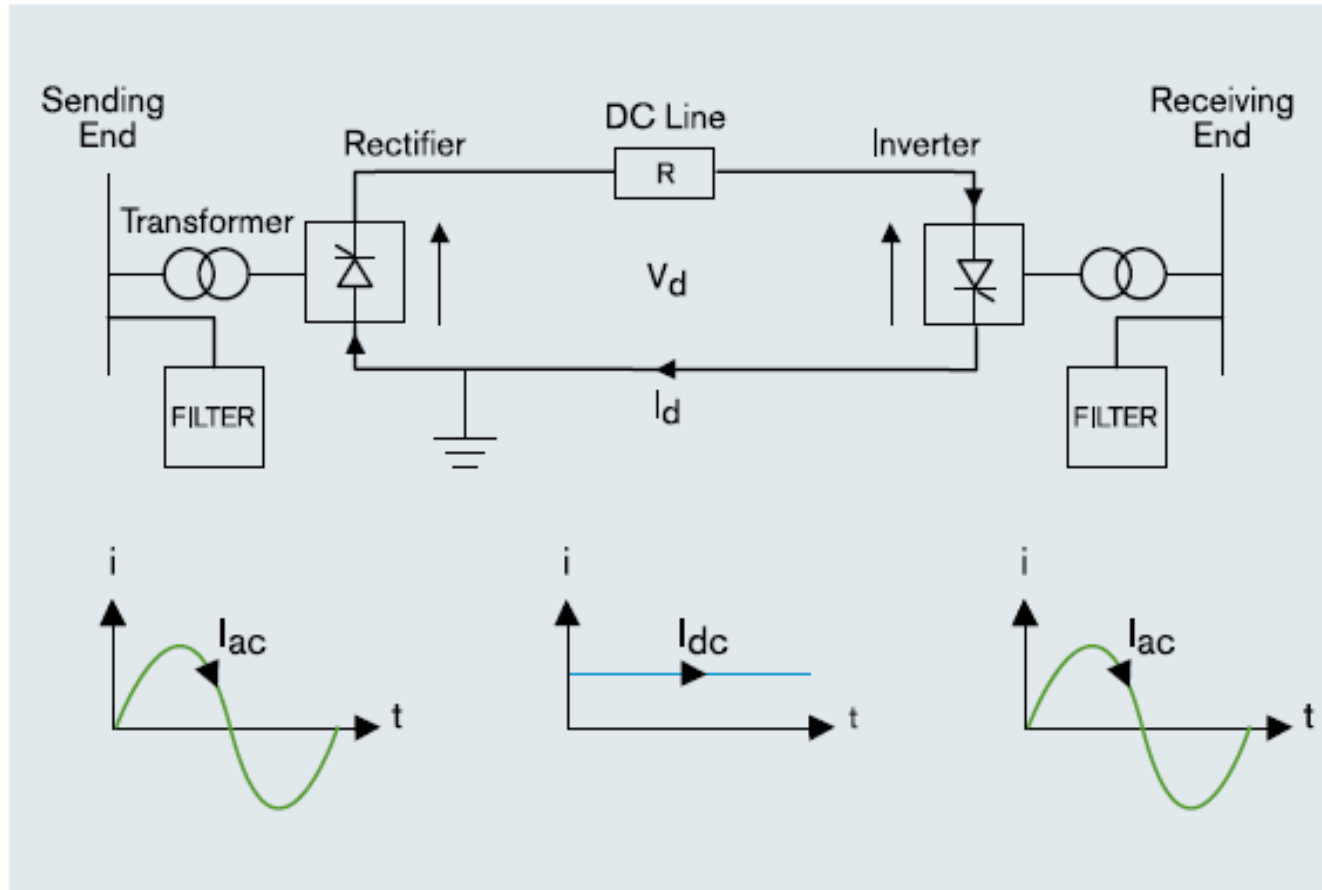
- **Nikola Tesla**

Finally, AC (alternating current) was globally adopted for power transmission because of

- Ease to Step up or down using transformer
- Rugged Squirrel cage Induction motors
- Easy to interrupt than DC Current



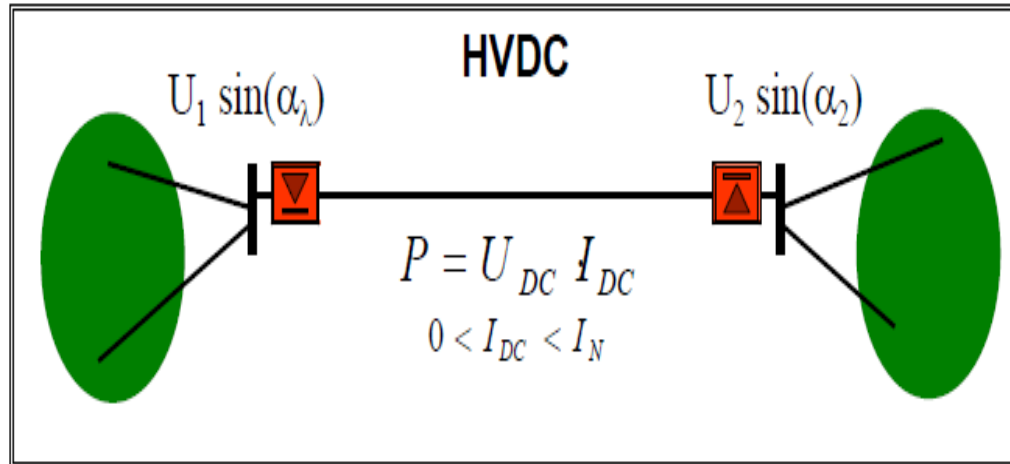
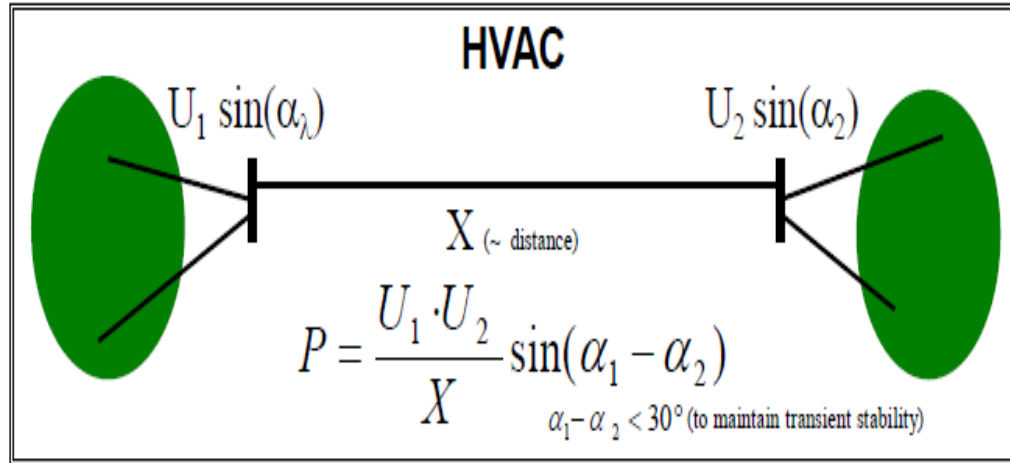
HVDC - High Voltage Direct Current



HVDC TRANSMISSION

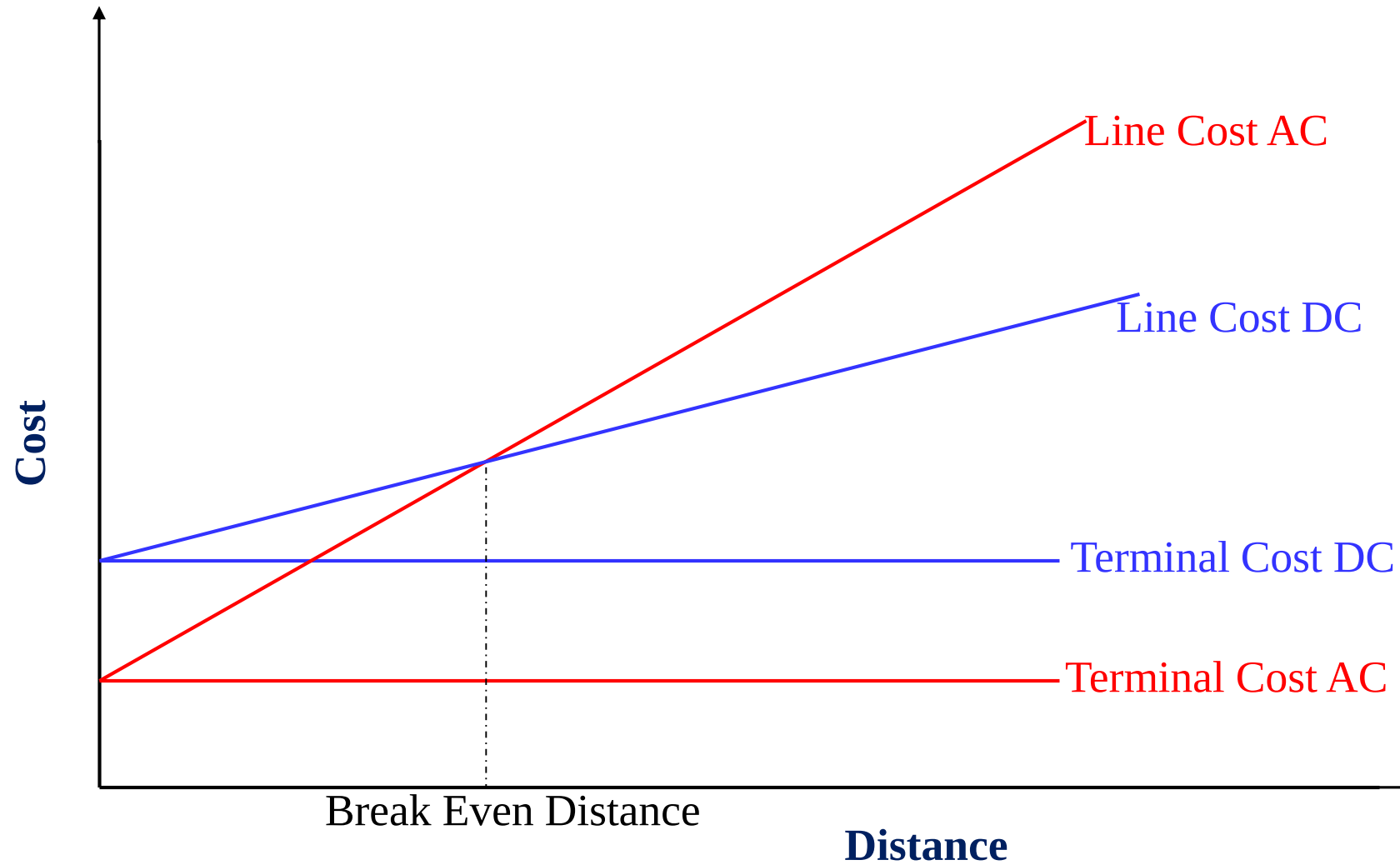
- Convert AC into DC (**Rectifier**)
- Transmit DC
- Convert DC into AC (**Inverter**)

Interconnection - HVAC VS HVDC



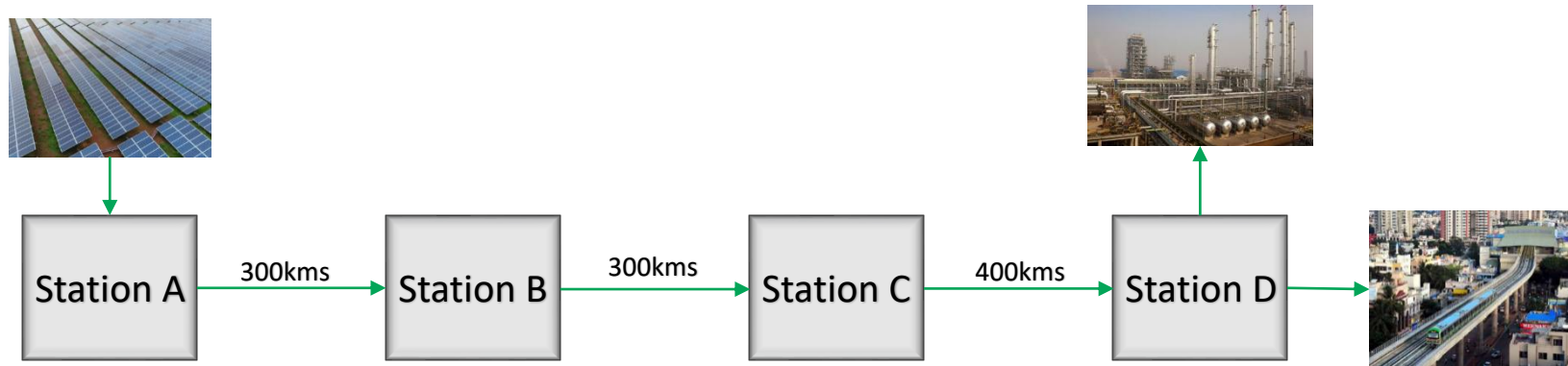
- HVDC Power flow is independent of
Line reactance -X (Distance)
System angles – α_1, α_2
- HVDC Power flow can be controlled by
controlling the difference of DC voltage
- HVDC Power flow direction can be changed by
changing the polarity of DC Voltage

Break Even Distance

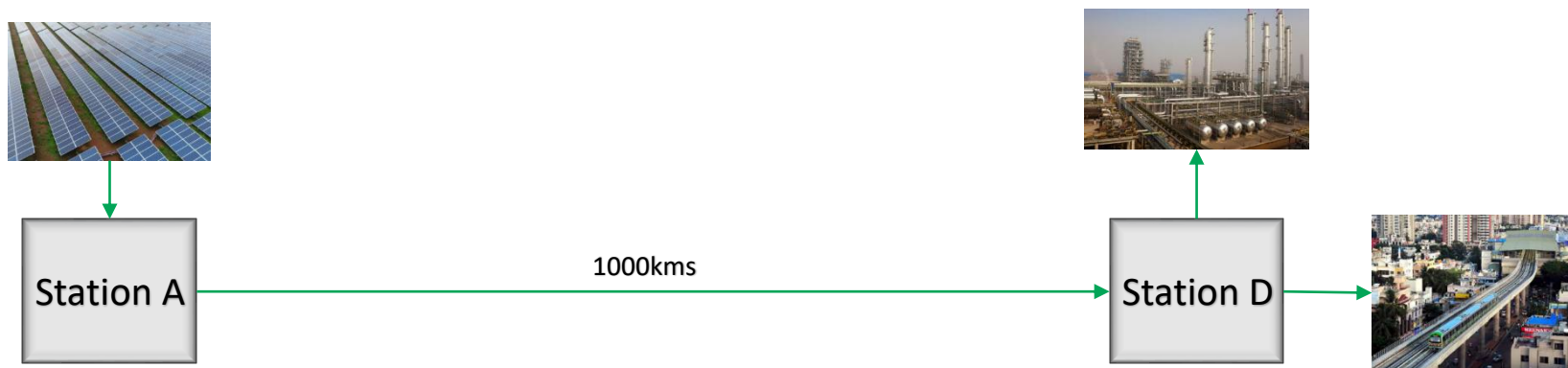


765kV HVAC (AIS) Vs 800kV HVDC 6GW@ 1000kms Point to Point Transmission

765kV HVAC (AIS) - 6GW@ 1000kms TRANSMISSION with 2 Nos D/c Towers

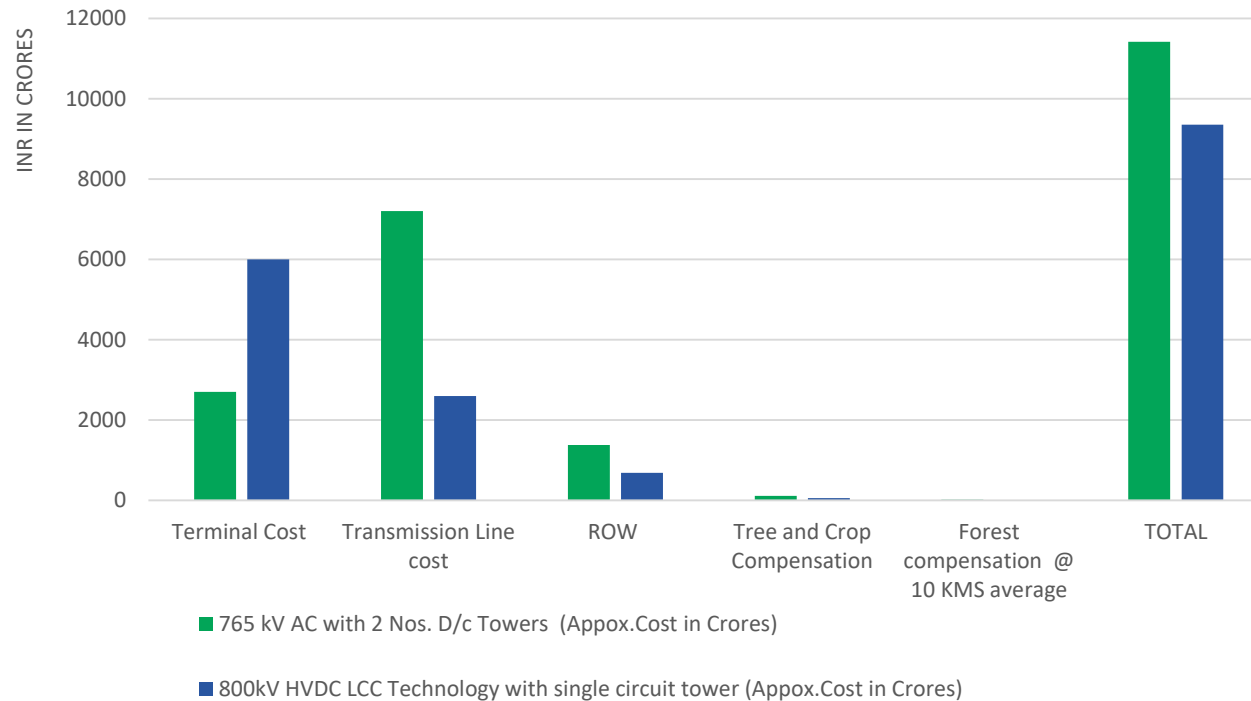


800kV HVDC - 6GW@ 1000kms TRANSMISSION with Single tower with DMR



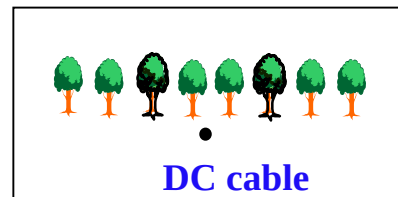
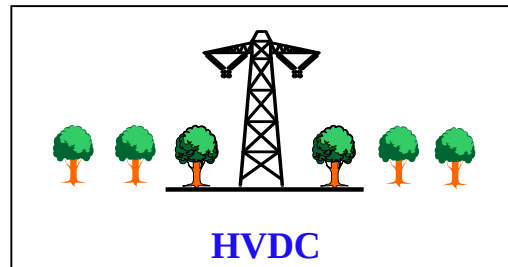
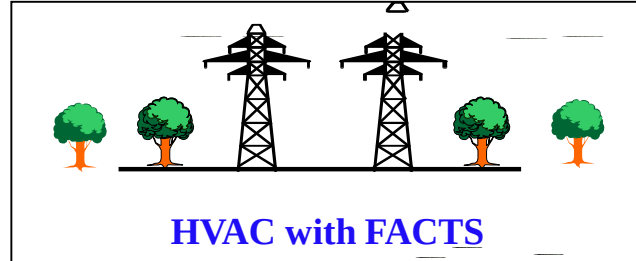
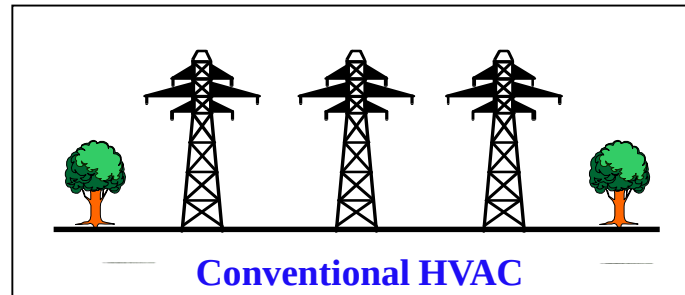
765kV HVAC (AIS) Vs 800kV HVDC

6GW@ 1000kms Point to Point Transmission



Tentatively overall cost of 765kV HVAC is around 2000 INR Crores higher than 800kV HVDC for 6GW transmission @1000kms.

