HVDC Transmission Systems

(05EE 6034)

Overview

1. Introduction

2. Syllabus

3. References

1. Introduction

- **HVDC Transmission Systems (05EE 6034)**
- 3 Credits Course
- Deals with
    - The importance of HVDC Transmission and HVDC Converters
    - The power conversion between AC to DC and DC to AC

2. Syllabus

Module 1: General Aspects and Converter Circuits

- Historical developments
- HVAC and HVDC links - comparison - economic, technical performance - reliability - limitation
- Properties of thyristor converter circuits - assumptions
- Choice of best circuit for HVDC converters
- Transformer connections

2. Syllabus

Module 2: Bridge Converters - Analysis and Control

- Analysis with gate control but no overlap
- Analysis with overlap less than 60 degrees
- Operation of inverters
- Basic means of control and power reversal
- Desired features of control
- Actual control characteristics.

2. Syllabus

Module 3: Misoperation of Converters and Protection

- Converter disturbance
- By pass action in bridges
- Commutation failure
- Basics of protection
- DC reactors
- Voltage and current oscillations
- Circuit breakers
- Over voltage protection

2. Syllabus

Module 4: Harmonics, Filters and Converter Charts

- Characteristic and uncharacteristic harmonics
- Troubles due to harmonics
- Harmonic filters
- Converter charts of direct current and voltage, active and reactive power
- Interaction between AC and DC systems
- Voltage interaction
- Harmonic instabilities - DC power modulation
- Design considerations of thyristor converters
- Converter transformers
- Smoothing reactions
- Overhead lines
- Cable transmission
- Earth electrodes
- Design of back to back thyristor converter system

3. References

1. E. W. Kimbark, *'Direct Current Transmission-Vol.1'*, Whley Interscience, New York 1971
2. J. Arrilage, *'High Voltage Direct Current Transmission'*, Peter Pereginver Ltd., London U.K. 1983
3. K. R. Padiyar, *'HVDC Transmission Systems'*, Wiley Eastern Ltd., New Delhi 1992

Thank You

*for internal private circulation only

HVDC Transmission Systems

(05EE 6034)

Module 1 - Overview

1. Historical Developments
2. Constitution of HVAC & HVDC Links
3. HVDC Links
    - Monopolar Link
    - Bipolar Link
    - Homopolar Link
4. Comparison between HVAC & HVDC Systems
    - Limitations of HVAC System
    - Advantages of HVDC Transmission
    - Disadvantages of HVDC Transmission
5. Converter Circuits
6. Choice of Best Circuit for HVDC Converter

1. Historical Developments

- Historical sketch : Initial supremacy of **DC Direct Current** → **Alternating Current** → **High Voltage DC Transmission**

Evolution

1831 :

- **Michael Faraday** → Electric current can be induced in a copper wire by a moving magnetic field → Dynamo & Electric Motor

1870's :

- Commercial use of electricity

1882 :

- **Thomas Alva Edison** → 1^{st} electric power system at *Pearl Street in New York*
    - Low Voltage DC Power System(110V)
    - 59 Customers, 1.6km in radius
    - DC generators driven by steam engines, cable, fuse, loads(mostly incandescent lamps)

1. Historical Developments

1884 :

- **Frank Sprague** developed motors (Electricity is more preferred for lighting and motor loads)

1886 :

- Limitations of DC system became apparent
    - High voltage drop & losses(→ Requirement of Voltage transformation)
- **William Stanley** of Westinghouse developed **Transformers** & **AC Distribution System**(150A)
- **George Westinghouse** - Westinghouse Electric Corporation

1888 :

- **Nikola Tesla** developed polyphase system

1889 :

- 1st AC Transmission System in USA
    - Between Willamette Falls and Portland, Oregon
    - Single Phase AC system, 4kV
    - 21km

1. Historical Developments

1890 :

- **Whether AC or DC?**

  Edison : DC System
  Westinghouse : AC System

  AC system became more feasible because

  - Easy Voltage Transformation using Transformers
  - Simple & Cheaper Generators & Motors

  ⟹ DC system is slowly dismantled & AC system became popular

1893 :

- 1^{st} **Three phase AC System** in California(at Niagra Falls)
  - 2.3kV, 12km

1. Historical Developments

1922 : 165kV AC System
1923 : 220kV AC System
1935 : 287kV AC System
1953 : 330kV AC System
1965 : 500kV AC System
1966 : 735kV AC System
1969 : 765kV AC System
1990 : 1100kV AC System