Environmental Impact

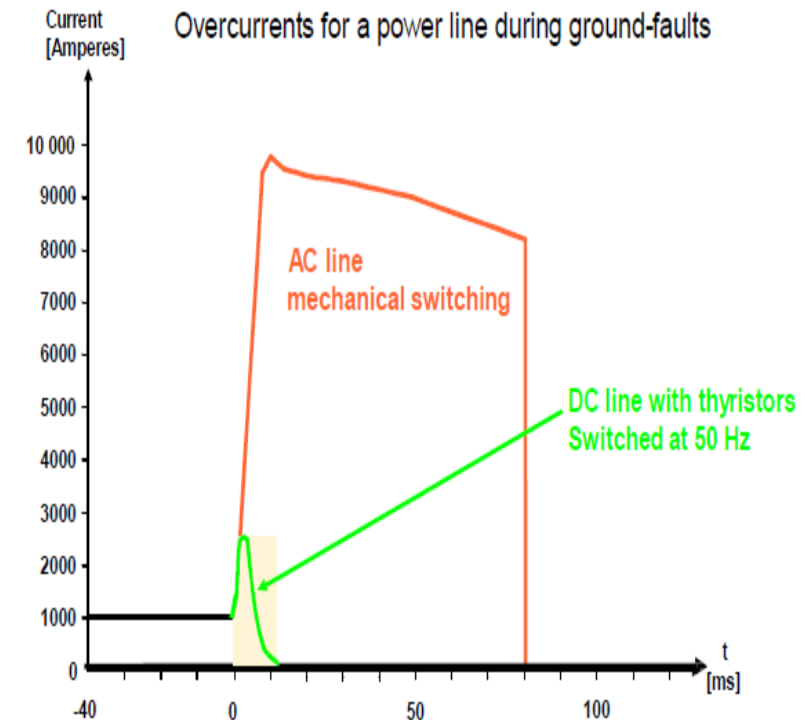


Lesser right of way (ROW) requirement as compared to HVAC

Advantages of HVDC Transmission

- Exact and fast Power flow control
- Asynchronous connection
- Less environmental impact
- Low losses for long distance transmissions
- Stability control
- Cable transmission

Controllability Power Semiconductor + micro processor



History of HVDC

- **1954 - First commercial HVDC link with mercury-arc valves**
100 kV, 20 MW, 100 kM HVDC submarine cable
- **1970 - First thyristor valves for HVDC**
80kV, 320 MW BtB Link at Eel River station
- **1997 - First commercial HVDC VSC Link(IGBT)**
Hällsjön and Grängesberg Link



Types of HVDC Schemes

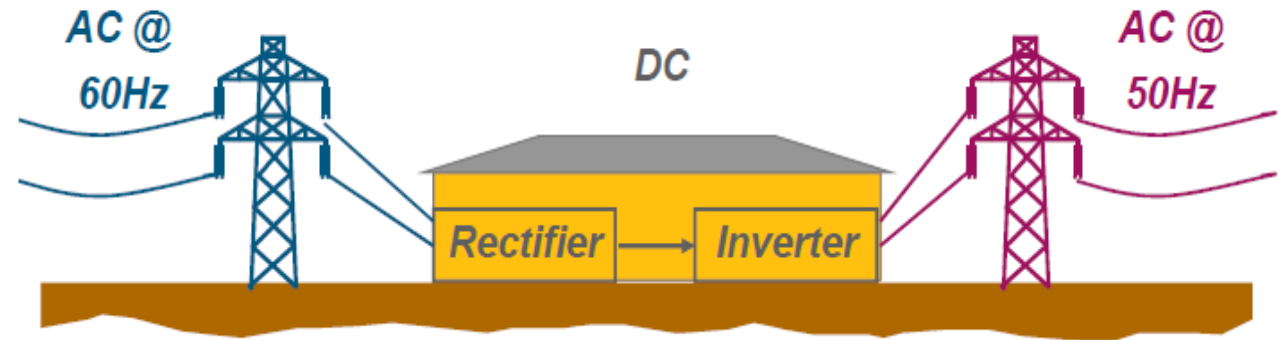
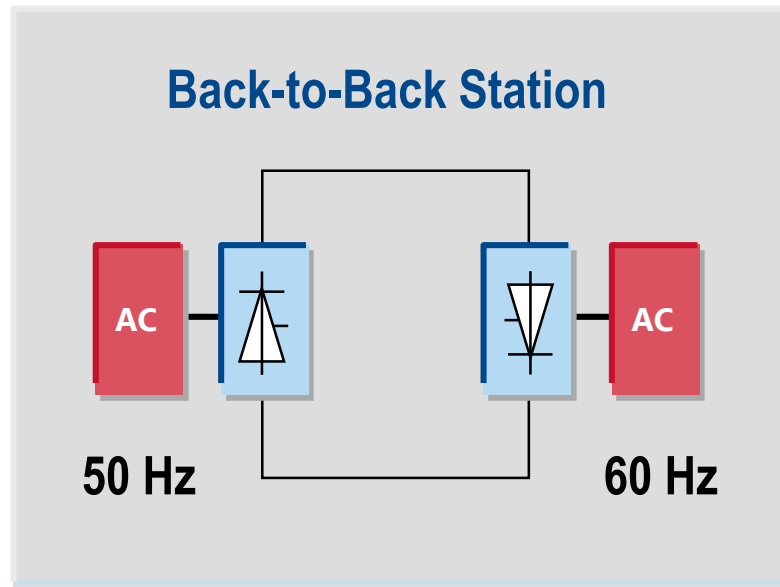
- HVDC Back to Back Link
- HVDC Point to Point Link
 - HVDC Submarine Link
 - HVDC Urban Infeed
 - HVDC Long Distance Link
- HVDC Multi terminal Link



HVDC Schemes – HVDC BtB Link

- To interconnect asynchronous systems or grids with different frequencies/voltages.
- Rectifier and Inverter are located in same station

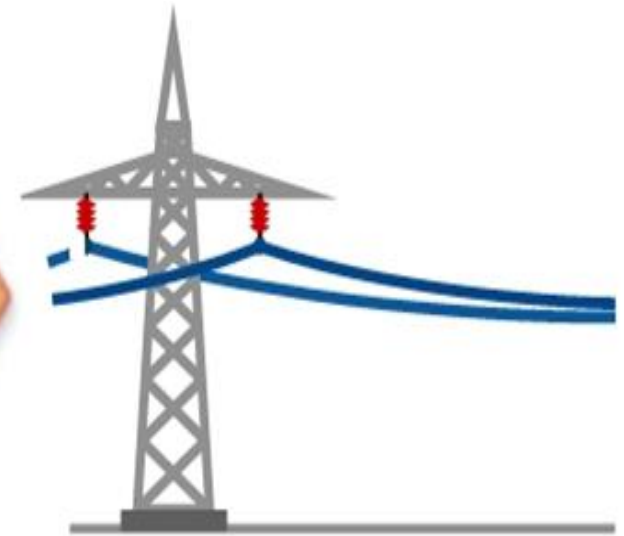
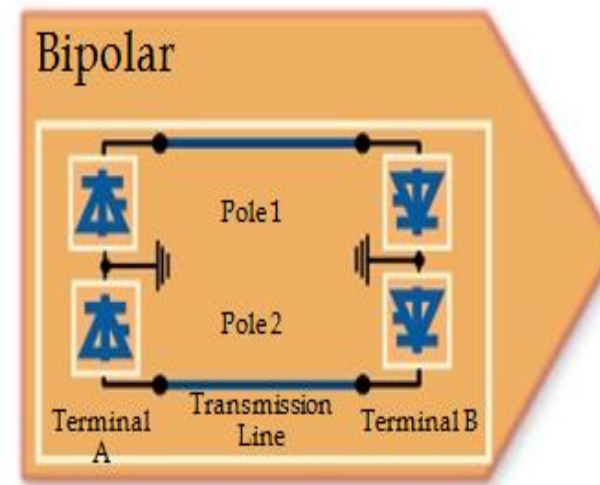
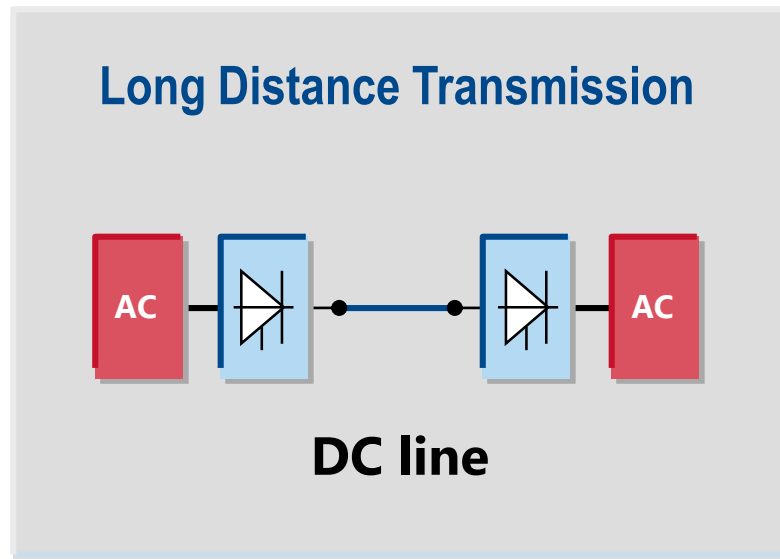
Solution: HVDC Back-to-Back Link



HVDC Schemes – Point to Point Link

- Economical & Environmental solution to transfer bulk power over long distance.
- Super Power Transmission highway

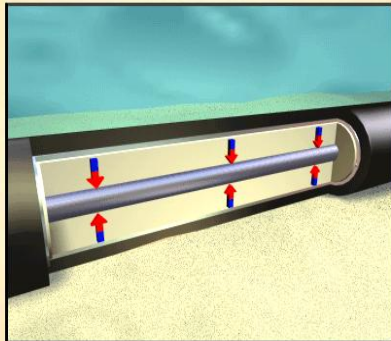
Solution: HVDC Long Distance Link



HVDC Schemes – Point to Point Link

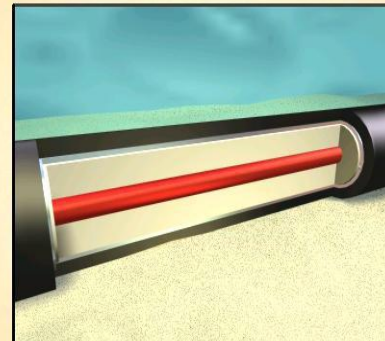
- **Urban Infeed**
- Less ROW & better Controllability
- No increment in short circuit level

Why not an AC cable transmission?



AC cable transmission = High capacitive losses.

Why not an AC cable transmission?

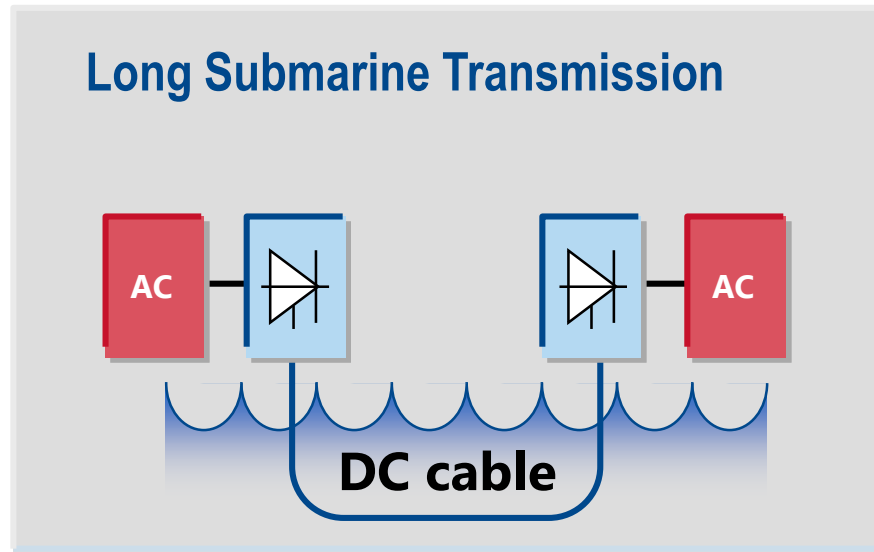


DC cable transmission = No capacitive losses.

HVDC Schemes – Point to Point Link

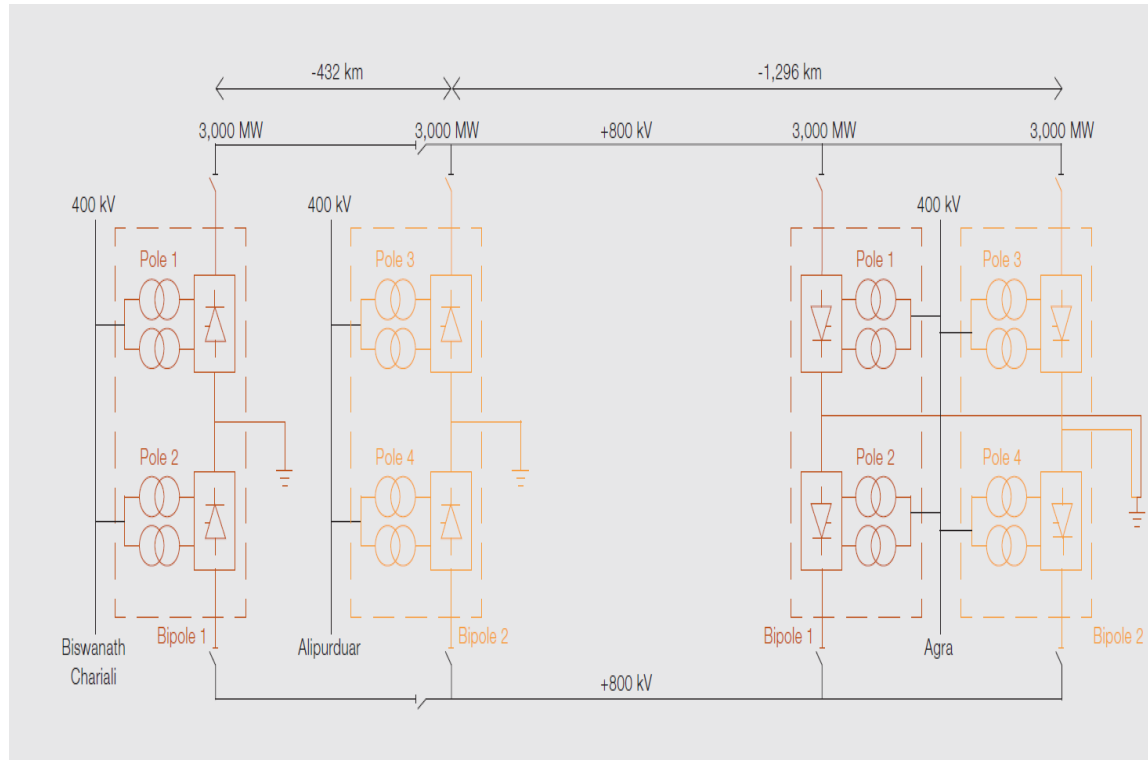
- Economical and feasible solution for connecting submarine cable applications, such as offshore wind farms - Shorter distances such as a few 10km/miles
- Renewable Integration

Solution: HVDC Submarine Link

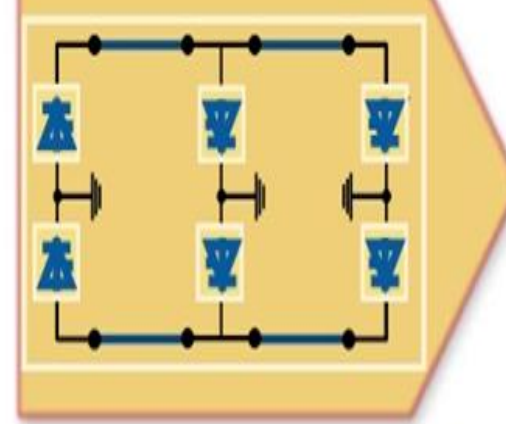


HVDC Schemes – Multi terminal Link

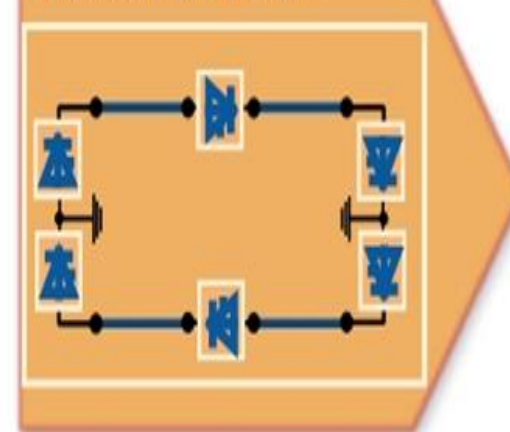
- Interconnection of multiple HVDC converters and facilitates the future expansion into HVDC grids.
- Off shore wind Integration



Terminals in Parallel



Terminals in Series



Journey of HVDC in POWERGRID

1989

- **70kV, 2 x 250 MW VINDHYACHAL BTB**
- ABB, LCC Technology
- First BTB Link in India, Connects WR and NR Grid

1990

- **500kV, 1500 MW RIHAND DADRI HVDC**
- ABB, LCC Technology, 814 km
- First Bipole HVDC Link in India

1997

- **205kV, 2 x 500 MW BHADRAWATI BTB**
- Alstom, LCC Technology
- Connects WR and SR Grid

1999

- **205/177kV, 2 x 500 MW VIZAG BTB**
- ABB & Alstom, LCC Technology
- Connects ER and SR Grid

2002

- **205kV, 1 x 500 MW PUSAULI BTB**
- Alstom, LCC Technology
- Connects NR and ER Grid

Journey of HVDC in POWERGID

2002

- **500kV, 2500 MW TALCHER KOLAR HVDC**
- Siemens, LCC Technology, 1368 km
- Connects SR and ER Grid

2010

- **500kV, 2500 MW BALIA BHIWADI HVDC**
- SIEMENS, LCC Technology, 780 km
- First Light Triggered Thyristor and Hot spare Converter Tx. used

2015

- **800kV, 6000 MW NEA MULTI TERMINAL HVDC**
- ABB, LCC Technology, 1728 km
- First UHV Multi terminal HVDC in the world.

2017

- **800kV, 6000 MW CHAMPA KURUKSHETRA HVDC**
- GE, LCC Technology, 1365 km
- First Parallel Bipole with DMR

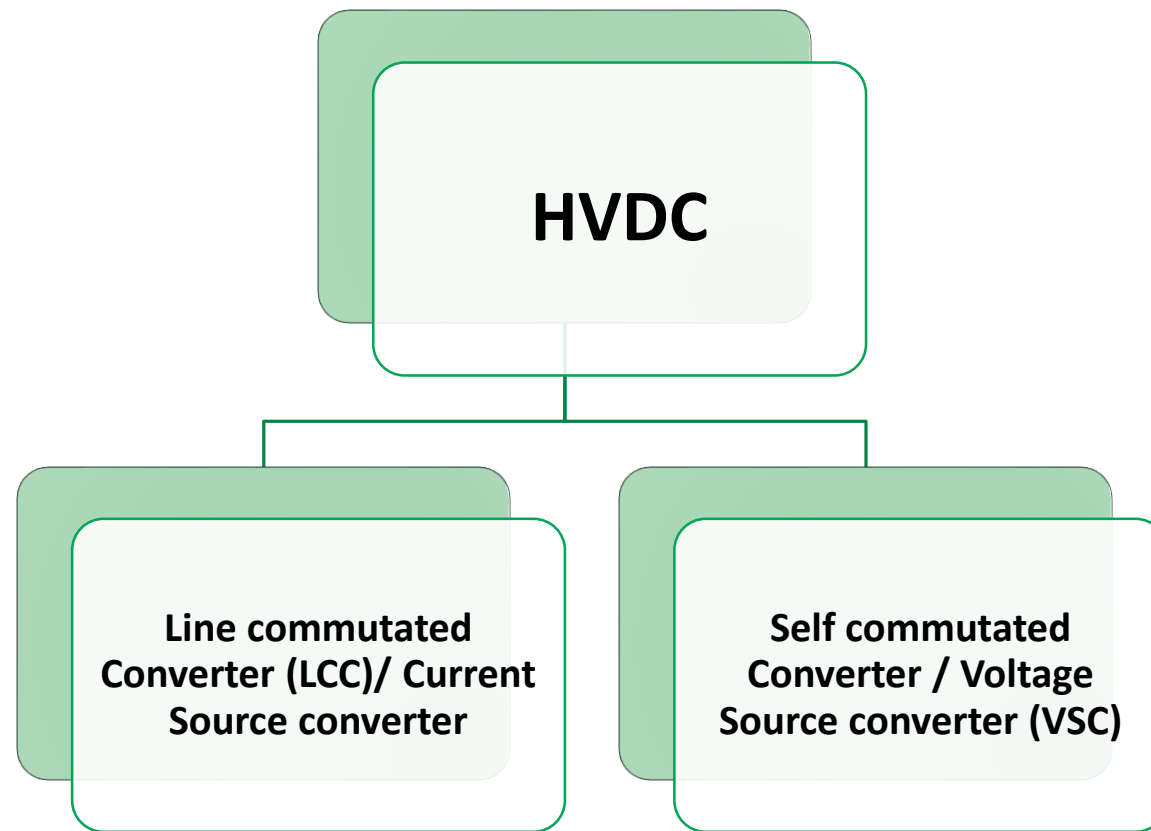
2020

- **800kV, 6000 MW RAIGARH PUGALUR HVDC**
- ABB, LCC Technology, 1750 km
- Parallel Bipole with DMR

2021

- **320kV, 2 x 1000 MW PUGALUR THRISSUR HVDC**
- Siemens, VSC Technology, 165 km (Cable- 27 km)
- First VSC and Combination of OHL & Cable link in India

Types of HVDC Converters



Line Commutated converter (LCC)

Switching Device : Thyristor

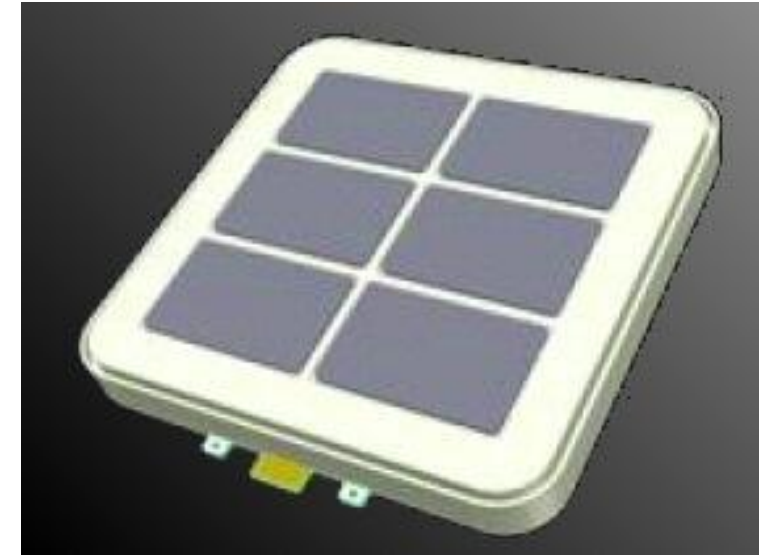
- Also known as Current source converter
- Thyristor - Semi controlled device
- Control system controls only “turn on” instant i.e. delaying firing
- “Turn off” is controlled by line voltage
- No Black start capability
- Converter can control active power / no reactive power control
- Requires AC filters



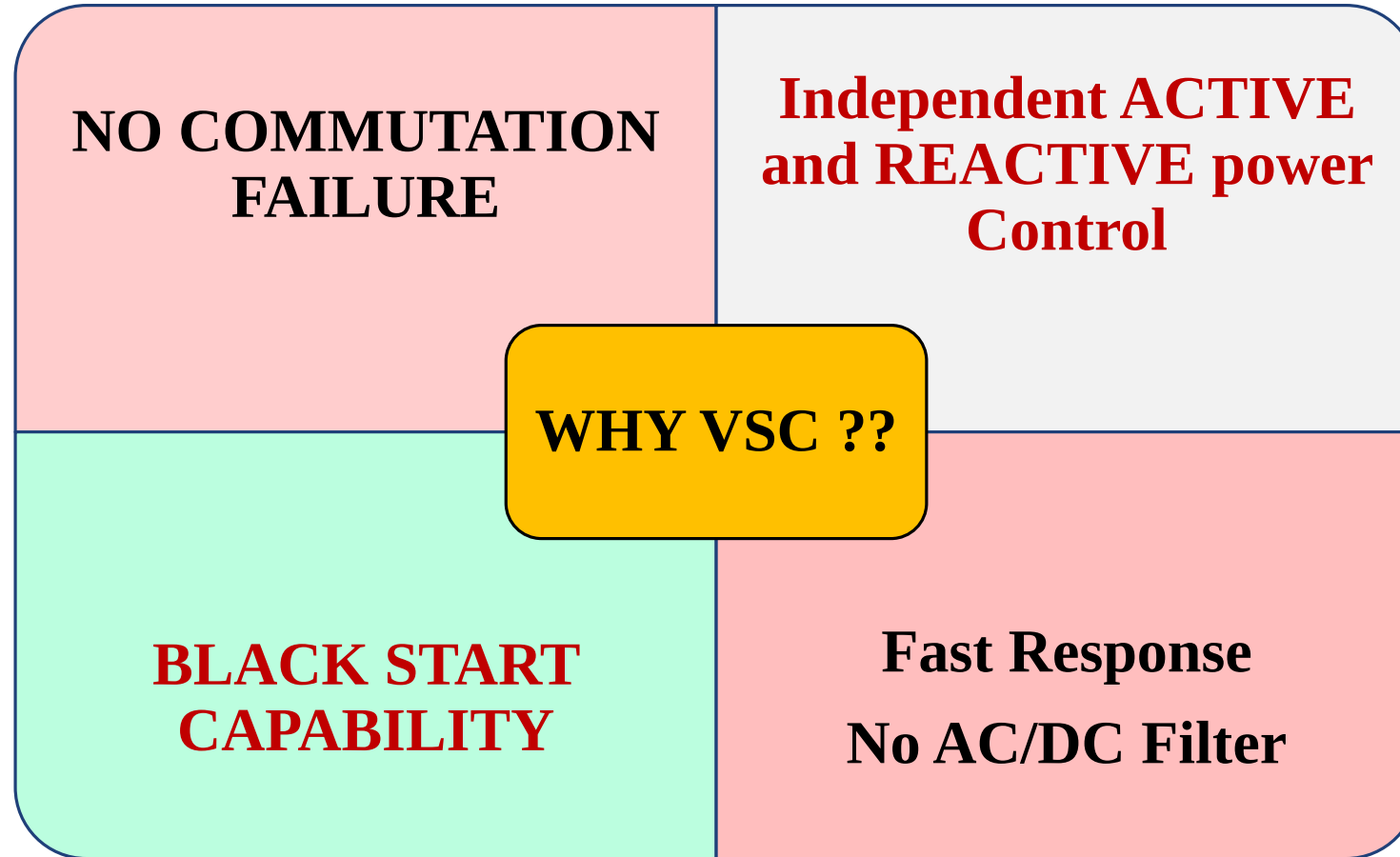
Voltage Source Converter (VSC)