Standard Voltage : **HV** - 115kV, 138kV, 161kV, 230kV
EHV - 345kV, 500kV, 765kV

Frequencies : 25Hz, 50Hz, 60Hz, 125Hz, 133Hz

USA - 60Hz
Europe & Asian Countries - 50Hz

1. Historical Developments

1880 - 1911 : DC System

- HVDC system designed by **Rene Thury**(French Engineer)
- 19 Thury systems were installed in Europe
- Moutiers to Lyons(France)
  - Installed in 1906
  - 180km(4.5km underground cable)
  - 4.3MW, 57.6kV, 75A
  - DC Series Generators were used
  - Constant Current Control Mode of Operation

1920 :

- **Transverters** were developed by **W. E. Highfield** & **J. E. Calverley**
  - Mechanical Converter(Polyphase transformer commutated by synchronously rotating bus-gear)

1938 :

- All Thury systems were dismantled
  - Safety problem
  - High Cost & Maintenance

1. Historical Developments

1936 :

- Between **Mechanicville Hydroelectric Plant**(of New York Power & Light Corporation) and **General Electric Factory** in **Schenectady**
  - 5.25MW, 30kV, 175A
  - Frequency conversion : **40Hz** to **60Hz**

1939 :

- **Wettingen Power Plant** near **Baden** to **Zurich(Switzerland)**
  - 0.5MW, 50kV, 10A
  - 30km

1950 :

- Mercury Arc Valve was developed $\implies$ AC to DC Conversion is made possible

1954 :

- 1st **HVDC Transmission System** between **Sweeden & Gotland Island**
  - 20MW, 100kV(Two converters of 10MW, 50kV, 200A in series)
  - 96km

1. Historical Developments

HVDC Systems in India

1989 :

- **Vindhyachal Back to Back HVDC Station**
    - ±70kV, 2×250MW
    - Vindhyachal(Uttar Pradesh) Super Thermal Power Stations to Singrauli(Madhya Pradesh) Super Thermal Power Stations
    - Bidirectional power flow capability
    - **First commercial Back to Back HVDC Station in India**

1991 :

- **Rihand(Uttar Pradesh) - Dadri(Delhi) HVDC Project**
    - ±500 kV, 1500 MW
    - Bipolar Transmission Link
    - 816 km
    - Coal-based Rihand Thermal Power Station

1. Historical Developments

1993 :

- Chandrapur Back to Back Station
  - 205kV, 2×500MW
  - Chandrapur(Maharashtra) Thermal Power Stations to Ramagundum(Telangana)
  - Second commercial Back to Back HVDC Station in India

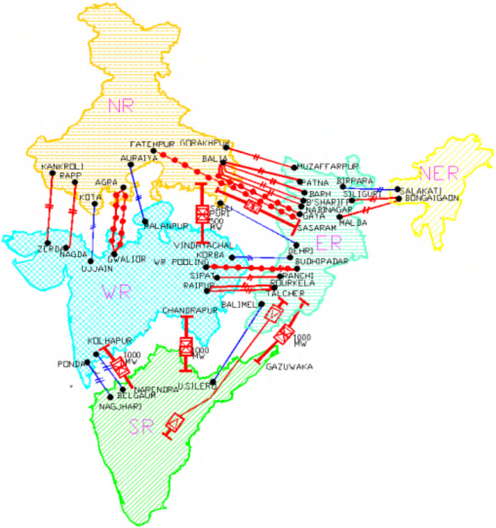
2003 :

- **Talchar Kolar HVDC Transmission Link**
  - ±500kV, 2500MW
  - **Longest (1369 Km.) commercial HVDC link in India**

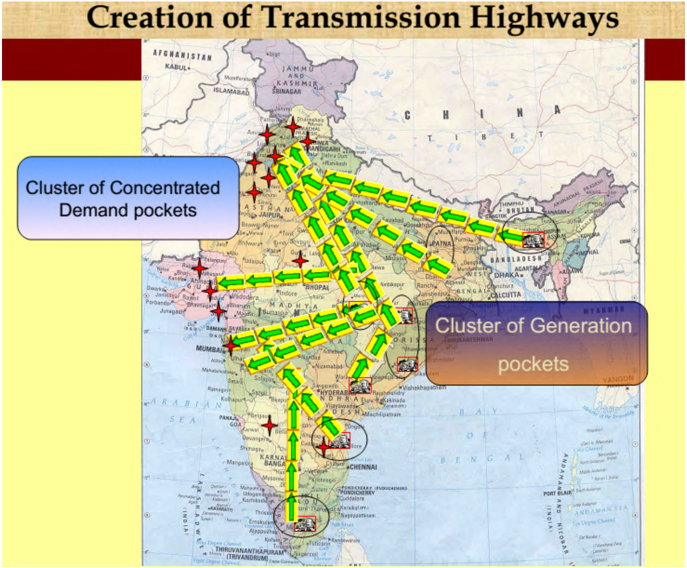
1. Historical Developments

- **Sasaram Back to Back Station**
  - 205kV, 1×500MW
  - Connects Pusauli to Sasaram(Bihar)
- **Gazuwaka Back to Back Station**
  - 205kV(Block-1) & 177kV(Block-2)
  - 2×500MW
  - Connects Jeypore to Gazuwaka(Andhra Pradesh) Thermal Power Stations
- **Ballia(Uttar Pradesh) - Bhiwadi(Rajasthan) HVDC Transmission Link**
  - ±500kV, 2500MW
  - 780Km
- **Biswanath(Assam) - Agra(Uttar Pradesh) HVDC Transmission Link**
  - ±600kV, 4000MW