Switching Device : IGBT

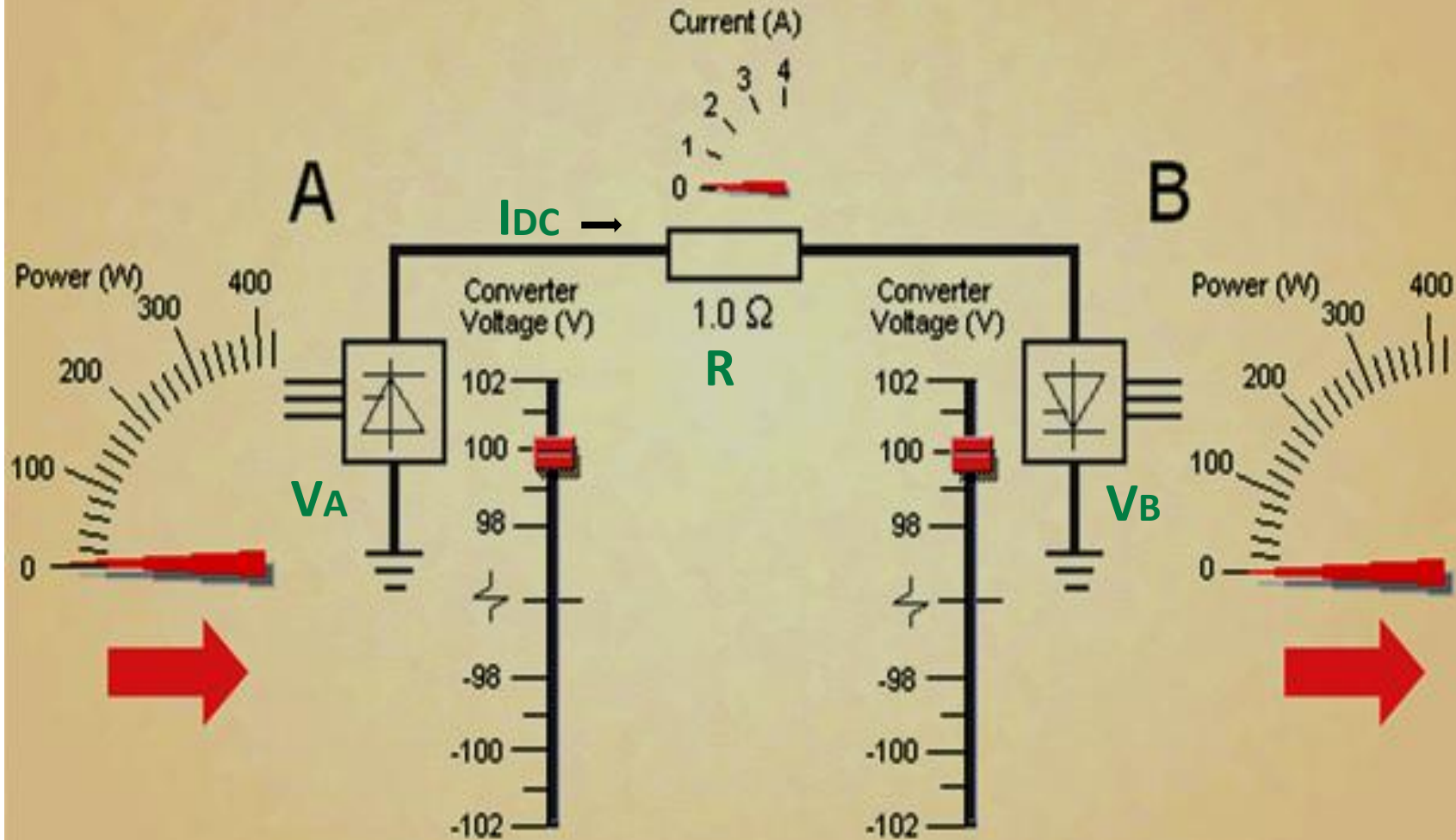
- Control system controls “turn on” & “turn off” instant
- Black start capability
- Converter can control active power & reactive power
- MMC & PWM
- No requirement of AC filters/ Less space



Advantages of VSC



How does HVDC work?



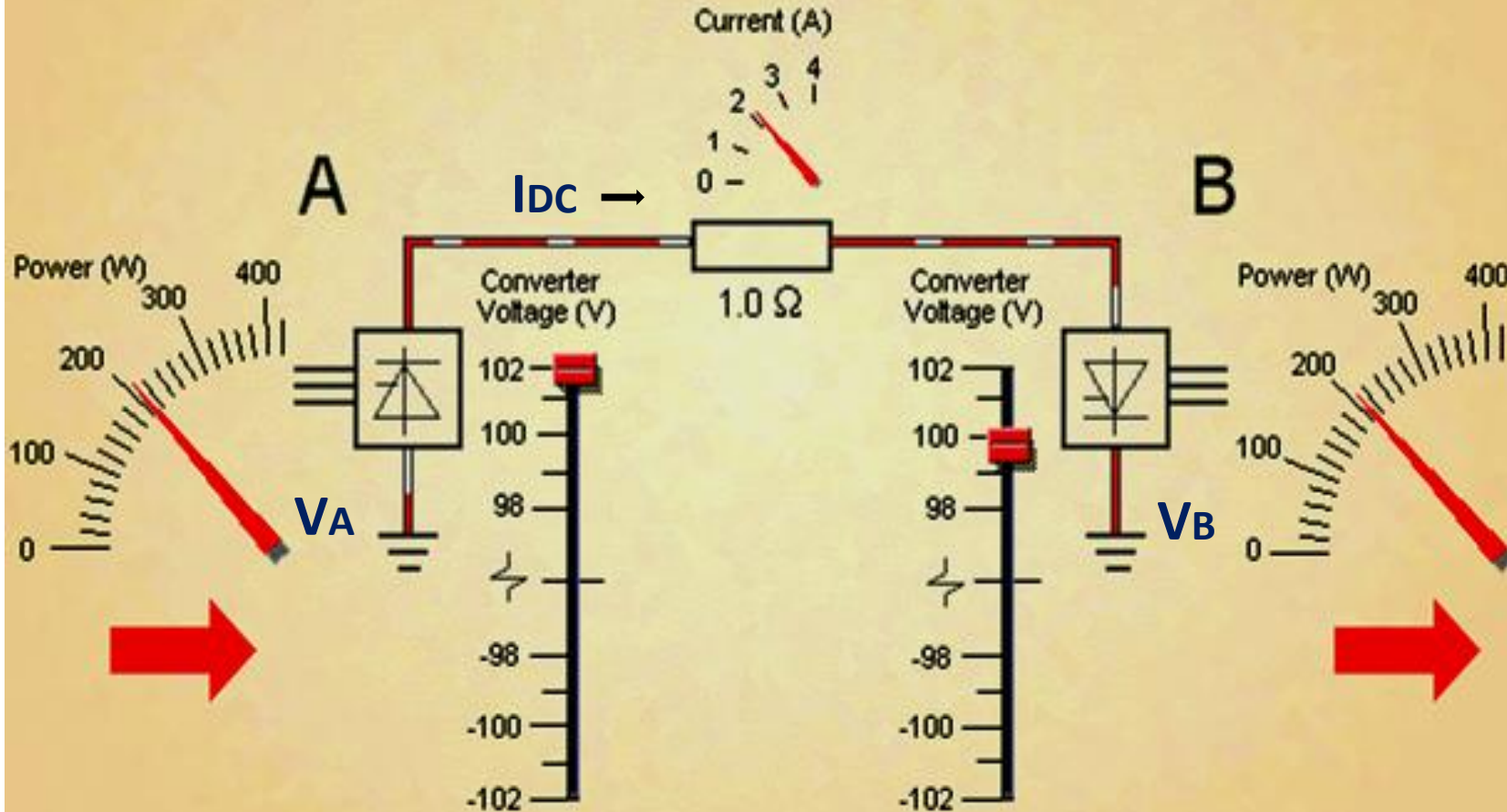
$$I_{DC} = (V_A - V_B) / R$$

$$P_A = V_A * I_{DC}$$

$$P_B = V_B * I_{DC}$$

$$P_L = I_{DC} * I_{DC} * R_L$$

How does HVDC work?



NORMAL POWER DIRECTION

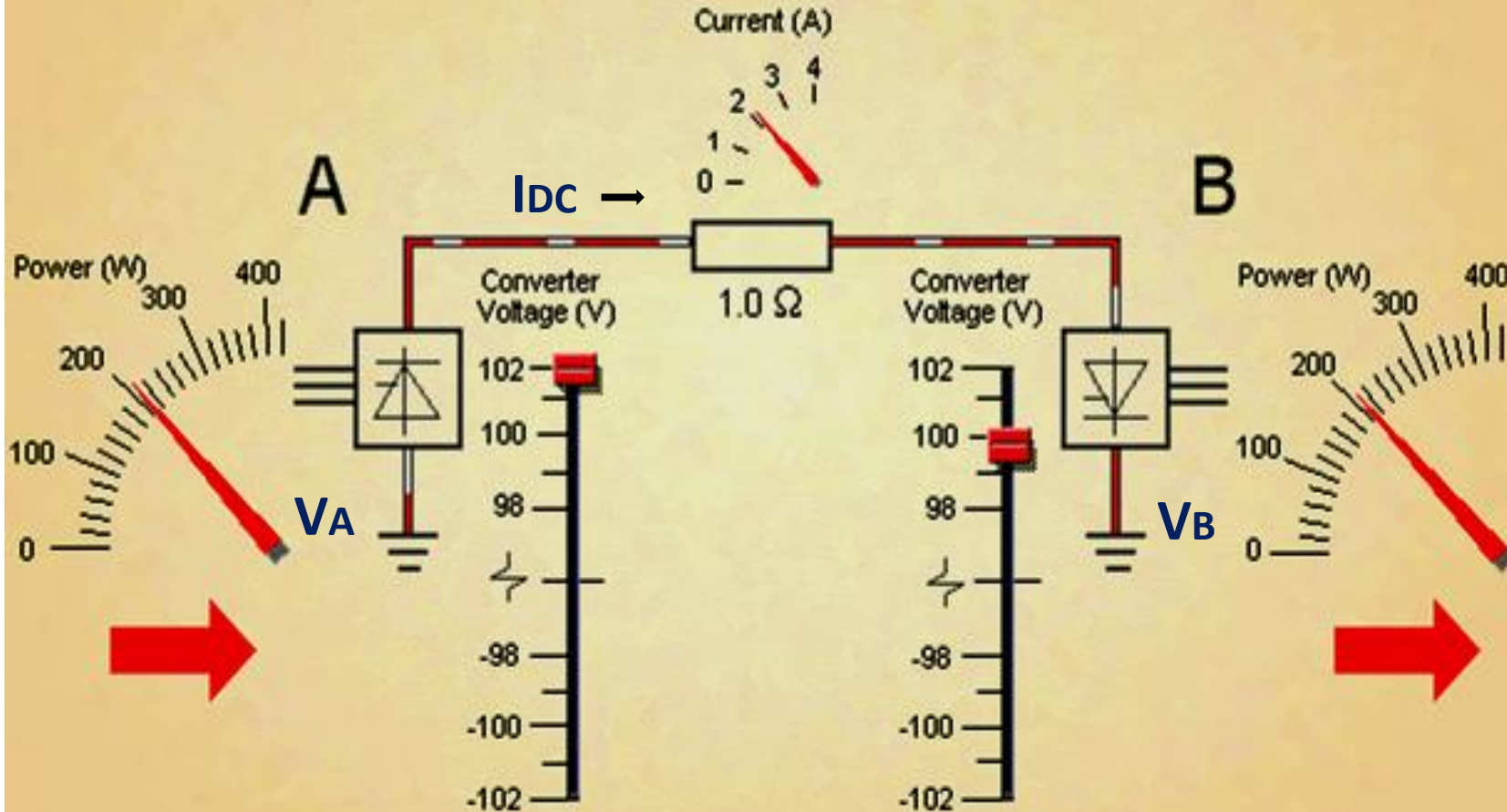
$$I_{DC} = (102 - 100) / 1 = 2 \text{ A}$$

$$P_A = 102 * 2 = 204 \text{ W}$$

$$P_B = 100 * 2 = 200 \text{ W}$$

$$P_L = 2 * 2 * 1 = 4 \text{ W}$$

How does HVDC work?



NORMAL POWER DIRECTION

$$I_{DC} = (102 - 101) / 1 = 1 \text{ A}$$

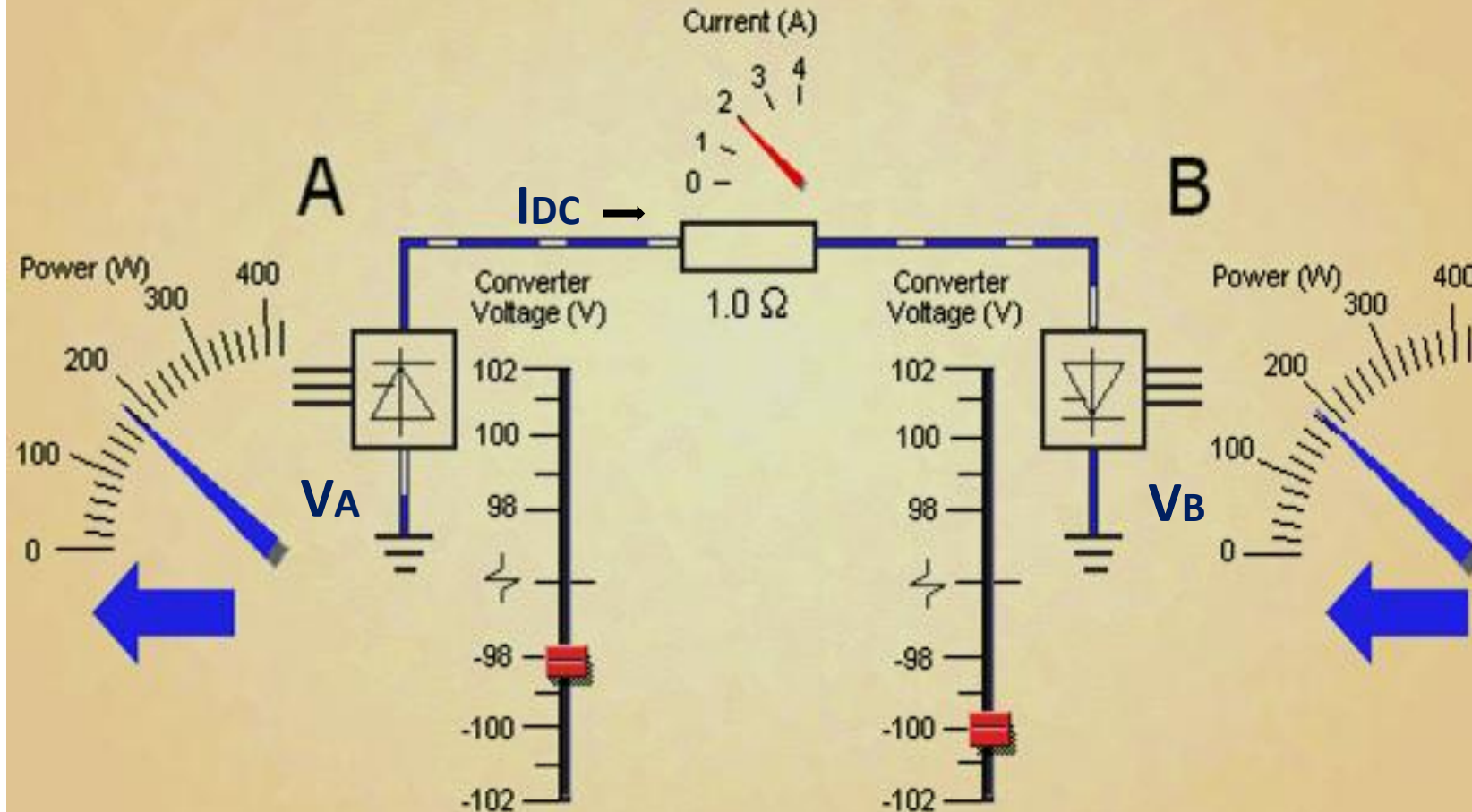
$$P_A = 102 * 1 = 102 \text{ W}$$

$$P_B = 101 * 1 = 101 \text{ W}$$

$$P_L = 1 * 1 * 1 = 1 \text{ W}$$

$$U_d = 1.35 * U_{ac.sec} * \cos \alpha$$

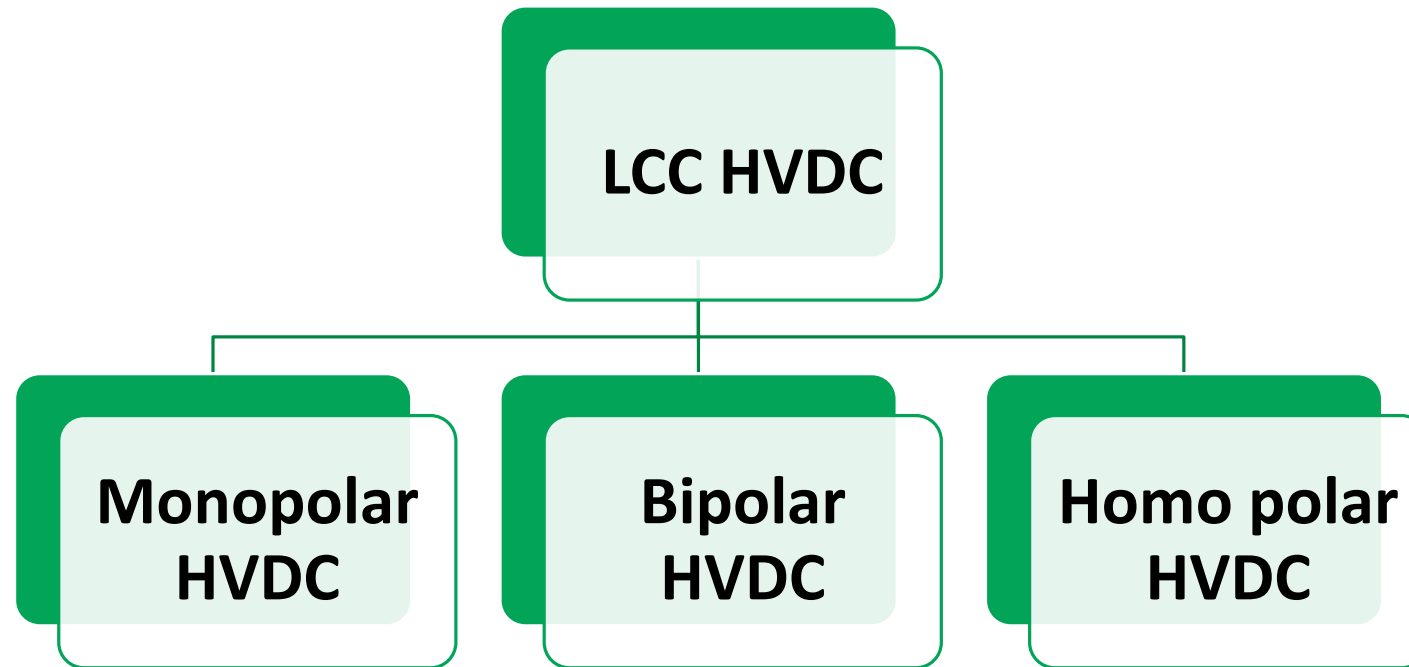
How does HVDC work?



REVERSE POWER DIRECTION

- Power flow reversed by reversing the converter voltage polarity.
- Current direction remains same since thyristor is unidirectional device.

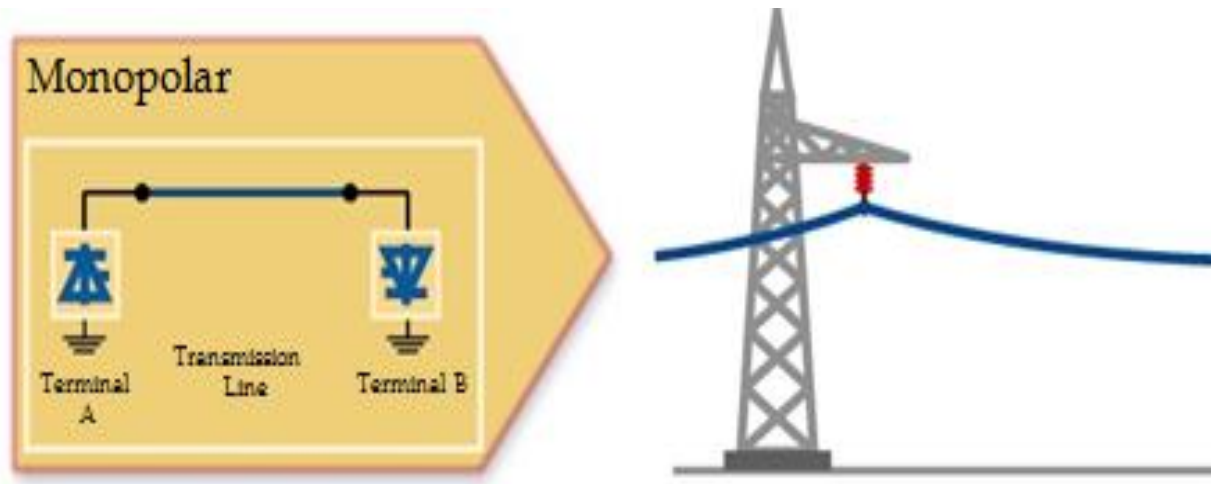
Types of LCC Configuration



Types of LCC Configuration

Mono Polar System:

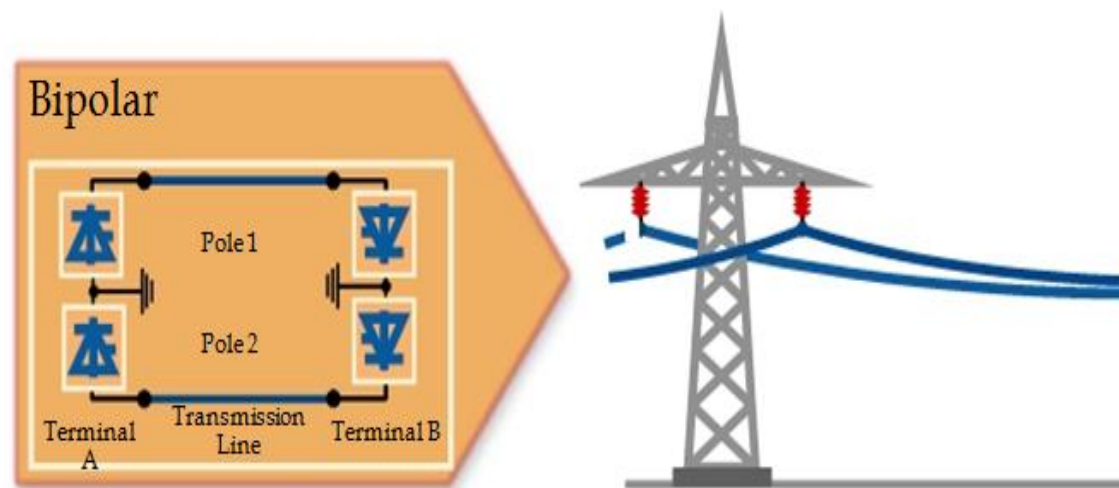
- One pole, one conductor for transmission and current return path is through earth.
- Mainly used for submarine cable transmission.