1. Historical Developments



1. Historical Developments

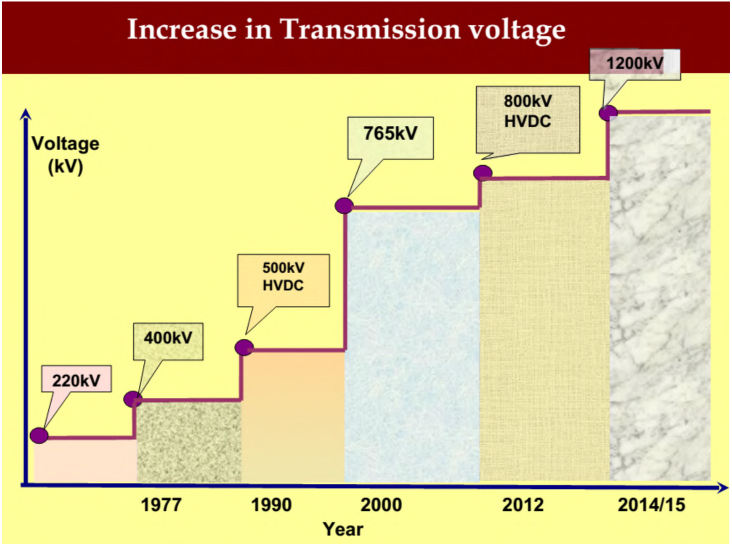


Creation of Transmission Highways

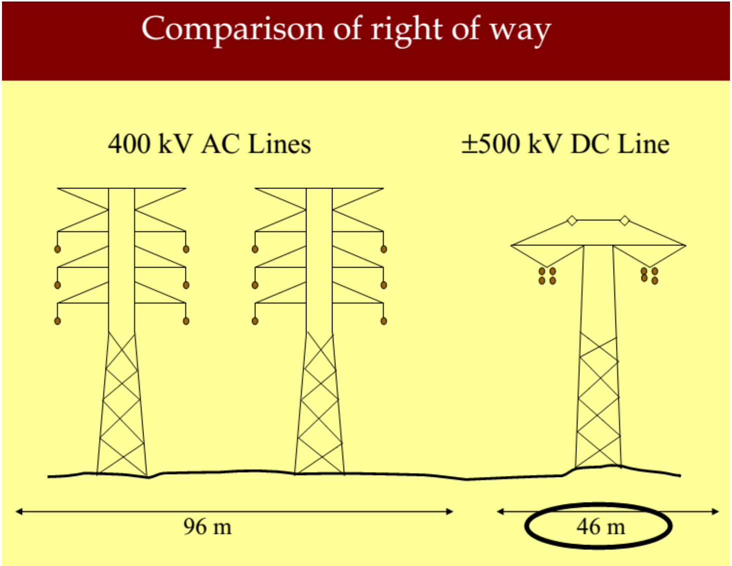
Cluster of Concentrated Demand pockets

Cluster of Generation pockets

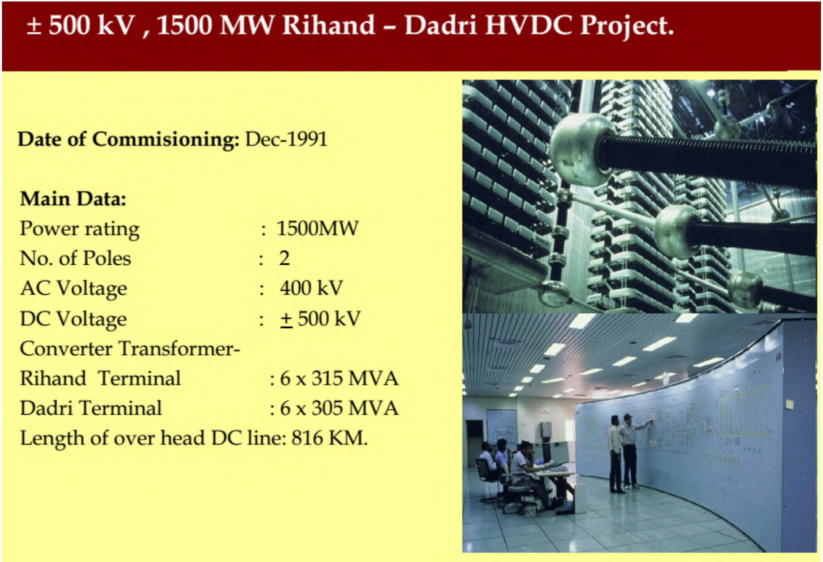
1. Historical Developments



1. Historical Developments



1. Historical Developments



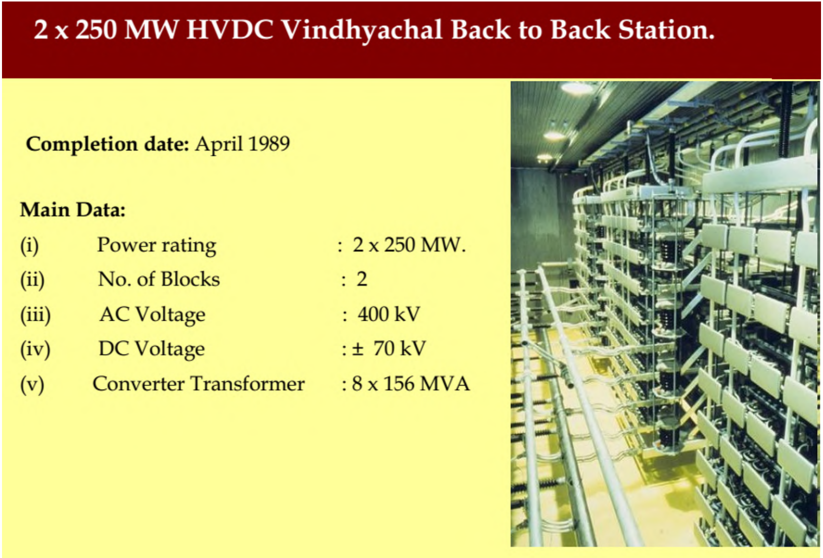
± 500 kV , 1500 MW Rihand – Dadri HVDC Project.

Date of Commisioning: Dec-1991

Main Data:

Power rating : 1500MW
No. of Poles : 2
AC Voltage : 400 kV
DC Voltage : ± 500 kV
Converter Transformer-
Rihand Terminal : 6 x 315 MVA
Dadri Terminal : 6 x 305 MVA
Length of over head DC line: 816 KM.

1. Historical Developments



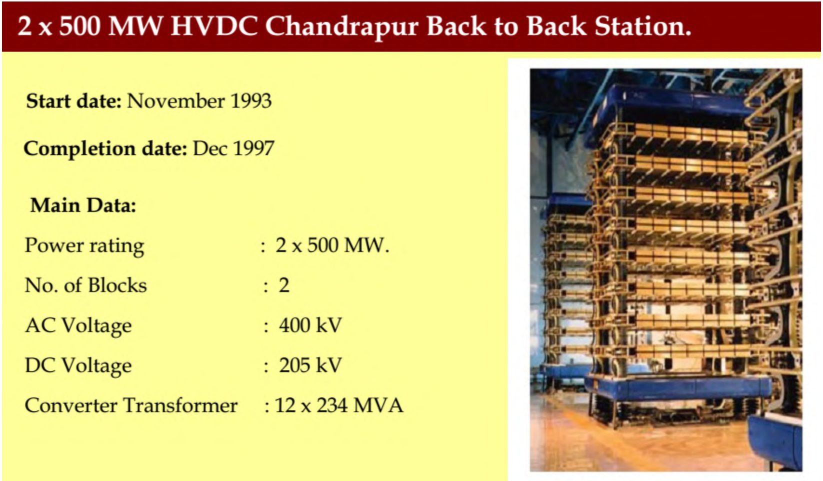
2 x 250 MW HVDC Vindhyachal Back to Back Station.

Completion date: April 1989

Main Data:

(i) Power rating : 2 x 250 MW.
(ii) No. of Blocks : 2
(iii) AC Voltage : 400 kV
(iv) DC Voltage : ± 70 kV
(v) Converter Transformer : 8 x 156 MVA

1. Historical Developments



2 x 500 MW HVDC Chandrapur Back to Back Station.

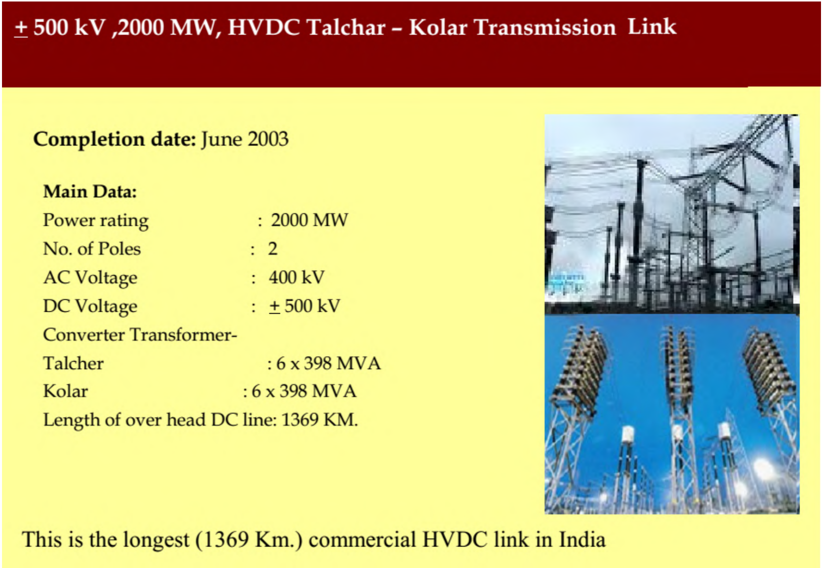
Start date: November 1993

Completion date: Dec 1997

Main Data:

Power rating : 2 x 500 MW.
No. of Blocks : 2
AC Voltage : 400 kV
DC Voltage : 205 kV
Converter Transformer : 12 x 234 MVA

1. Historical Developments



± 500 kV ,2000 MW, HVDC Talchar – Kolar Transmission Link

Completion date: June 2003

Main Data:

Power rating : 2000 MW

No. of Poles : 2

AC Voltage : 400 kV

DC Voltage : ± 500 kV

Converter Transformer-

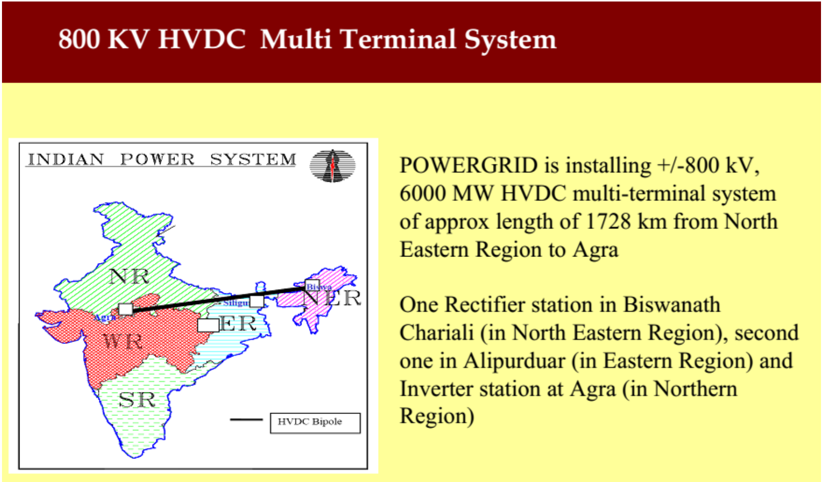
Talcher : 6 x 398 MVA

Kolar : 6 x 398 MVA

Length of over head DC line: 1369 KM.