Types of LCC Configuration

Bipolar System:

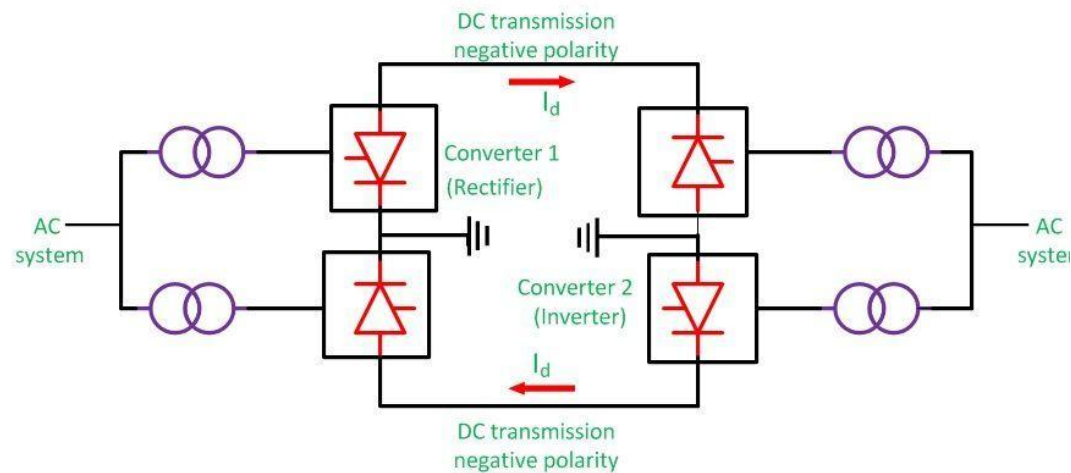
- Two poles, two conductors in transmission line, one positive with respect to earth & other negative
- The mid point of Bi-poles in each terminal is earthed via an electrode line and earth electrode.
- In normal condition power flows through lines & negligible current through earth electrode. (in order of less than 10 Amps.)



Types of LCC Configuration

Homo polar System:

- Two poles at same polarity & current return path is through ground
- Poles are operating in parallel and less insulation cost



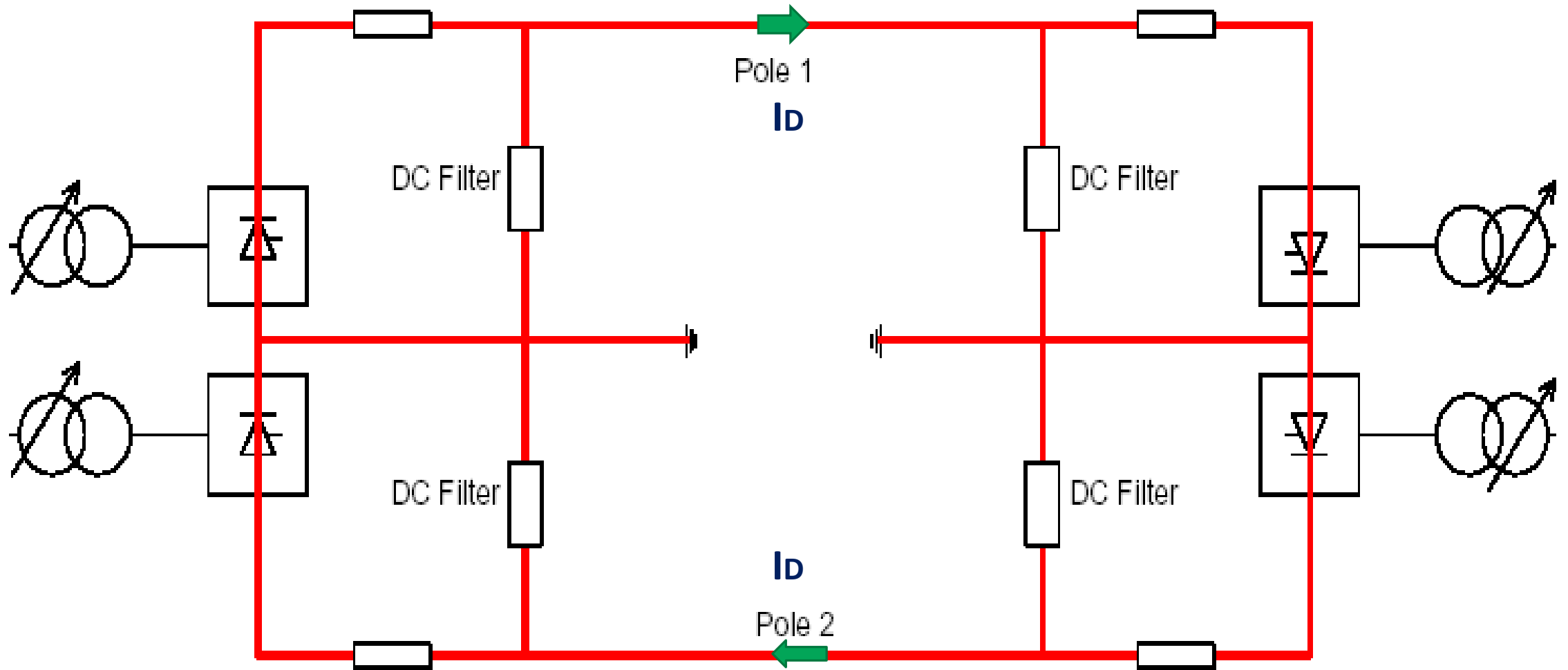
Modes of Operation in Bipolar HVDC

- Bipolar Ground Return Mode
- Monopolar Ground Return Mode(MGR)
- Monopolar Metallic Return Mode(MMR)
- Reduced Voltage Mode

Bipolar Ground Return Mode

- Normal mode of operation when both poles are in service
- Both poles shares equal power and zero ground current
- Least losses among all operation modes
- Rated station capacity can be utilized only in this mode

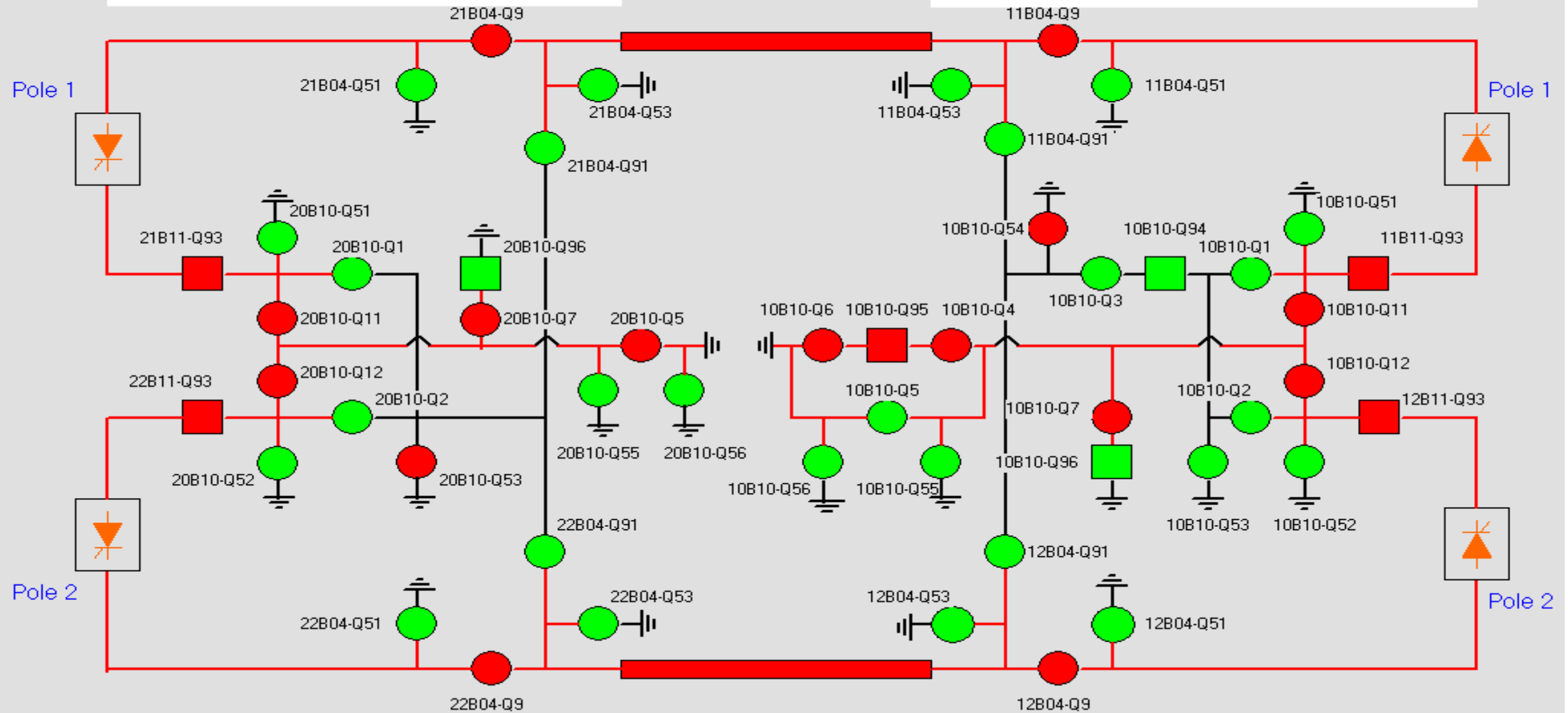
Bipolar Ground Return Mode of operation



KOLAR

Bipole Configuration

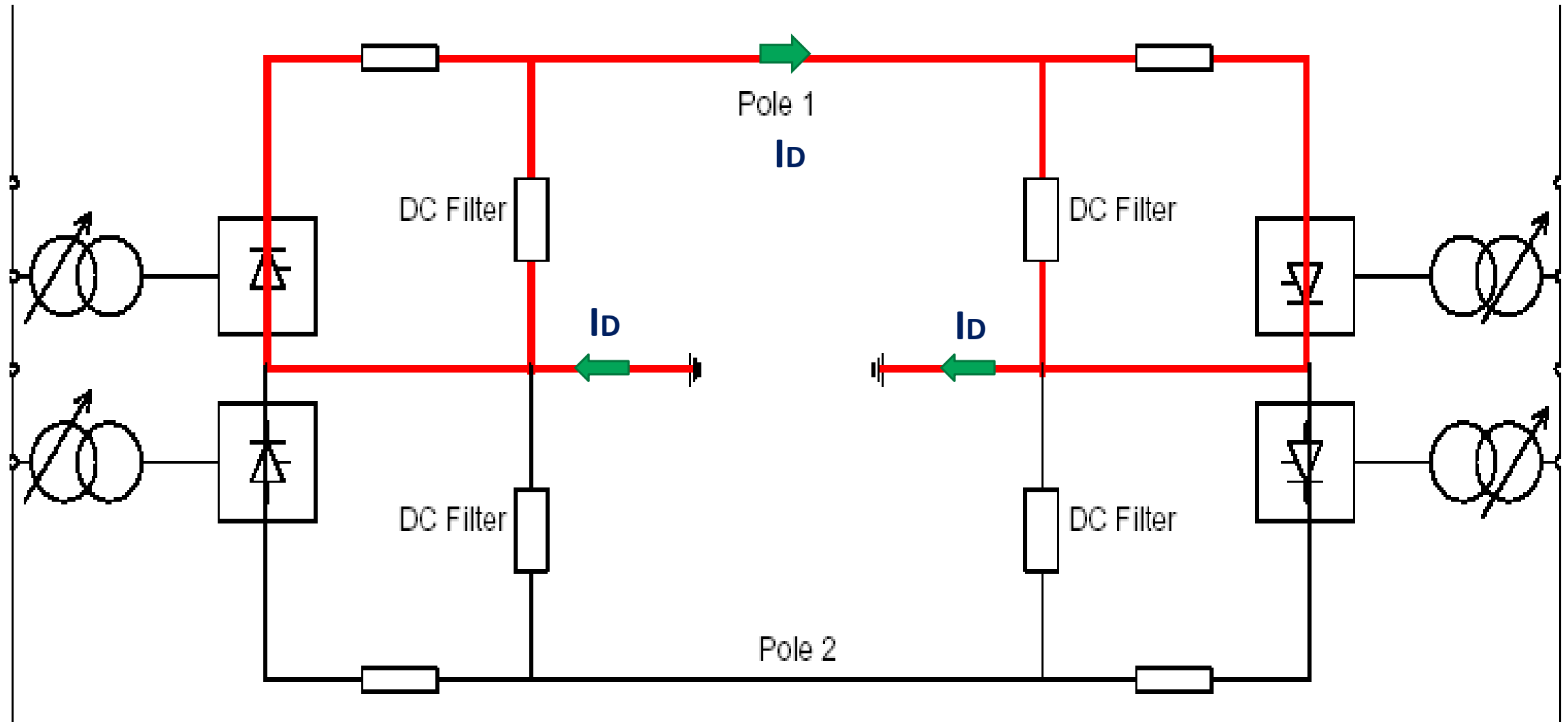
TALCHER



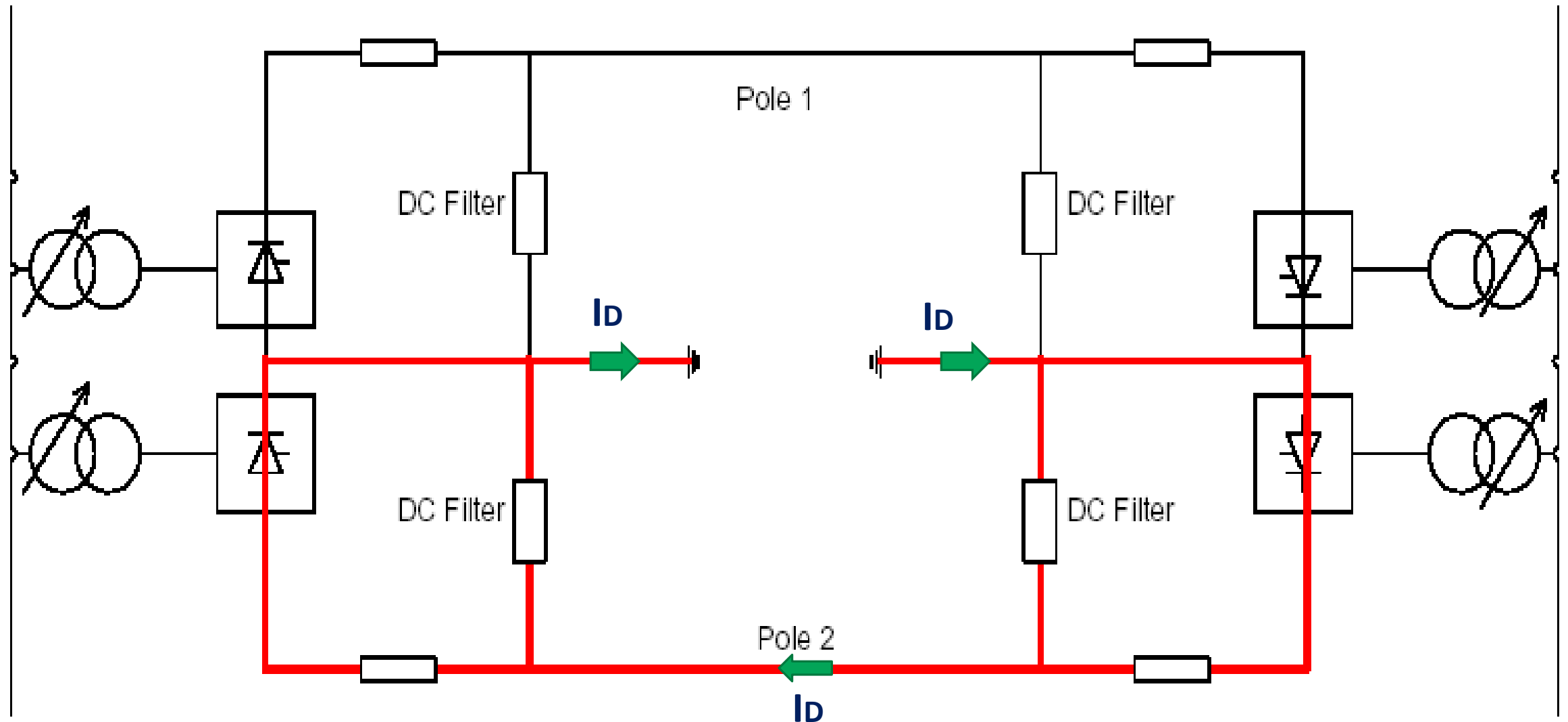
Monopolar Ground Return Mode

- When any one pole trips, system automatically comes to Monopolar Ground Return mode.
- Electrode line will be in the circuit and DC current returns through the electrode ground path
- Half of the rated station capacity can be utilized
- Losses less than MMR mode
- Scarcely operated mode due to limited electrode life

MONOPOLAR GROUND RETURN OPERATION – POLE 1



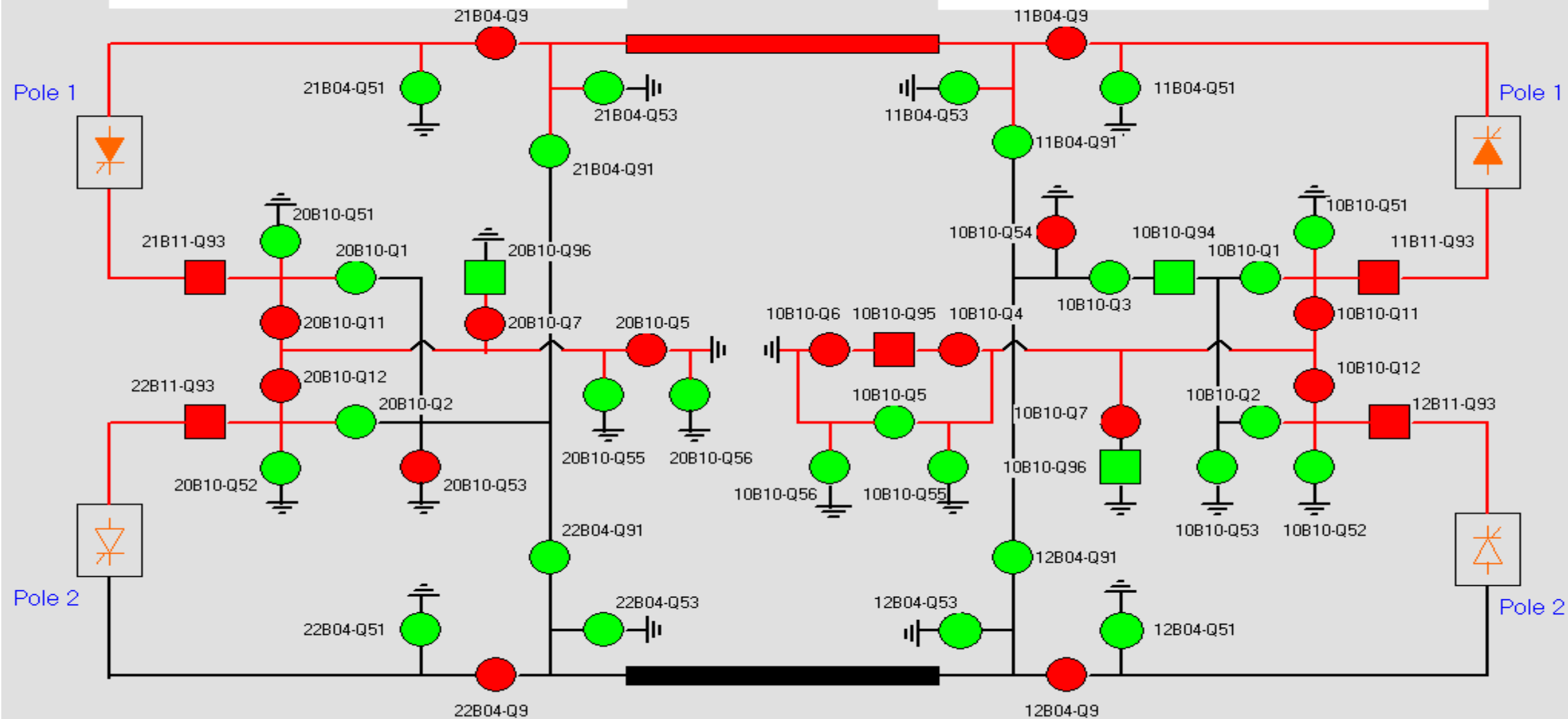
MONOPOLAR GROUND RETURN OPERATION – POLE 2



KOLAR

Pole 1 GR mode

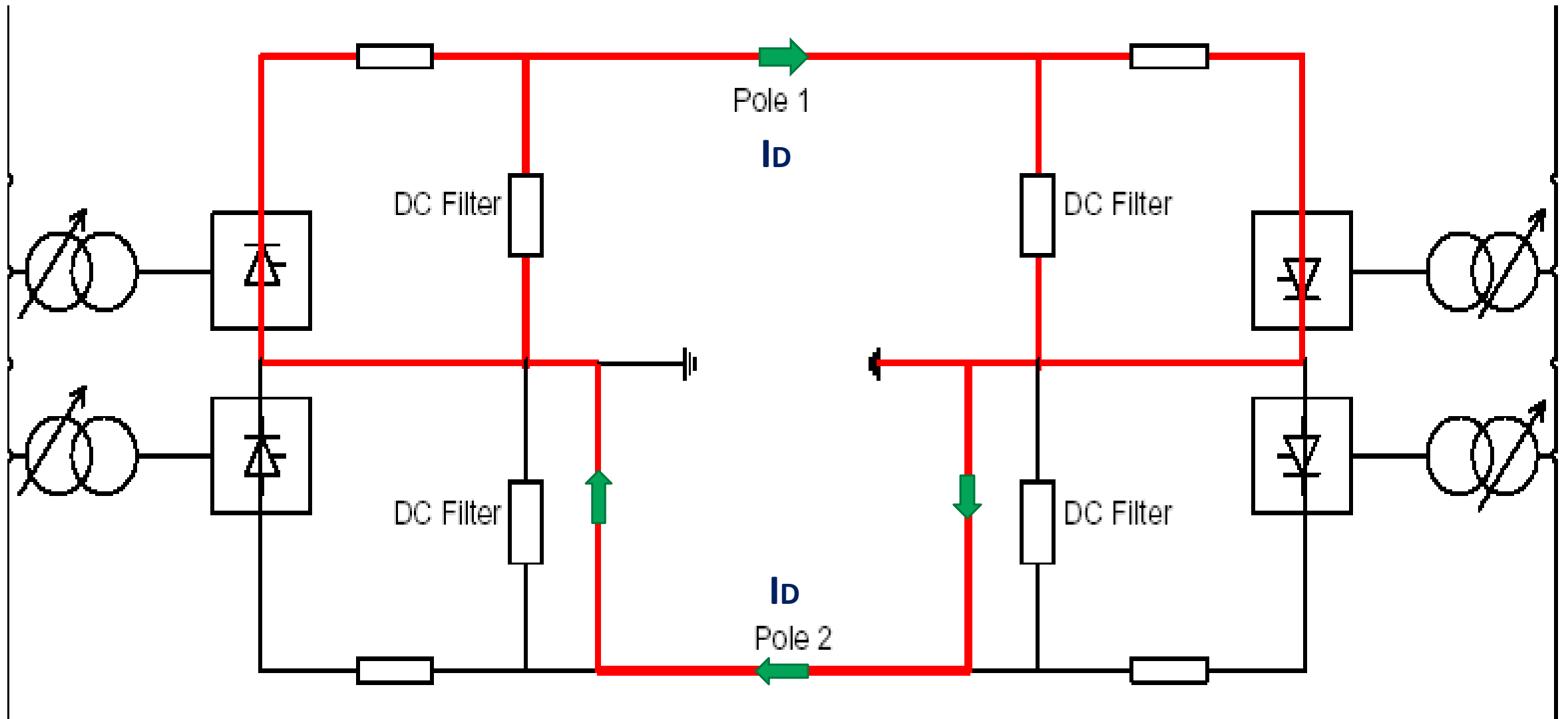
TALCHER



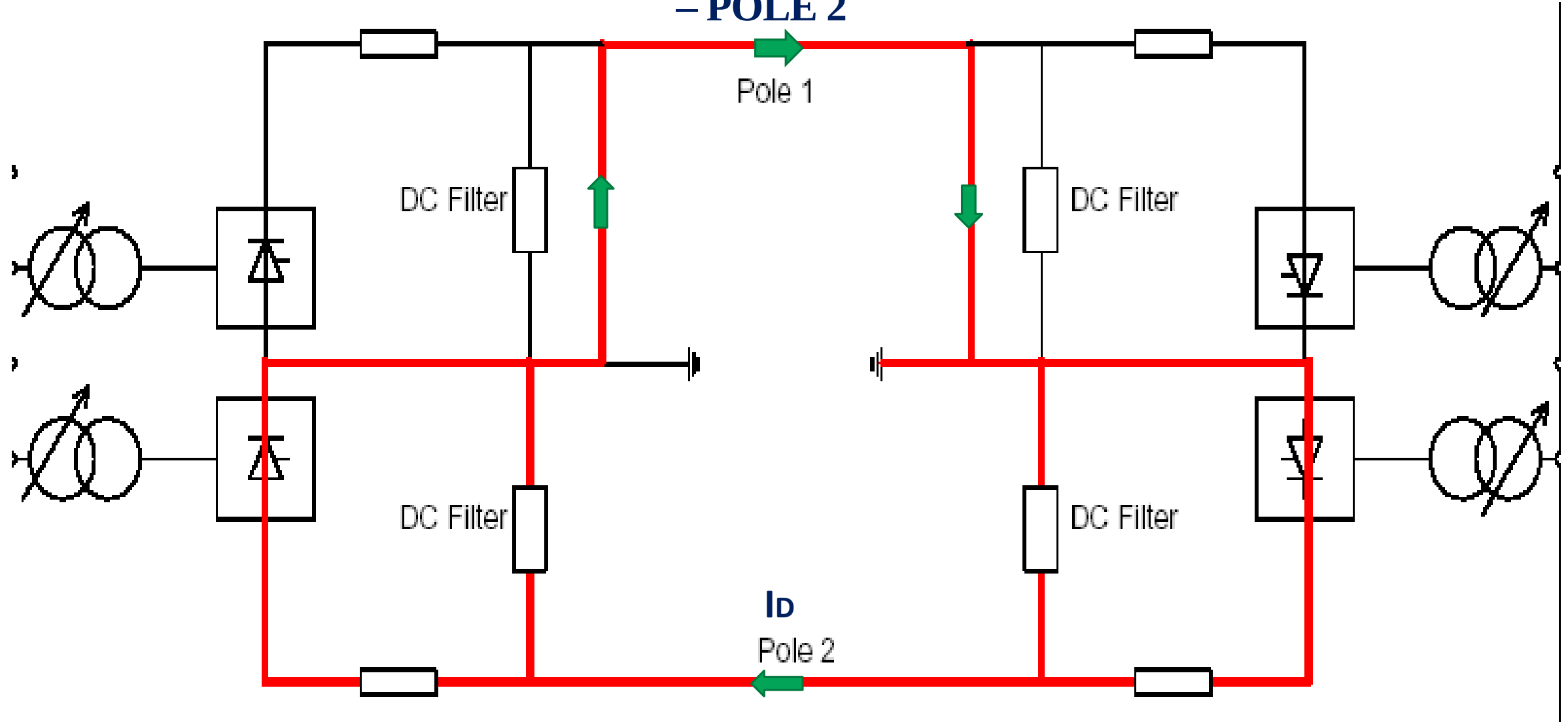
Monopolar Metallic Return Mode

- When both the HVDC lines are available / healthy but one pole is out of service, this is preferred mode of operation
- Mainly used when valve hall or other equipment pertaining to any of the pole is under maintenance / shutdown
- Have higher losses compared to bipolar mode
- Electrode will be out of circuit
- Half of the rated station capacity can be utilized

MONOPOLAR METALLIC RETURN OPERATION – POLE 1



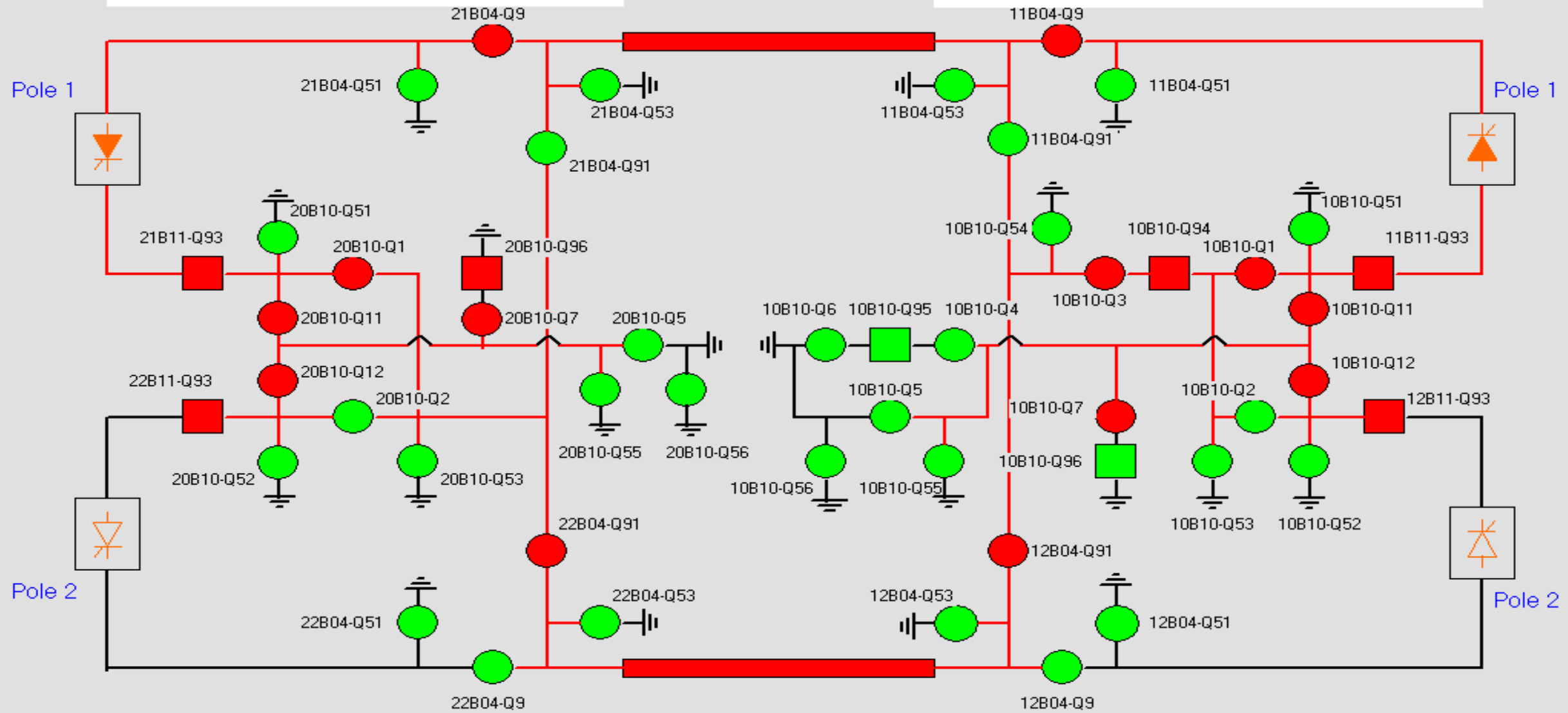
MONOPOLAR METALLIC RETURN OPERATION – POLE 2



KOLAR

Pole 1 MR mode

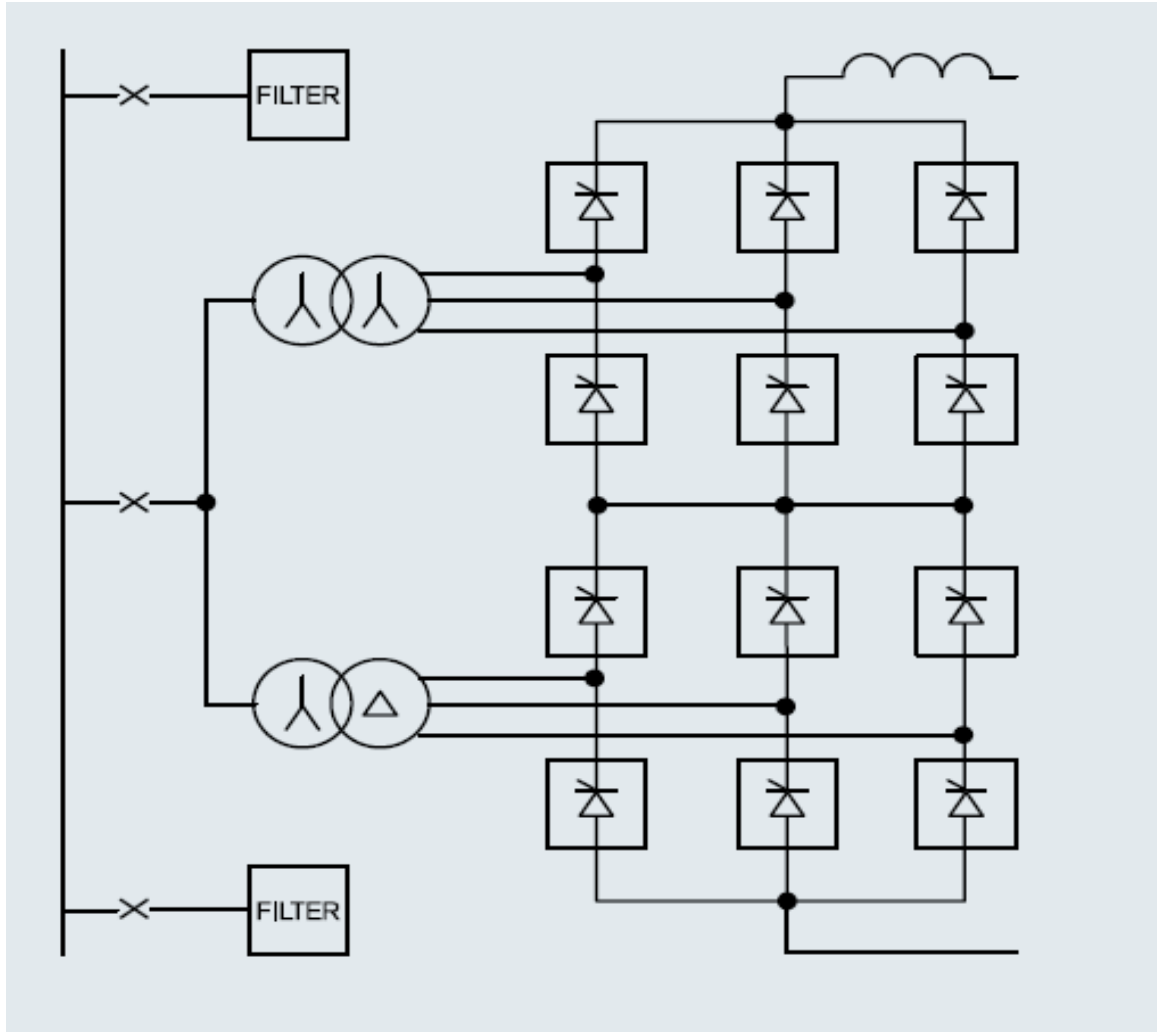
TALCHER



Reduced Voltage Mode (RVO) of operation

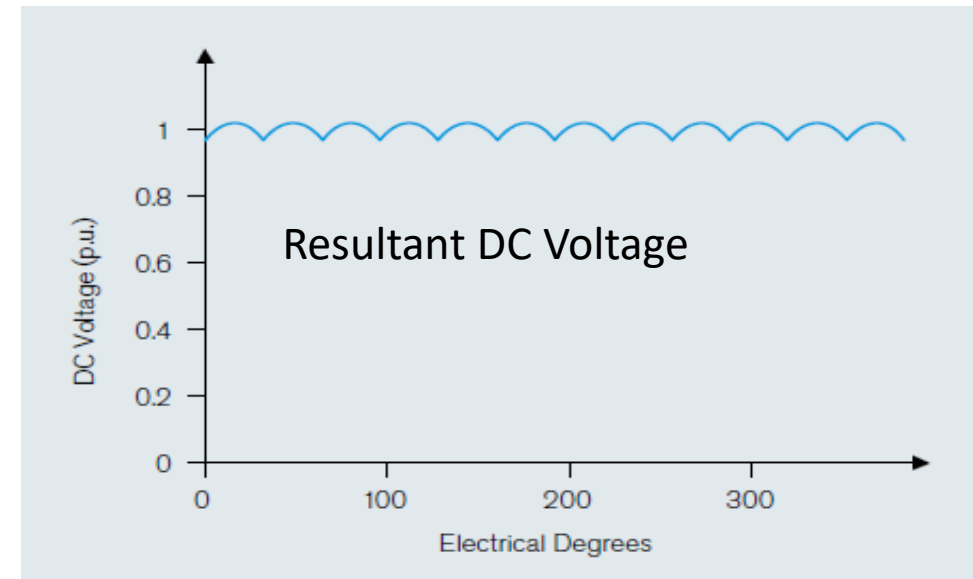
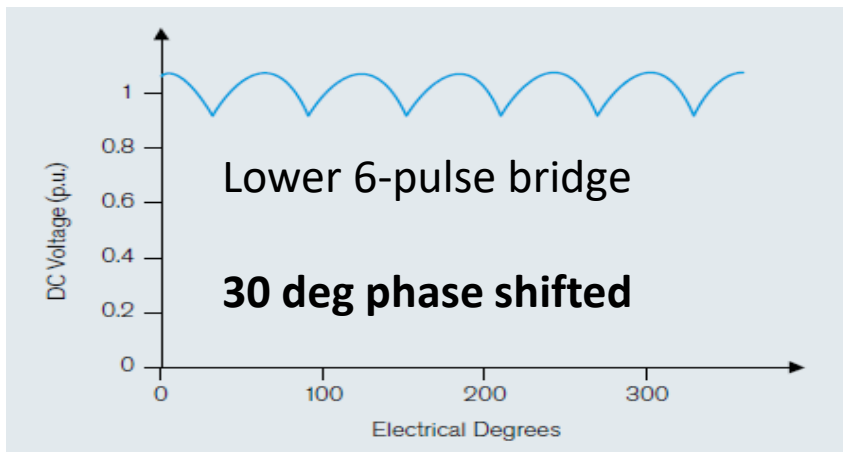
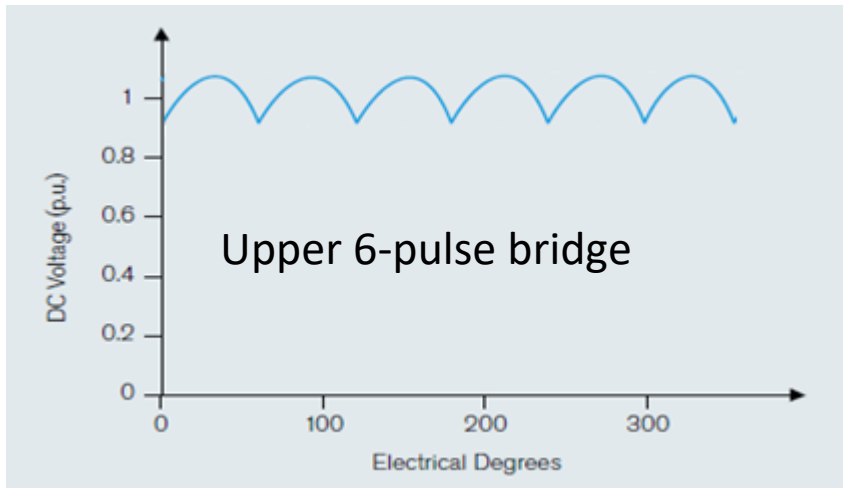
- Operating voltage is 80% of the rated voltage
- Pole switches to this mode automatically after unsuccessful recovery from DC line fault
- This allows operation of HVDC even during weak insulation in the line or associated equipment (insulators puncture etc.)
- Under worse or foggy weather conditions, when atmospheric insulation level is reduced operator can switch to this mode
- Power transfer capability of the pole reduces to 80% of the normal rated capability
- Higher losses than normal voltage mode

HVDC Converter



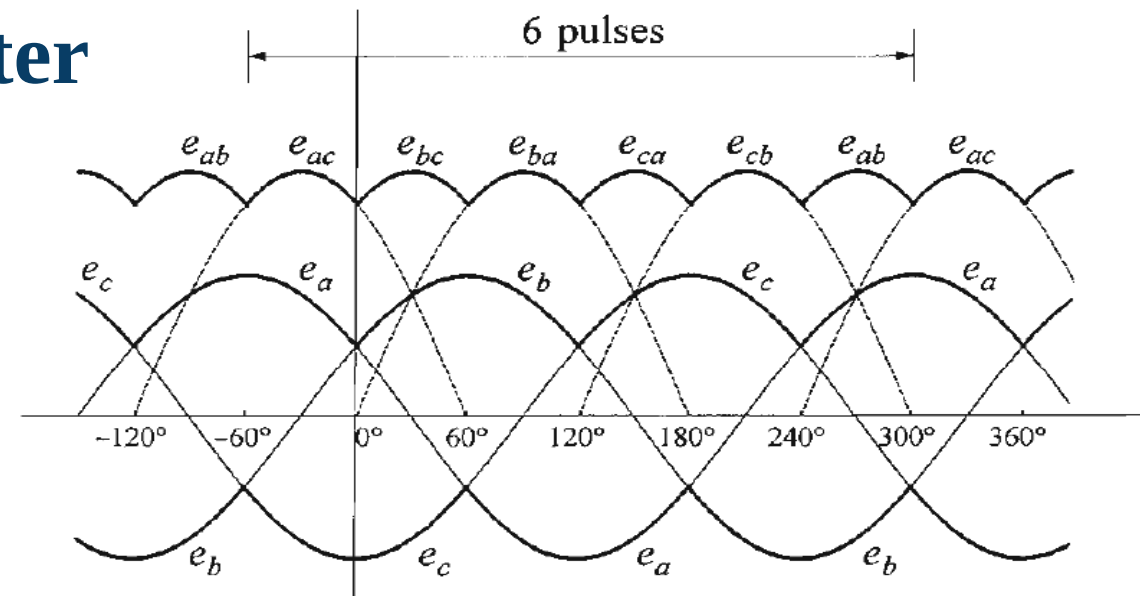
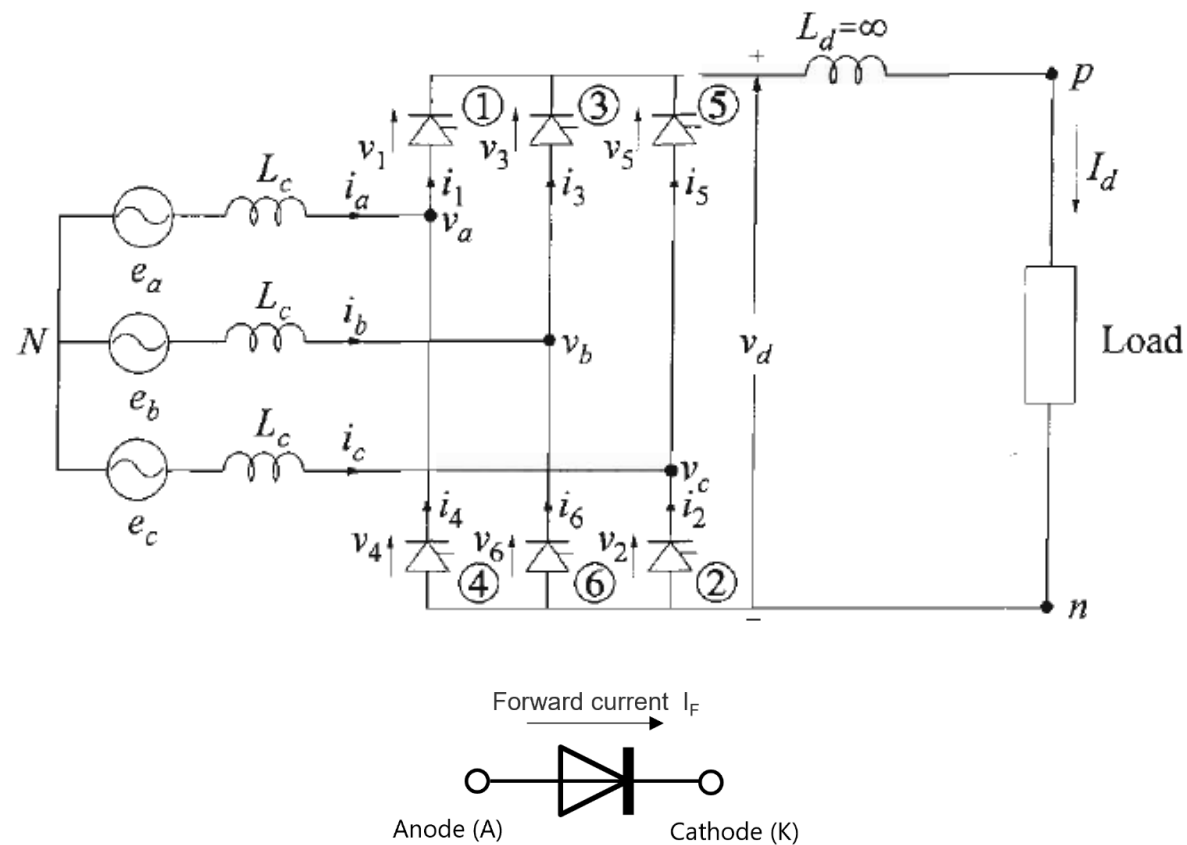
- Two 6 pulse bridges connected in series
- Graetz bridge converter.
- Commonly adopted in all HVDC applications
- Better utilization of converter transformer and less PIV rating of valves.
- 30° phase shift - Star and Delta windings
- Less filter requirement – No 5th and 7th order filters