This is the longest (1369 Km.) commercial HVDC link in India

1. Historical Developments

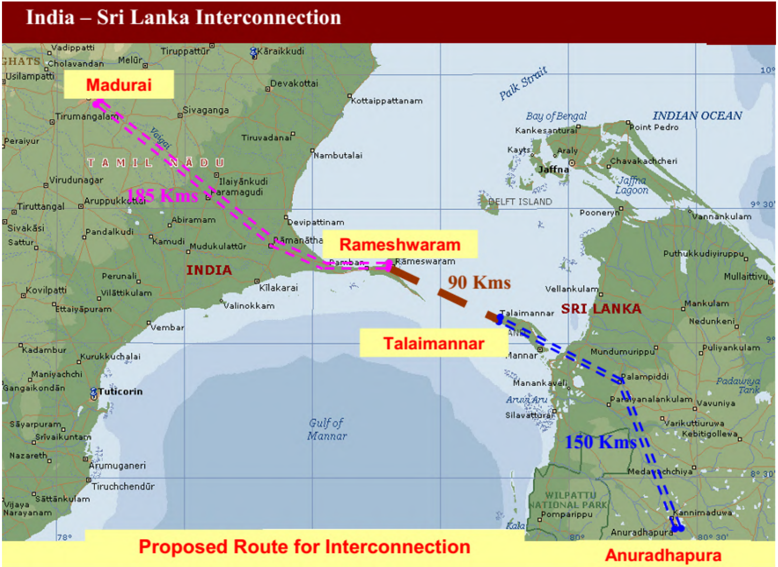


800 KV HVDC Multi Terminal System

POWERGRID is installing +/-800 kV, 6000 MW HVDC multi-terminal system of approx length of 1728 km from North Eastern Region to Agra

One Rectifier station in Biswanath Chariali (in North Eastern Region), second one in Alipurduar (in Eastern Region) and Inverter station at Agra (in Northern Region)

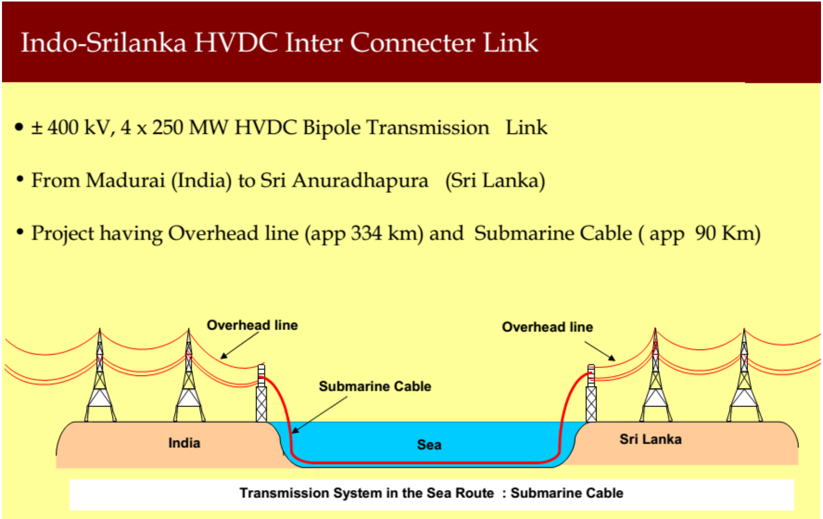
1. Historical Developments



India – Sri Lanka Interconnection

Proposed Route for Interconnection

1. Historical Developments

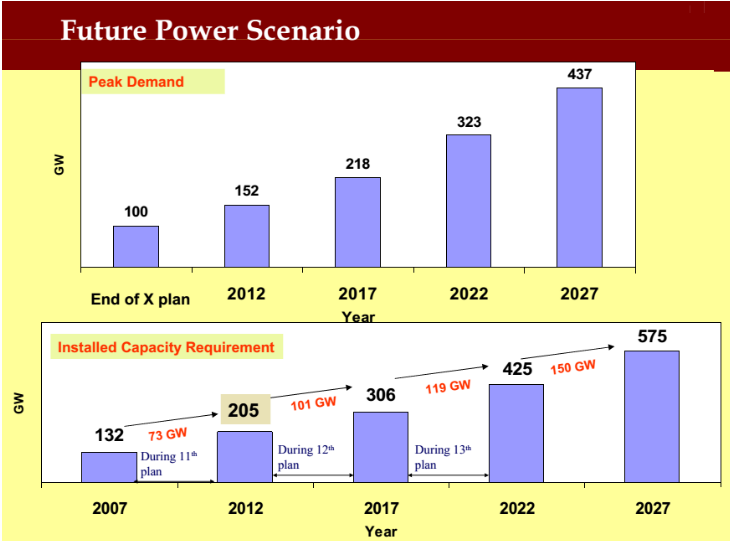


Indo-Srilanka HVDC Inter Connecter Link

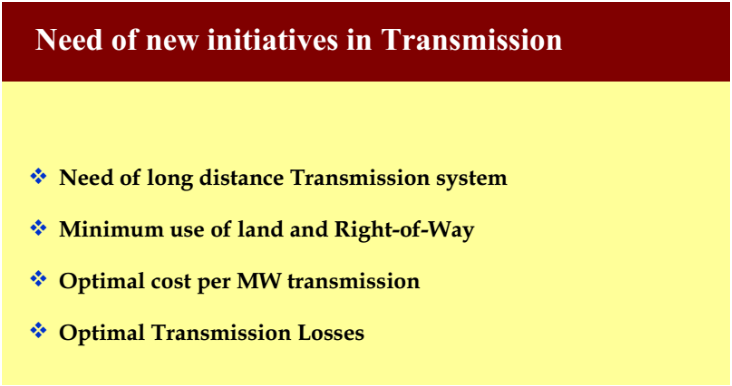
- ± 400 kV, 4 x 250 MW HVDC Bipole Transmission Link
- From Madurai (India) to Sri Anuradhapura (Sri Lanka)
- Project having Overhead line (app 334 km) and Submarine Cable (app 90 Km)