12 Pulse Bridge converter



DC voltage - 12 pulse converter bridge

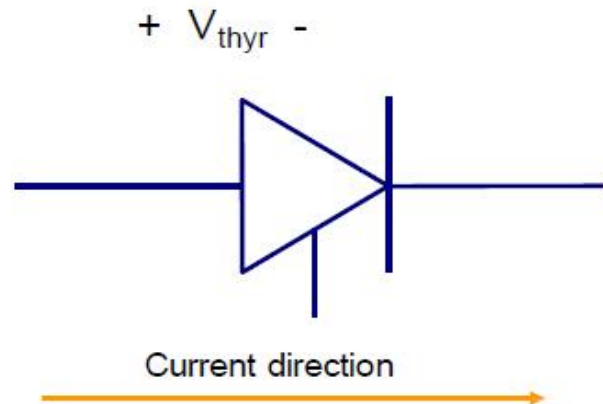
Uncontrolled 6 Pulse Bridge converter



Cycle	Period	Valves	Voltage
1	-60 to 0 deg	1-2	eac
2	0 to 60 deg	3-2	ebc
3	60 to 120 deg	3-4	eba
4	120 to 180 deg	5-4	eca
5	180 to 240 deg	5-6	ecb
6	240 to 300 deg	1-6	eab
1	300 to 360 deg	1-2	eac

$$U_d = 1.35 * U_{ac} = U_{dio}$$

Controlled 6 Pulse Bridge converter - Thyristors



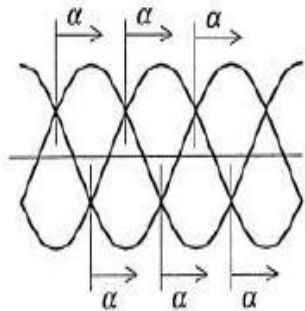
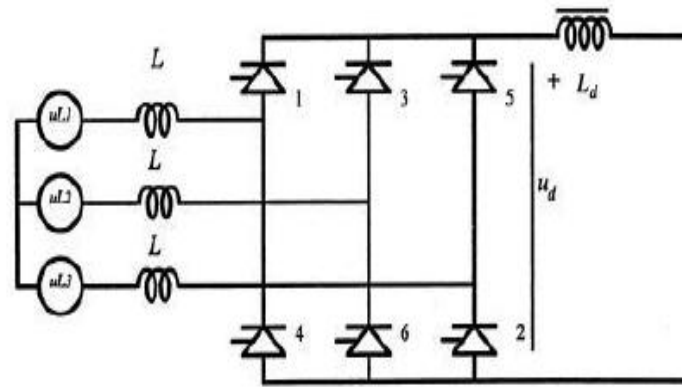
- Block high voltage in both directions
- Conduct current in forward direction
- Turn on when given firing pulse and positive voltage
- Turn off when the thyristor current crosses zero



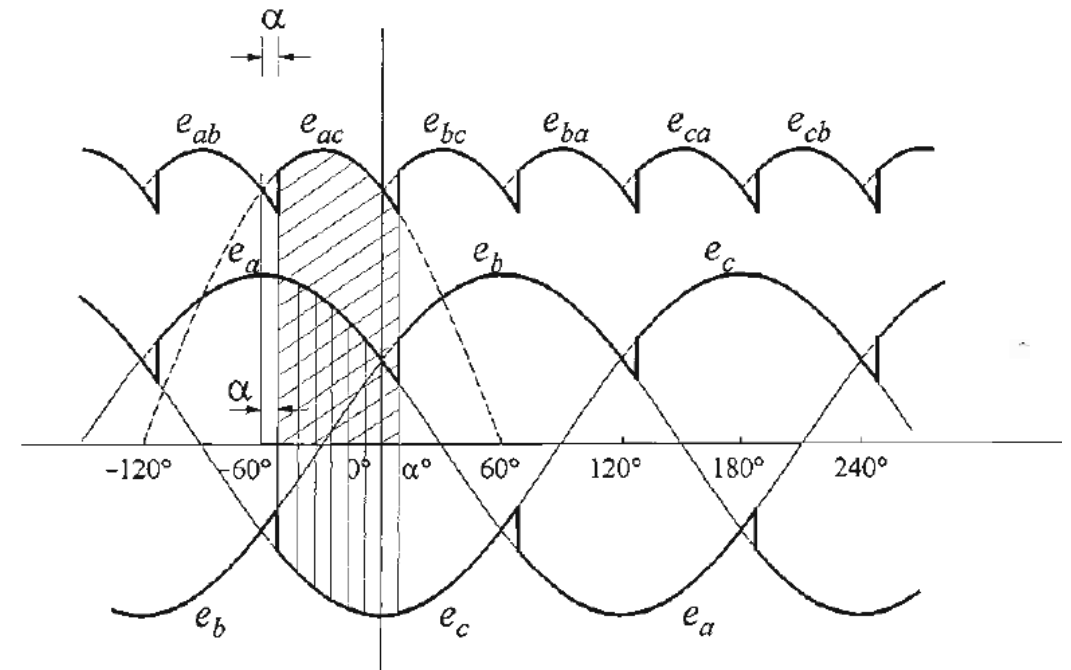
Modes of Operation

- Forward Blocking mode
- Forward Conduction mode
- Reverse Blocking mode

Controlled 6 Pulse Bridge converter - Thyristors



$\alpha > 0^\circ$ (el. degrees)



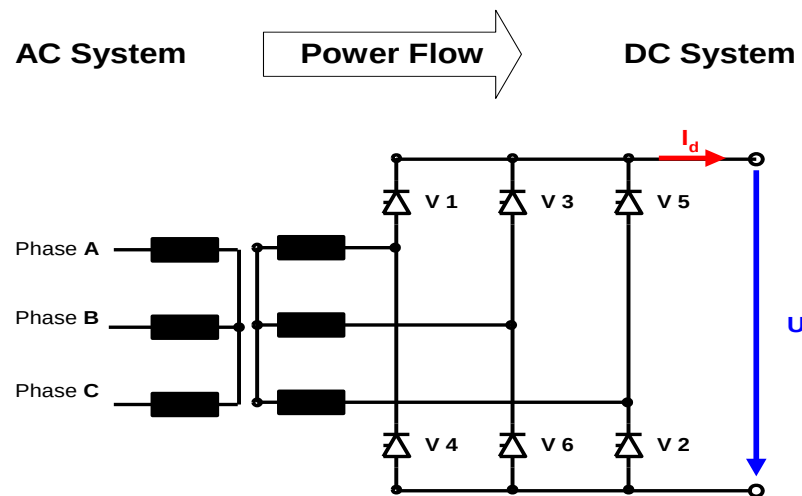
The delay from the point where the valve voltage becomes positive until the valve is turned on is called the firing angle, or alpha.

$$U_d = U_{dio} * \cos \alpha$$

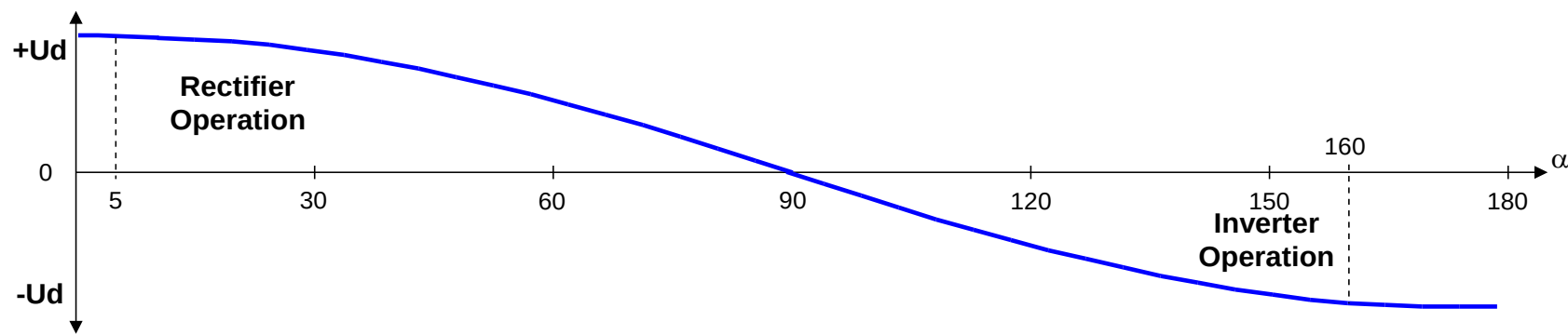
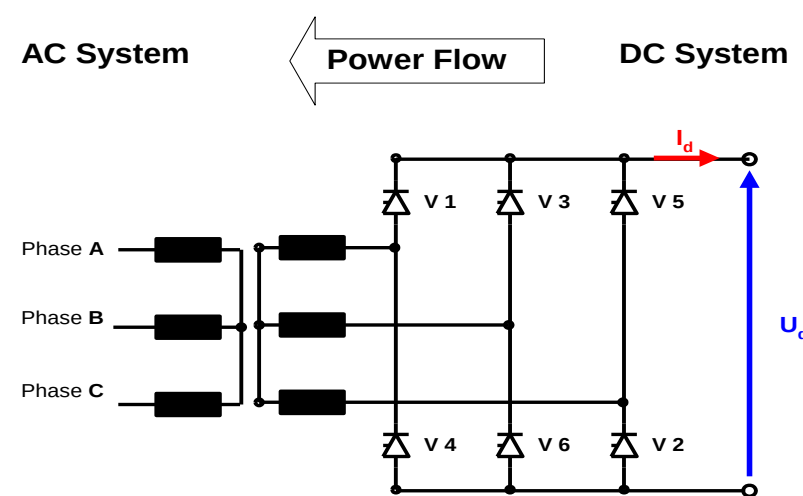
$$U_d = 1.35 * U_{ac} * \cos \alpha$$

Control of DC Voltage

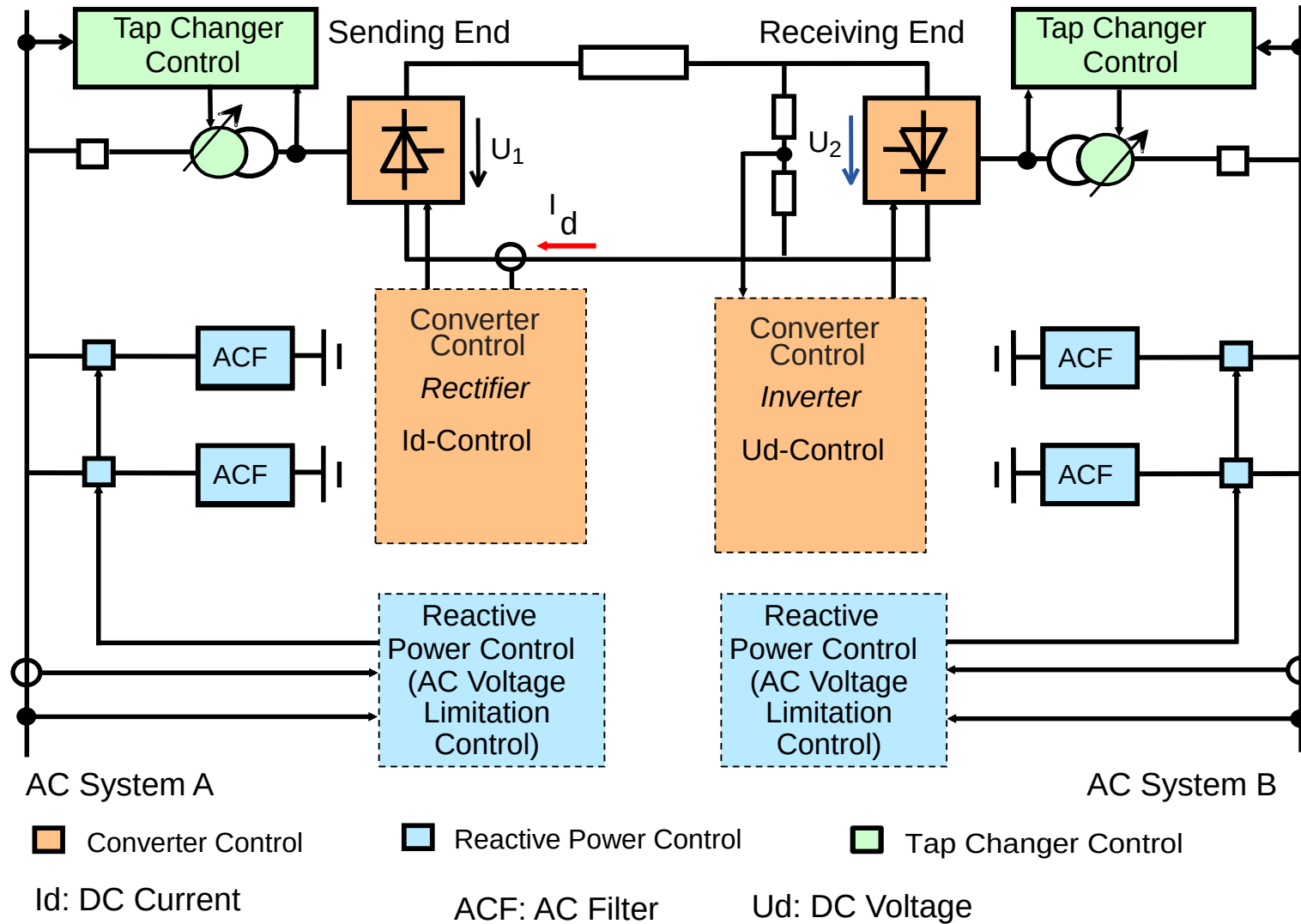
Rectifier Operation



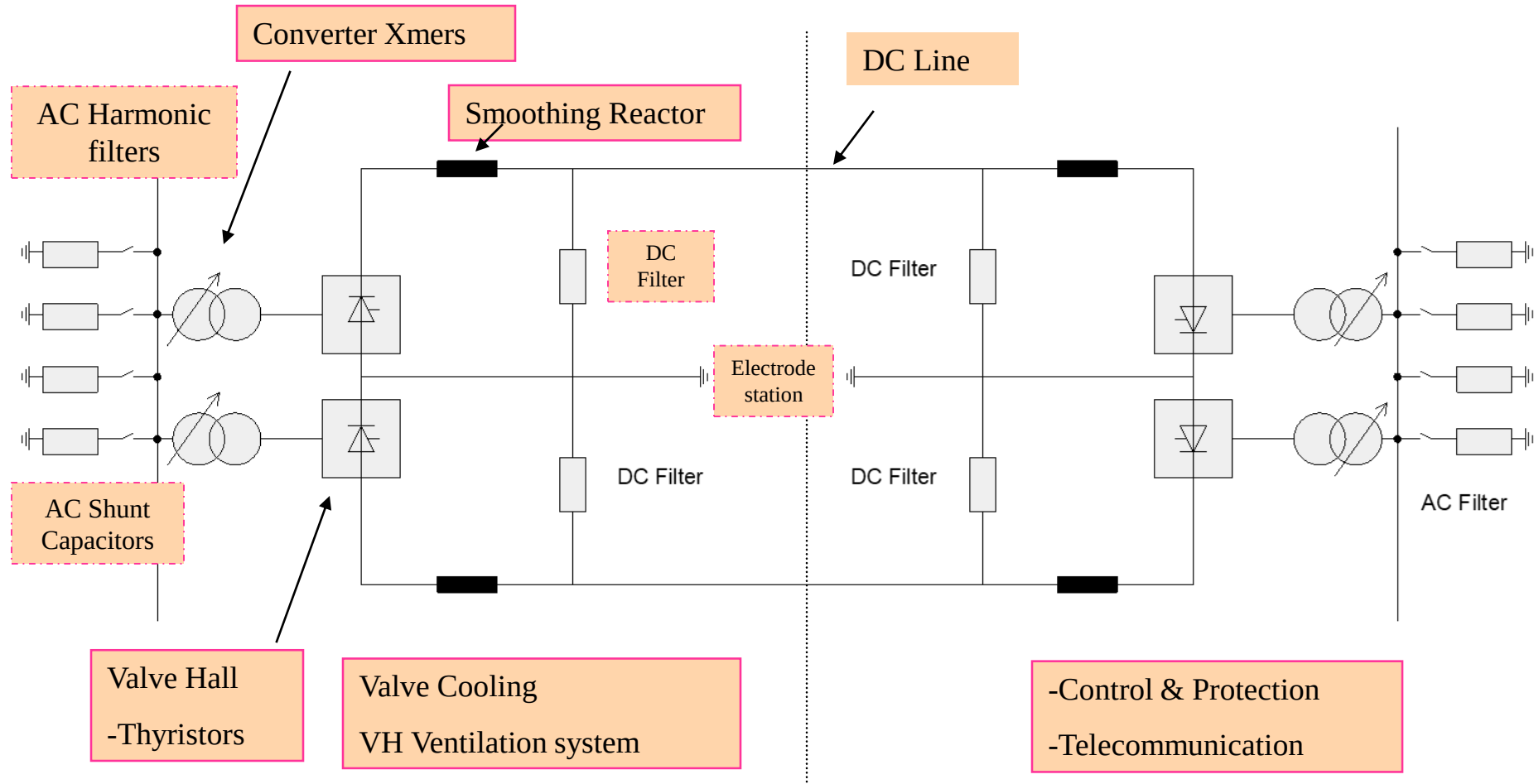
Inverter Operation

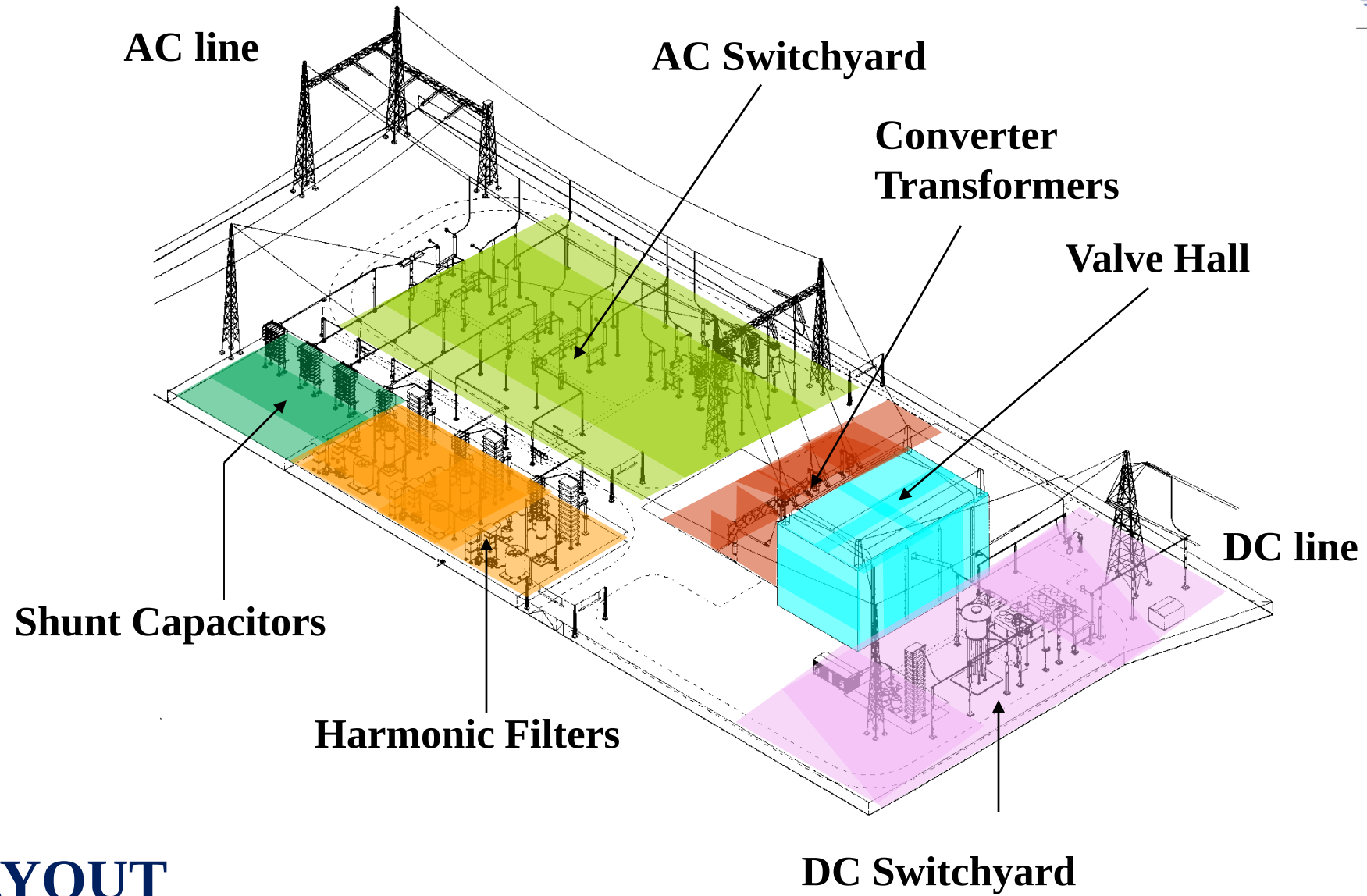


HVDC Control Philosophy



Basic Components of HVDC Terminal



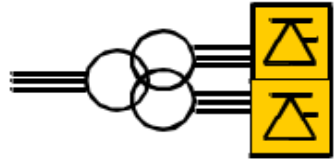


HVDC LAYOUT

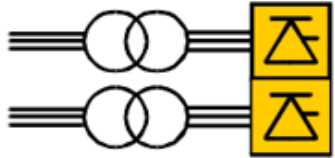
Converter Transformer

- Special transformers designed for interfacing the HVDC converter with the HVAC network
- Designed to handle the harmonic fluxes & DC voltages
- Designed for rugged and reliable On load Tap changing operation
- 30° phase shift - Star and Delta windings
- Reactive impedance in the AC supply to reduce short circuit currents and to control the rate of rise in valve current during commutation
- Total weight of Converter Transformer at Kolar HVDC – 461 Ton

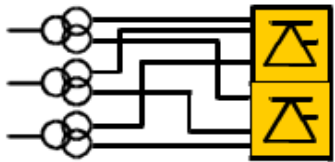
Converter Transformer Configurations



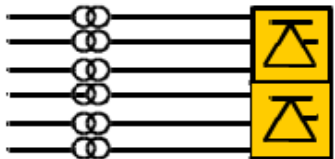
1. Three phase three winding



2. Three phase two winding



3. Single phase three winding



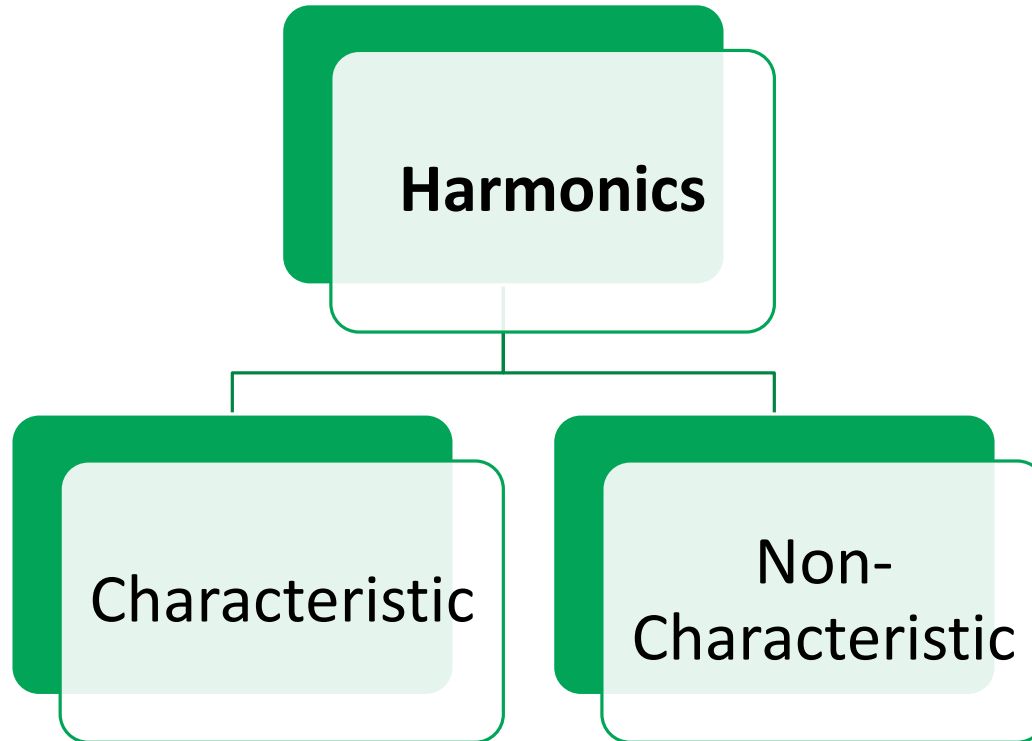
4. Single phase two winding

DC Smoothing Reactors



- Connected in series in each converter with each pole
- Decreases harmonic voltages and currents in the DC line
- Smooth the ripple in the DC current
- Prevents the current from becoming discontinuous at light loads
- Limits crest current (di/dt) in the rectifier due to a short circuit on DC line
- Limits current in the bypass valve firing due to the discharge of the shunt capacitances of the dc line

AC Harmonics



Characteristic Harmonics

DC-AC Conversion process generates – Harmonics
(square wave current from converter bridges)

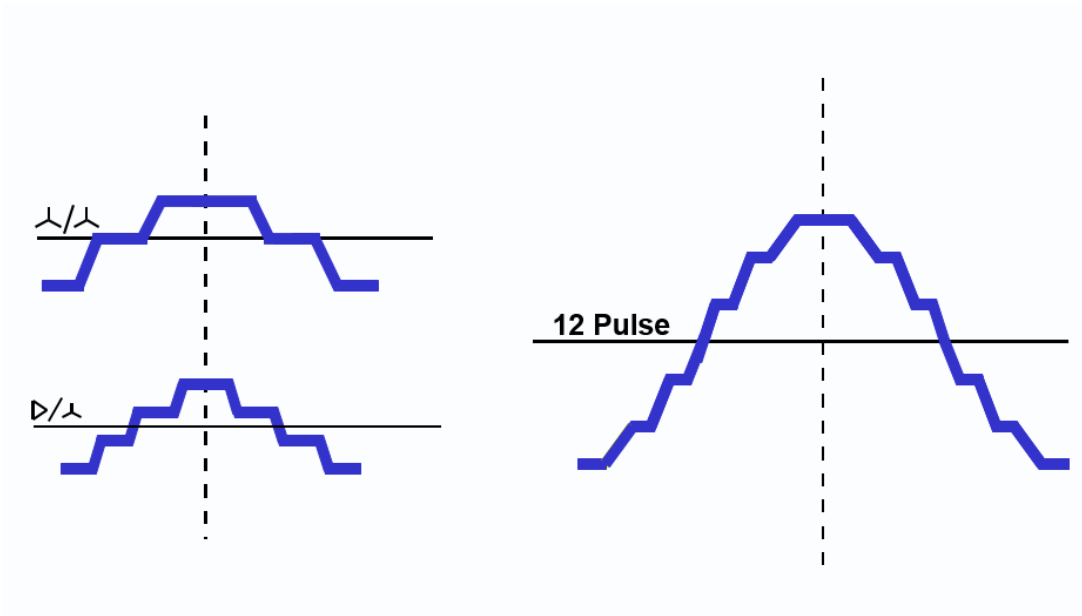
Under Ideal operating condition

AC side Harmonics

- Generated harmonics – $(12n \pm 1)$ harmonics
- Predominant harmonics – 11,13,23,25,35,37

DC side Harmonics

- Generated harmonics – $(12n)$ harmonics
- Predominant harmonics – 12,24,36



Non-Characteristic Harmonics

☐ Unbalance of the converter transformers

- Reactance Imbalance between Phases
- Reactance Imbalance between Bridges
- Difference in Converter Transformer Turns Ratio

☐ Firing Angle Asymmetry

☐ AC Voltage Unbalance

☐ Ripple in DC current

☐ AC Back ground harmonics

AC Filters / Shunt capacitors



Purpose:

- To Filter out the Harmonics
- To Reactive power support to converters

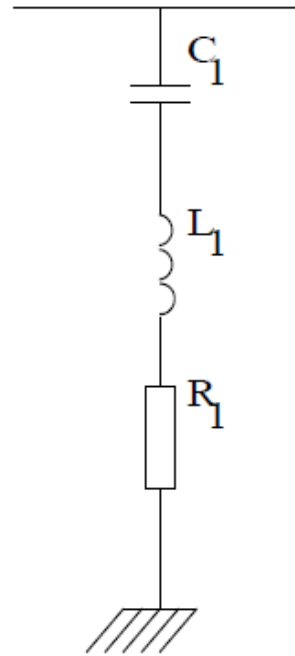
Effects of Harmonics:

- Telephone Interference
- Increased Transformer/motor losses
- Overheating of Generators/Capacitors
- Converter control Instability

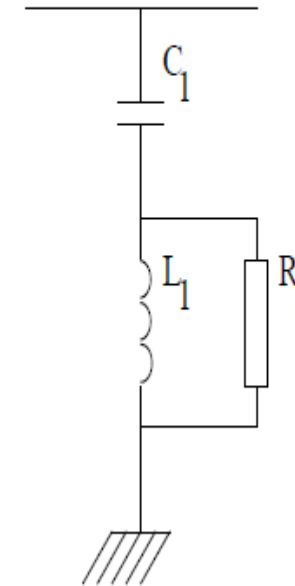
Types of AC Filters

- Tuned filter (Single, double and triple tuned filter)
- Damped filter (Single, double and triple tuned filter)
- C-type filter

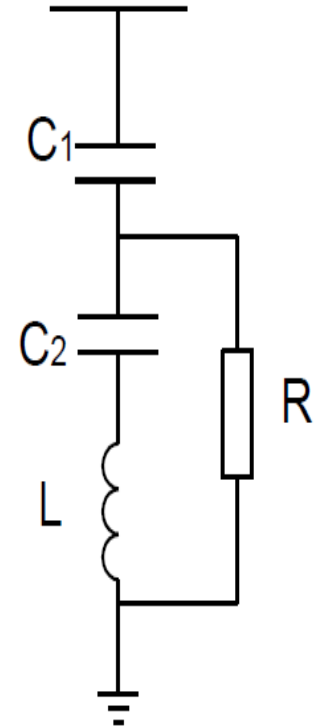
Tuned filter



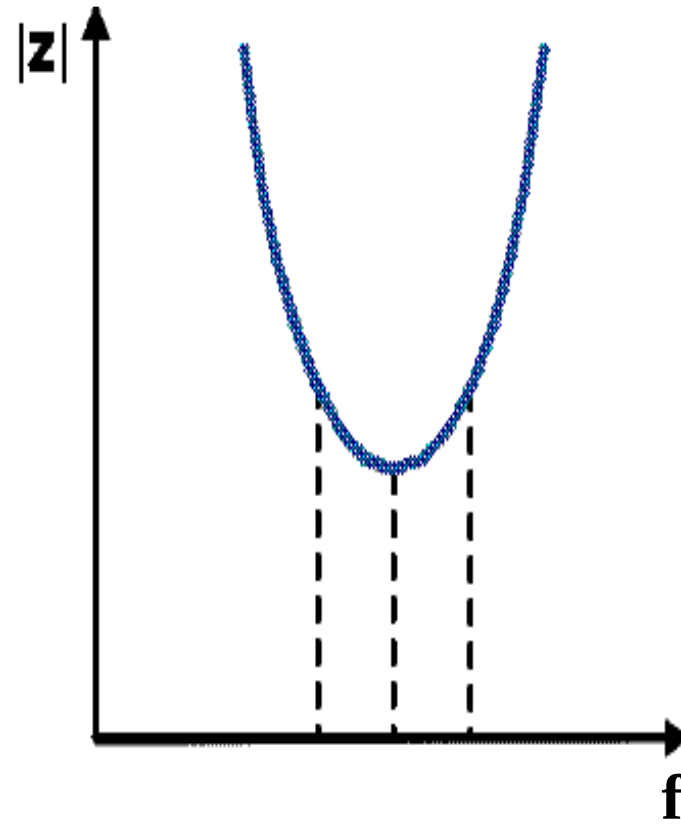
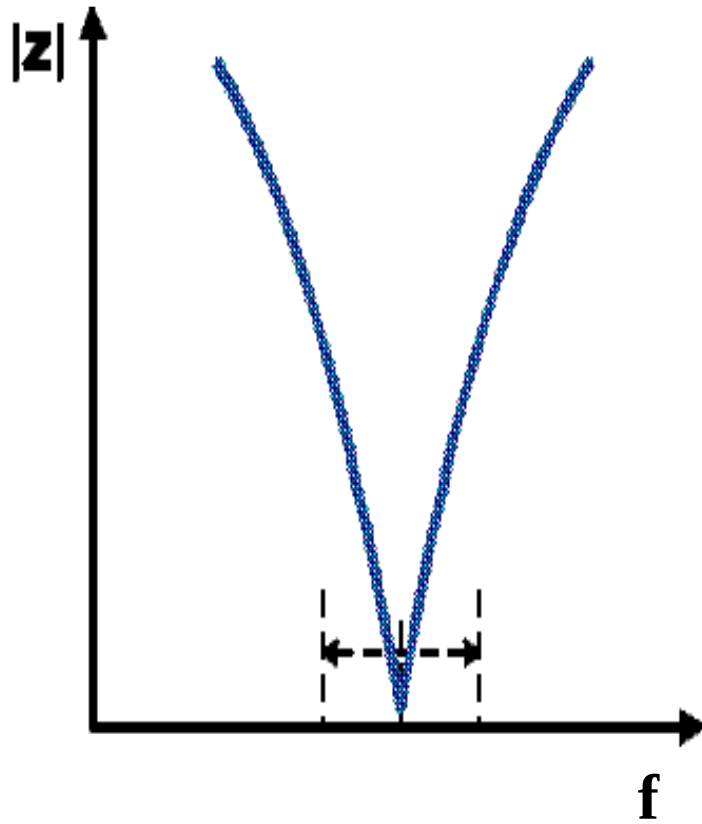
Damped filter



HP3 filter (C-type)

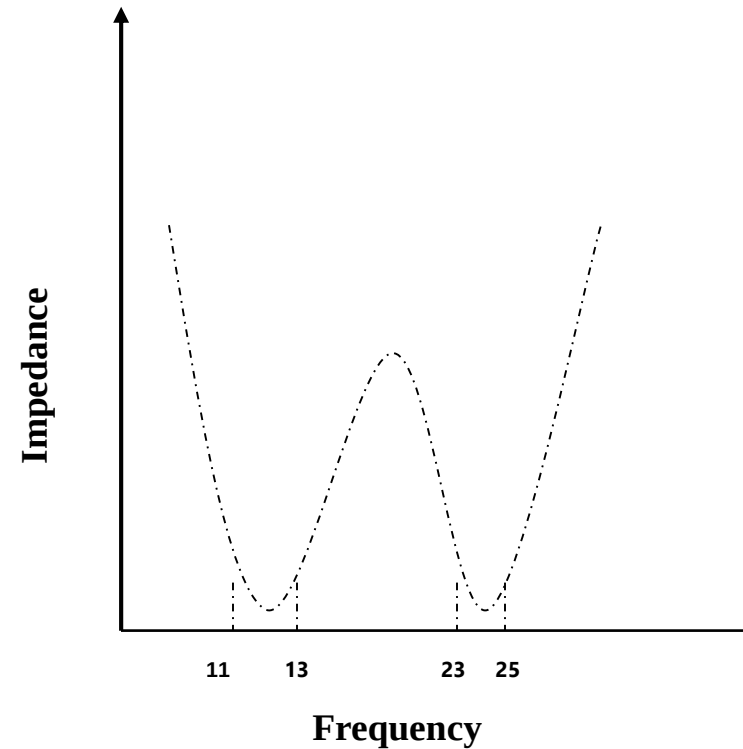
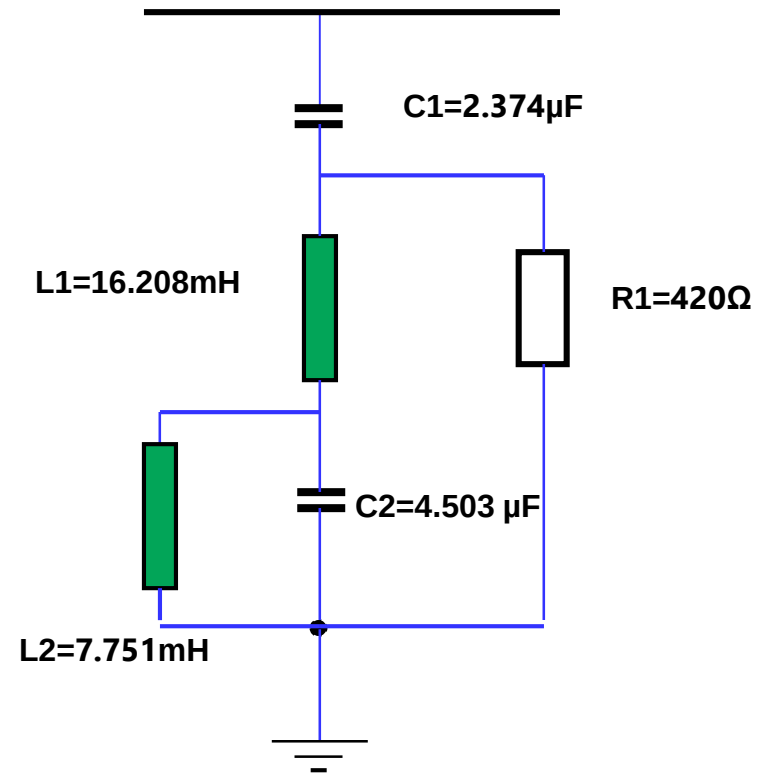


Tuned vs Damped filters



$$q = \frac{\omega_0 L}{R}$$

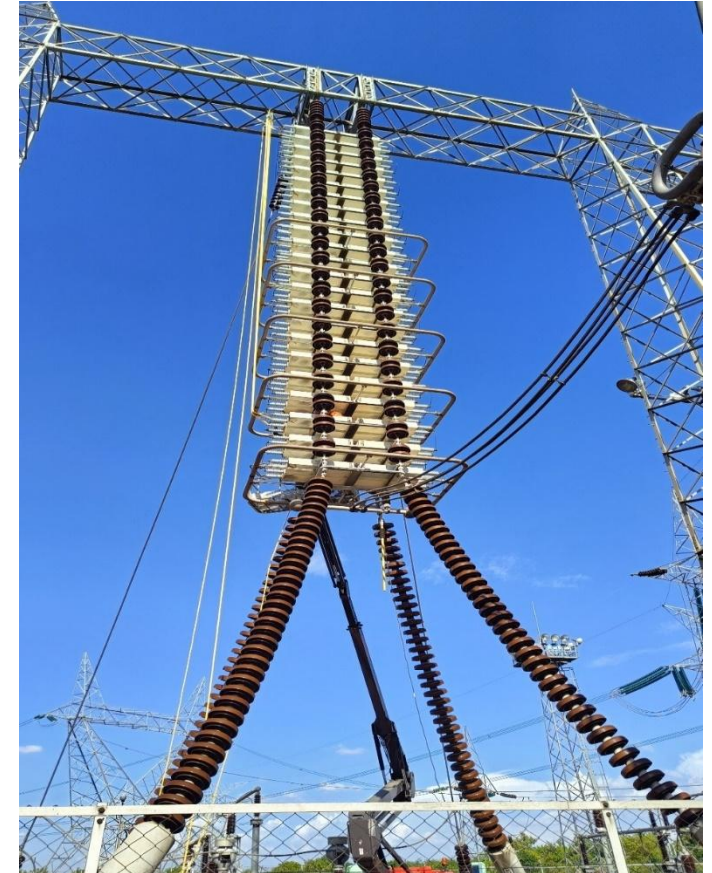
12/24 Double Tuned damped Filter – 120 MVA_r



Impedance Graph

DC Filters

- Reduce the harmonic currents in the DC system to an acceptable level
- Mainly used for restricting telephone interference level from the DC transmission lines
- Avoid the resonance of the DC system at frequencies close to fundamental and second harmonic.
- Limit the transient currents reaching the valve hall



High Frequency Filters

- Turn on and turn off of thyristor valve generates high frequency noise.
- High frequency noise may cause interference with the AC Line PLCC communication.
- HF Filters are installed in both AC and DC side to avoid any telecommunication/PLC interference.



Valve Cooling

- HVDC converters require efficient cooling of thyristor via heat sinks.
- Single closed loop deionized water system.
- Two redundant centrifugal circulating pumps to circulate the water
- Heat transfer to the ambient is provided by dry coolers
- Two ion exchanger chambers to maintain the conductivity of water



Valve Cooling

Valve Cooling Pump

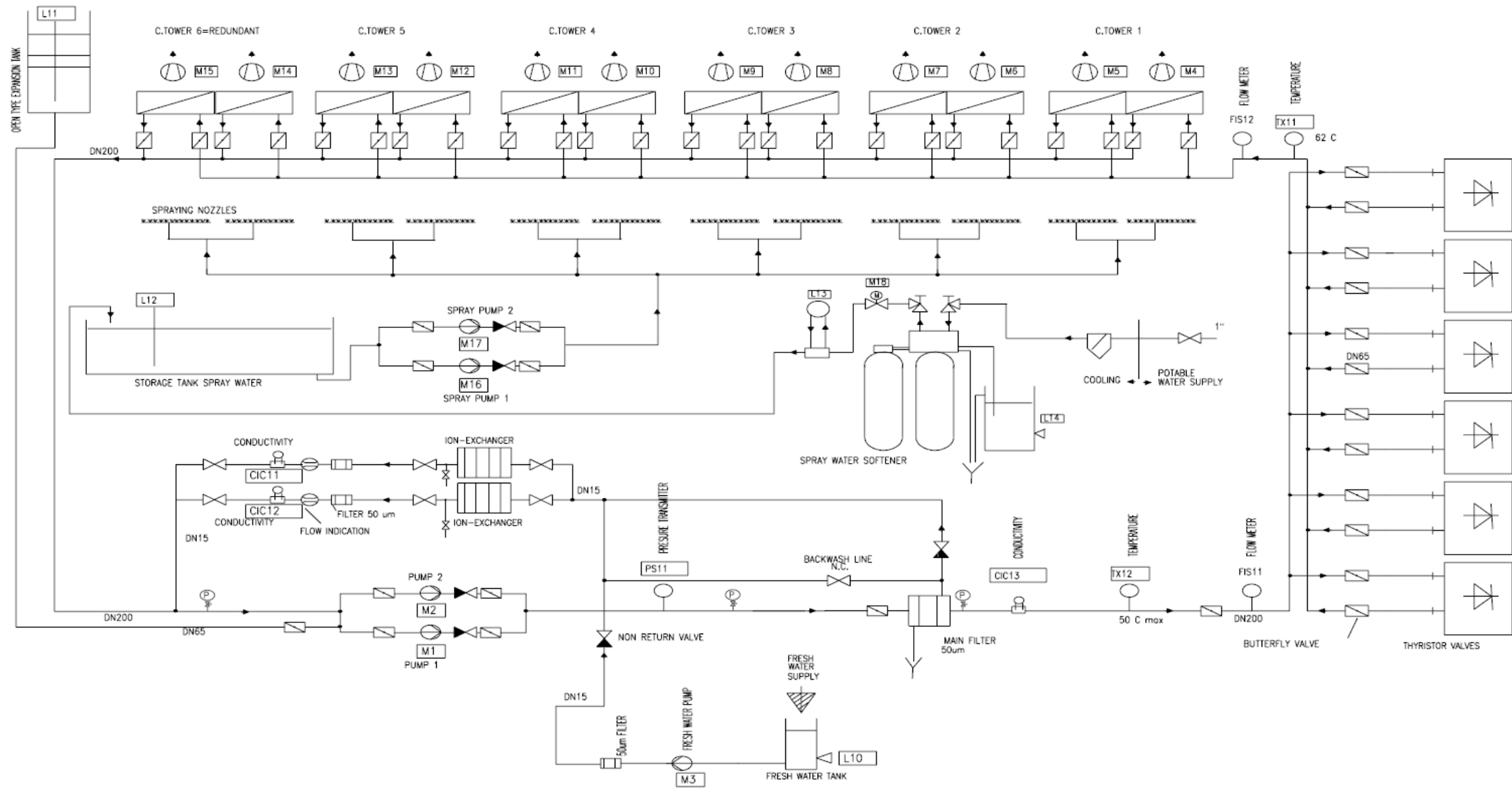


Ion Exchanger Chamber



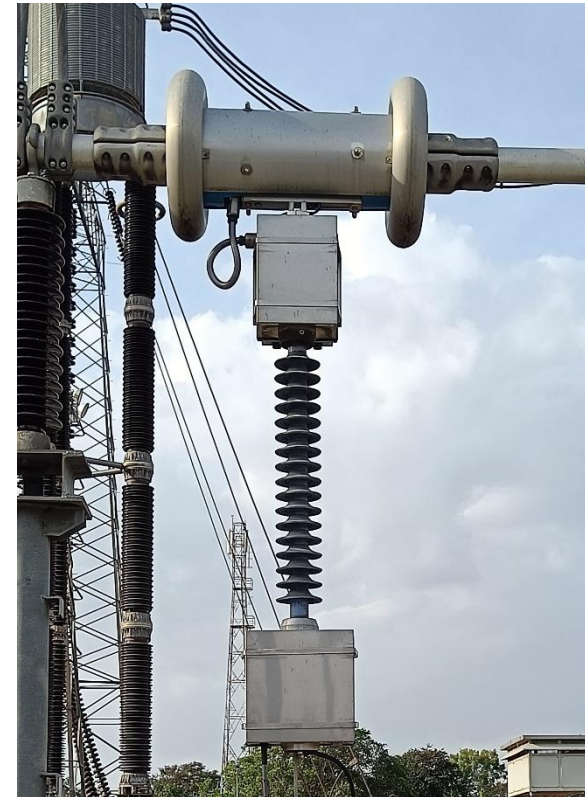
Valve cooling Tower





DC Measuring Devices

- ❑ Measurement on DC side is required for Control, Monitoring and Protection
- ❑ AC CTs cannot be used on DC side – Saturation effect
- ❑ DC Current Measurement
 - ❑ Shunt Resistance method
 - ❑ Zero flux CT
 - ❑ Optical current transducer
- ❑ DC Voltage Measurement
 - ❑ RC Voltage divider
 - ❑ Optical voltage transducer