Transmission System in the Sea Route : Submarine Cable

1. Historical Developments



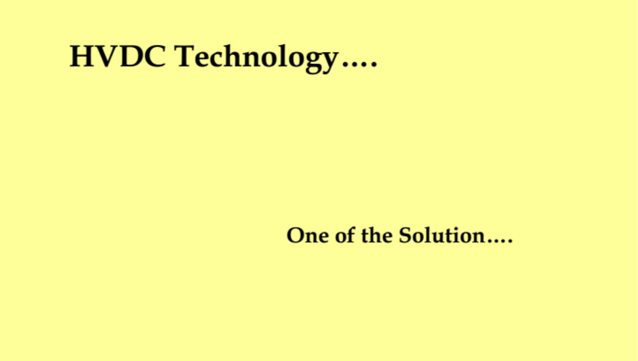
1. Historical Developments



Need of new initiatives in Transmission

- Need of long distance Transmission system
- Minimum use of land and Right-of-Way
- Optimal cost per MW transmission
- Optimal Transmission Losses

1. Historical Developments



HVDC Technology….

One of the Solution….

2. Constitution of HVAC & HVDC Links

Transmission Link : Transmission Line with it's terminal and auxiliary equipments

Valve : Devices having inherent unidirectional conduction

1. **3-Phase AC Line**

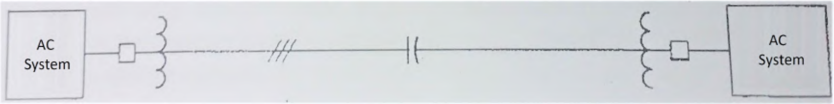


Figure 1 : Single Line Diagram of 3-Phase AC Line

- Transformers at both ends
  - Step-up Transformer at sending end
  - Step-down Transformer at receiving end
- Inductive reactance → series compensation
- Series capacitor banks are required.

2. Constitution of HVAC & HVDC Links

2 Two Circuit 3-Phase AC Line

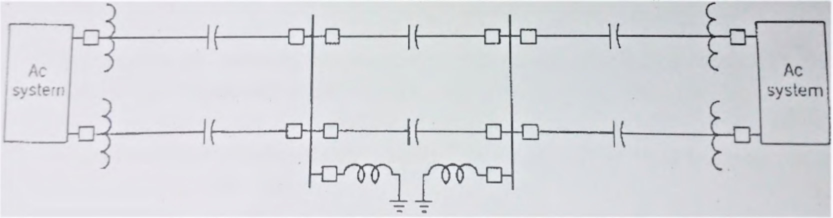


Figure 2 : Single Line Diagram of Two Circuit 3-Phase AC Line

- **Three pole switching** is preferred(avoids unbalance operation)
- Two-parallel three-phase circuits → **Reliable operation**

2. Constitution of HVAC & HVDC Links

- Two-circuit AC Links are sectionalized by means of **Intermediate Switching Stations**
  - Limiting overvoltage when a line is energised from one end
  - Provide place for connection of grounding transformers to limit overvoltages of unfaulted phases w.r.t ground when one phase is faulted to ground
  - Limiting the decrease in stability power limit due to switching out one circuit to clear a fault or for line maintenance
  - For connection of intermediate loads or generation
- **Shunt Reactors** → for limiting the voltage at light loads

2. Constitution of HVAC & HVDC Links

② Single Circuit DC Link

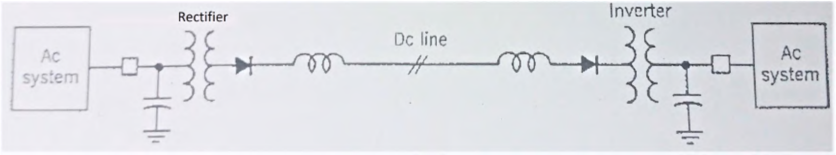


Figure 3 : Single Circuit DC Link

- Usually two conductors(**Bipolar**) or only one conductor, return path being earth/seawater(**Monopolar**)
- Converters on both ends
  - Sending end converter → **Rectifier**
  - Receiving end converter → **Inverter**
- **Power Reversal**