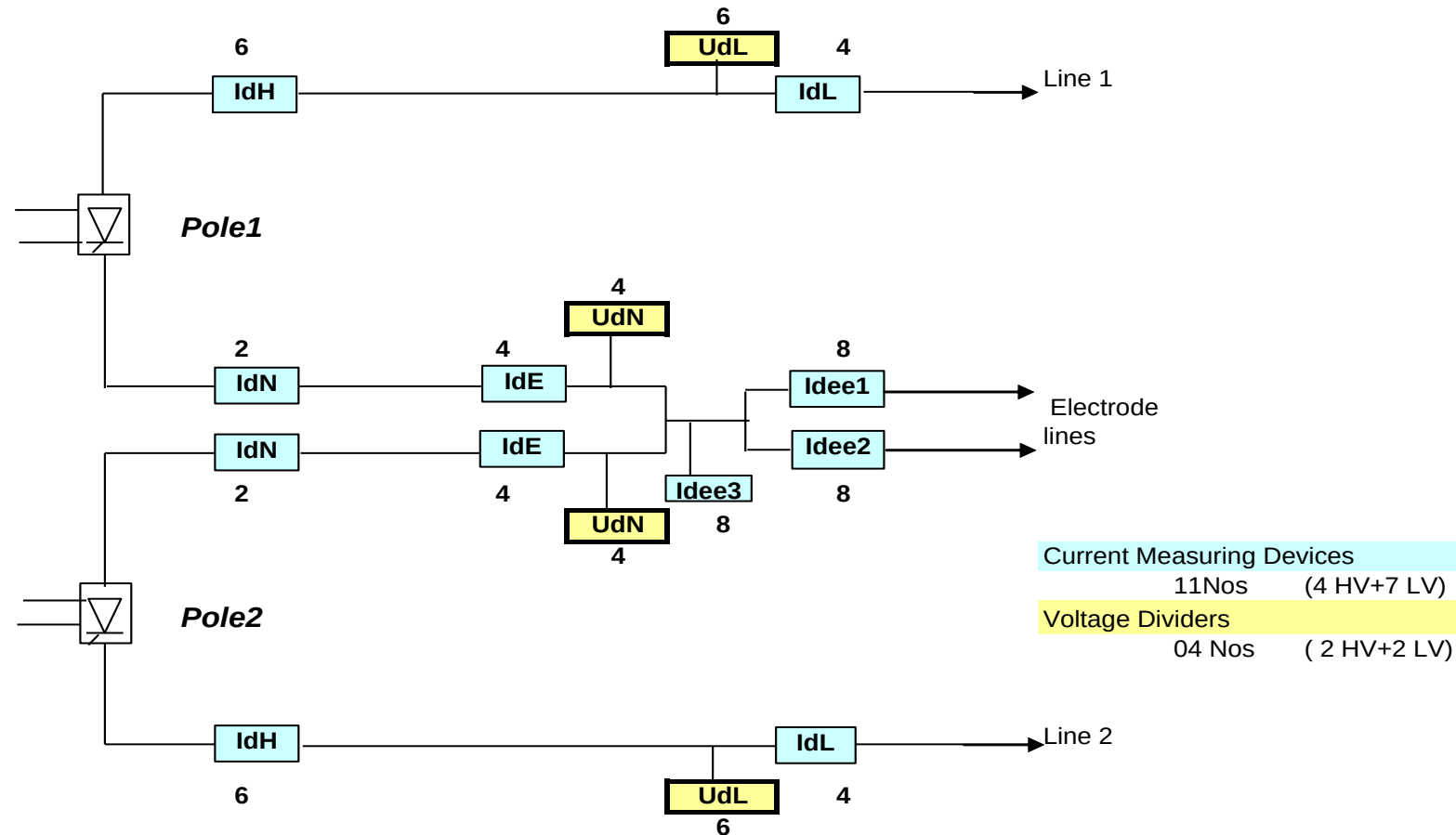


DC Current Optodyn



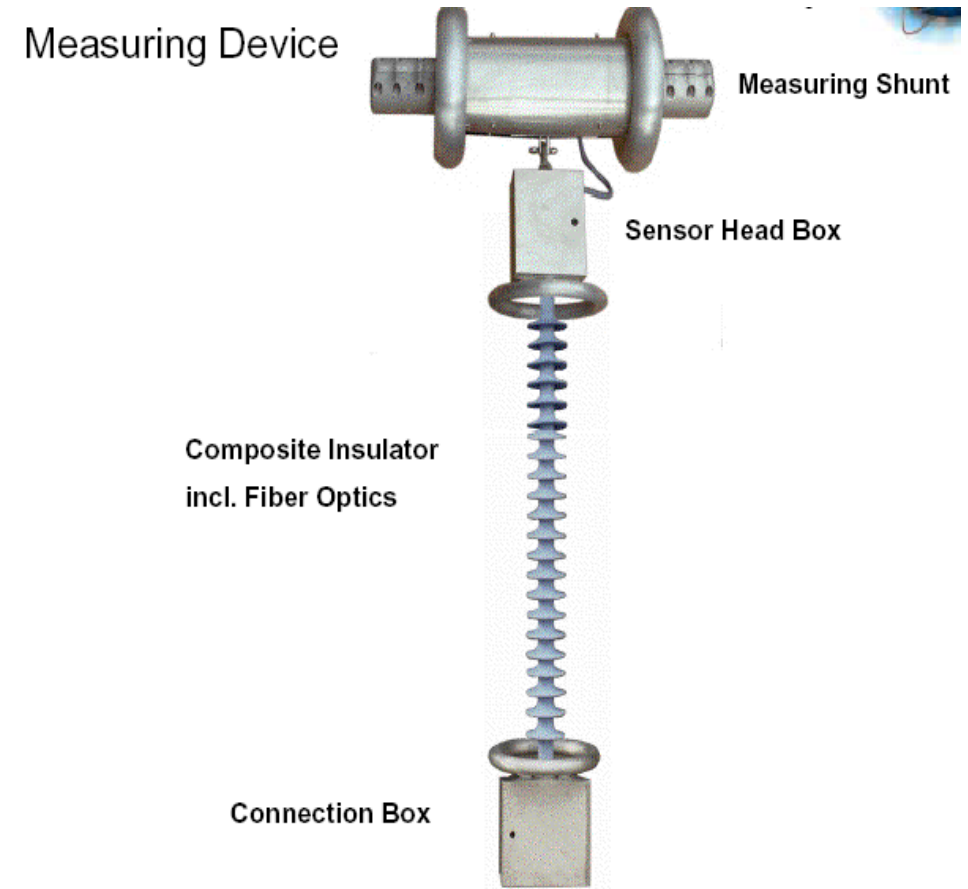
DC Voltage Divider

DC Measuring Devices – Layout at Kolar

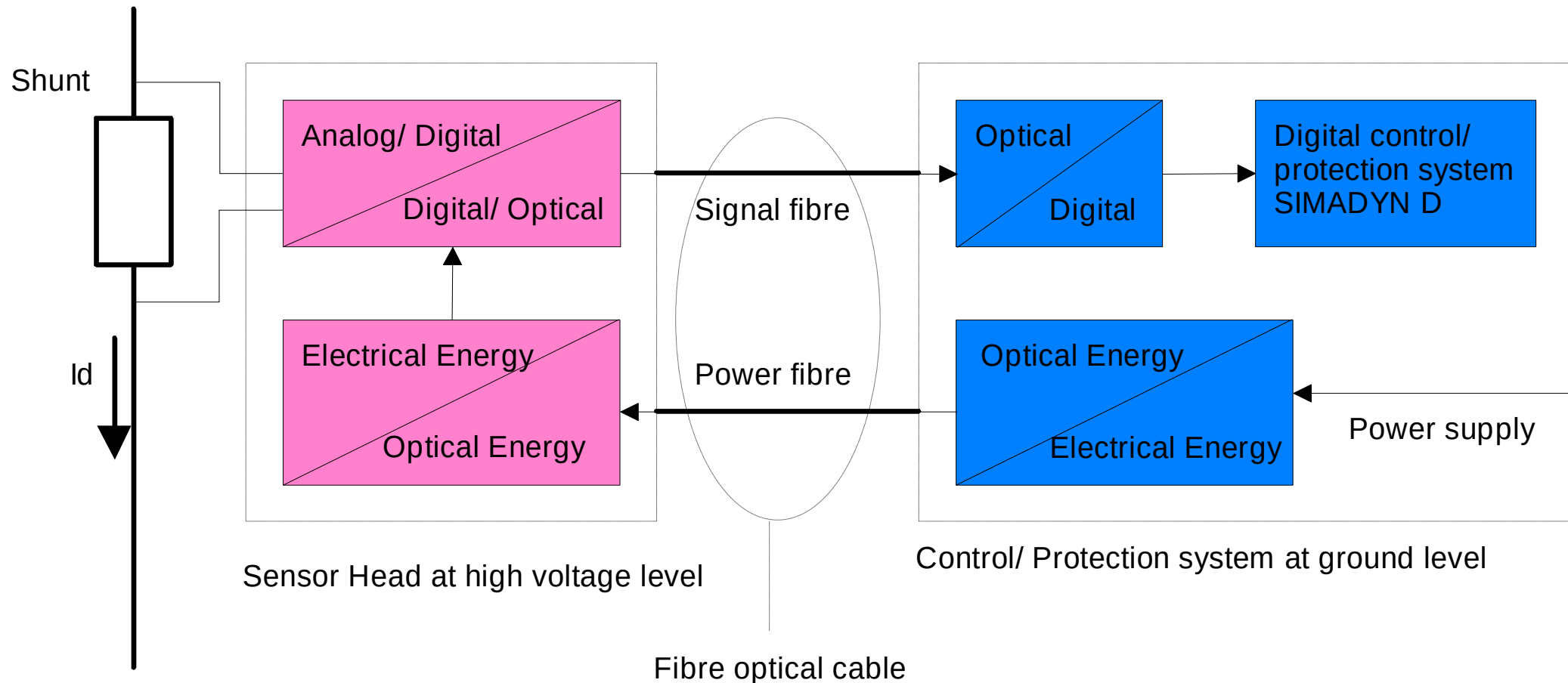


DC Measuring Devices

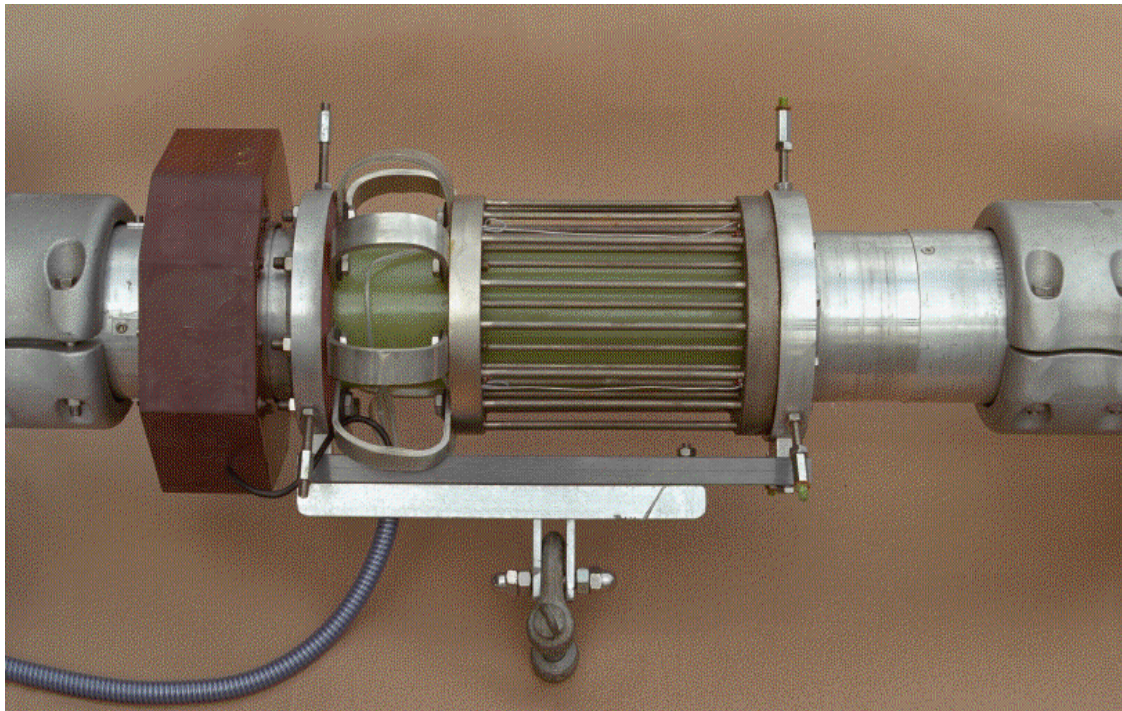
- Resistive DC Shunt Measurement - low value resistor (R)
- Voltage drop(V) from the shunt will be taken for determining the current ($I = V/R$)
- To avoid electromagnetic interference, signals are transmitted in optical form
- Excellent dynamic performance
- Less weight and support structure
- Full redundancy up to the measuring location



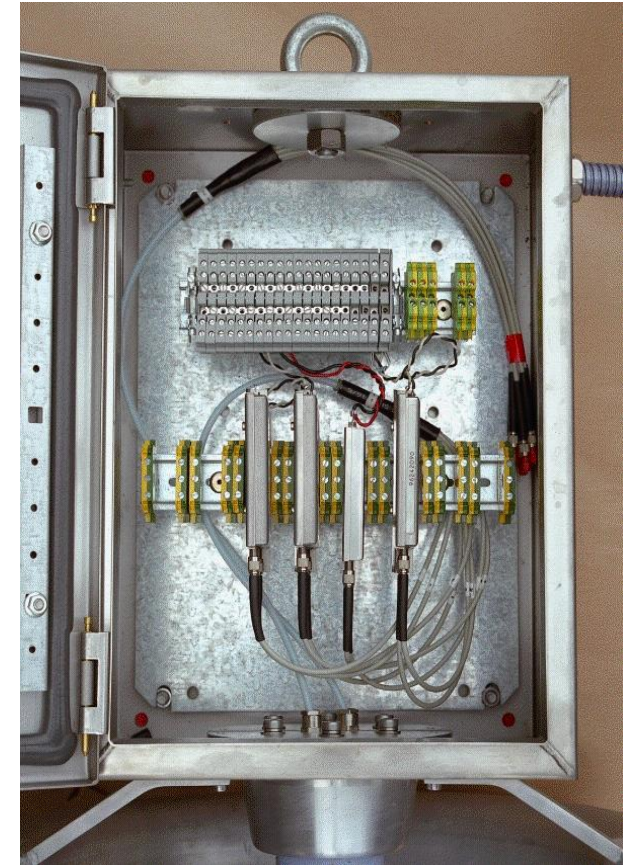
DC Measuring Devices – Functional concept



DC Measuring Devices – Optodyn

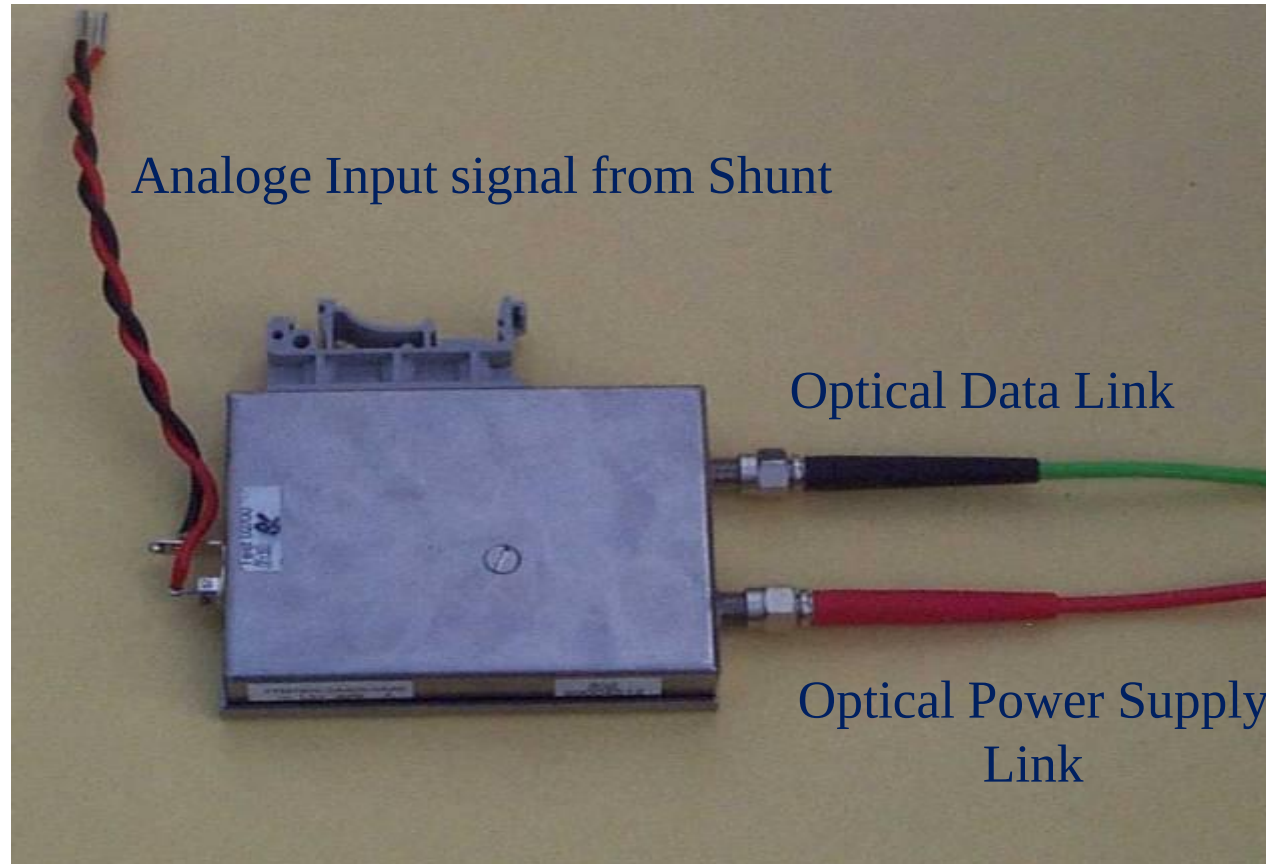


DC shunt Assembly

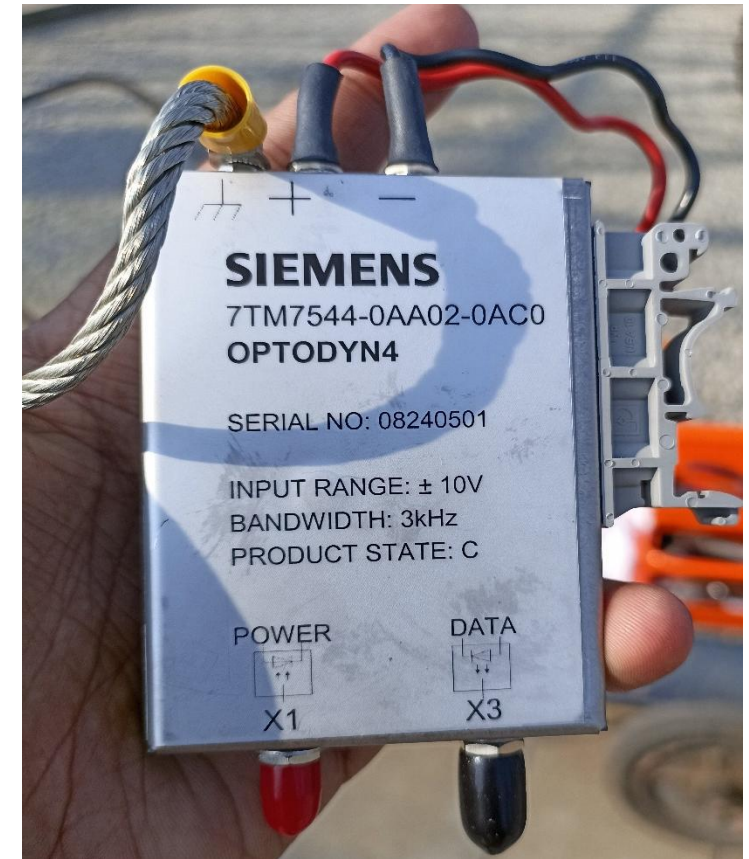


Sensor Head Box

DC Measuring Devices – Optodyn



Optodyn Sensor





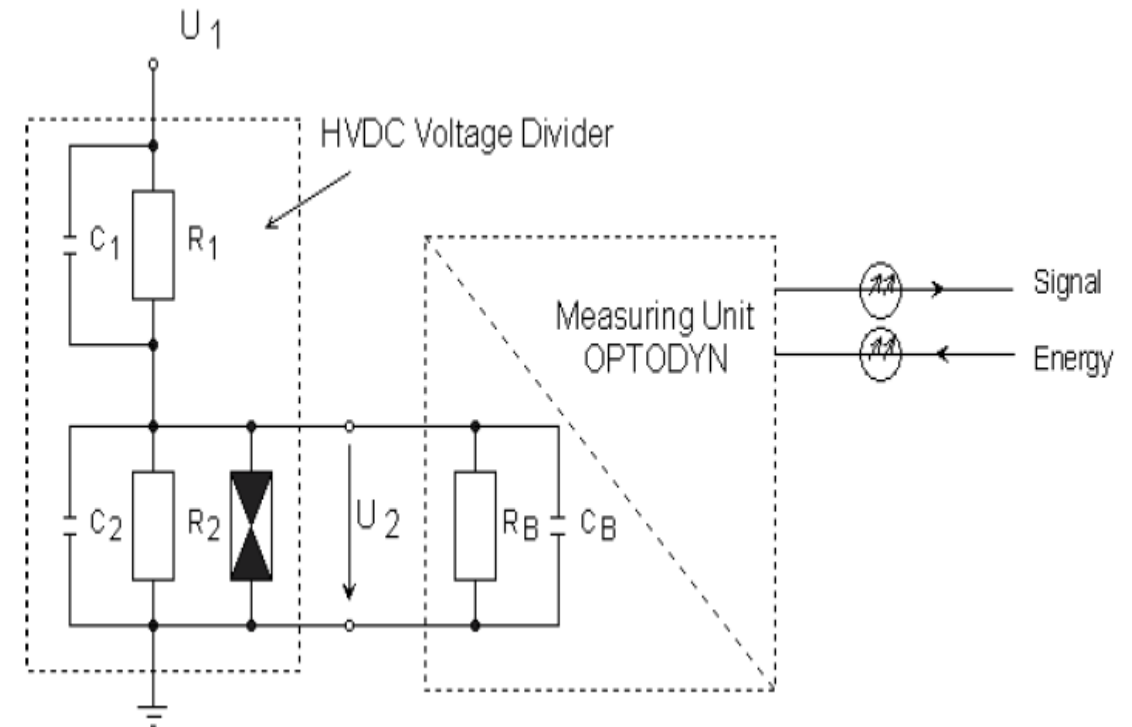
FO Distribution Panel

DC Measuring Devices – SIMADYN



DC Measuring Devices – DC Voltage divider

- Capacitive & resistor divider circuit
- Drop across the resistor scaled for determining the voltage
- Optical conversion process is same as the current measuring device
- Ratio – (500 kV : 5V), (60kV : 5 V)
- Tolerance – 0.2%
- Response time – $33\mu\text{s}$



HV DCVD



LV DCVD



HV DCVD Secondary Box



THANK YOU