2. Constitution of HVAC & HVDC Links

- **Circuit beakers** on AC sides → clear faults in transformers or for taking whole DC link out of service.
- **Grid Control of Valves** → for clearing faults on DC side or misoperations of valves
- **Harmonic Filters** and **Shunt Capacitors** on AC side → supply reactive power to the converter
- **DC Smoothing Reactors** → Large inductances connected in series with each pole

2. Constitution of HVAC & HVDC Links

❸ Two circuit DC Link

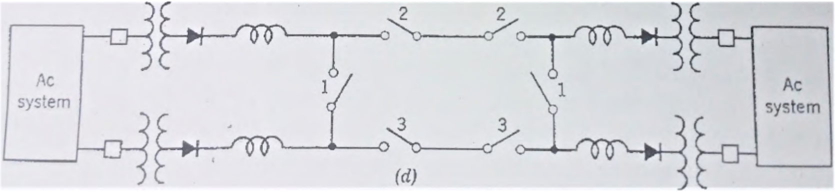


Figure 4 : One-pole of a four-conductor DC Link

During fault on lower conductor

- Converters on lower conductor would be controlled to bring the voltage & current on it to zero
- Open bus-tie switch-3 → isolates faulted line
- Raise converter voltages to equality with those adjacent converters
- Close bus-tie switch-1
- All converters are utilised

Operation time ≈ 0.3 sec

3. HVDC Links

1. **Monopolar Link**

Figure 5 : Monopolar Link

- One Conductor usually of negative polarity
- Ground or sea acts as return path

3. HVDC Links

② Bipolar Link

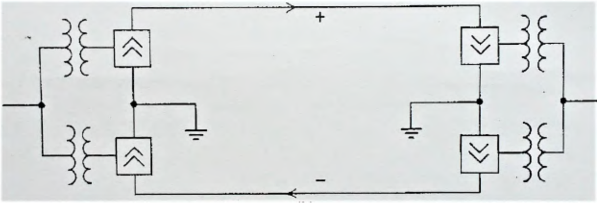


Figure 6 : Bipolar Link

- Positive & Negative polarity conductors
- Each terminal has two converters of equal rated voltages in series on DC side
- junction between converters are grounded at both ends
- Normally both poles conduct equally
- In case of fault on one conductor → other conductor with ground return can carry up to half of the rated load

3. HVDC Links

2 Homopolar Link

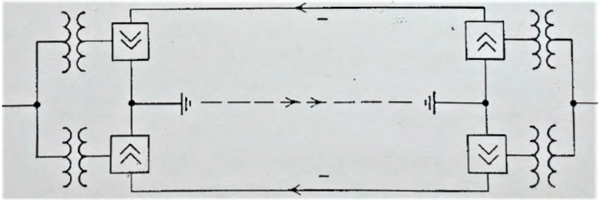


Figure 7 : Homopolar Link

- Two or more conductors of **same polarity** usually negative & always operates with ground return
- In case of fault on one conductor → converter will be connected to the remaining conductor → carries more than half of rated power with increased line loss
- **Less power loss due to corona**
- Negative polarity is preferred for overhead line because of smaller radio interference

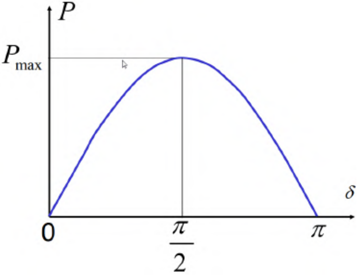
4. Comparison between HVAC & HVDC Systems

1. Limitations of HVAC System
2. Advantages of HVDC System
3. Disadvantages of HVDC System

4.1 Limitations of HVAC Transmission

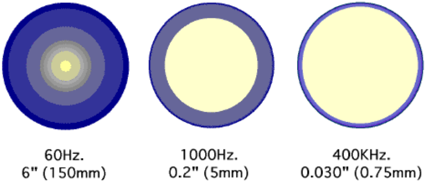
1. **Reactive Power Loss**
   - $P_L = I^2 R$
   - $Q_L = I^2 X_L - V^2/X_C$
   - $Q_L = 0$ for HVDC $\Longrightarrow$ Transfer of more power than HVAC
2. **Stability**

- $0 < P < P_{max}$
- $0 < \delta < \pi/2$
- Two adjacent nodes angle difference is normally less than 30^o
- Continuous control is necessary for stable operation
- No such issue in HVDC



4.1 Limitations of HVAC Transmission

3. **Current Carrying Capacity**
   - $\overrightarrow{I_L} = \overrightarrow{I_p} + \overrightarrow{I_q}$
   - Low for AC system than DC system due to the presence of I_q
4. **Skin Effect**



- Non-uniform current distribution across the cross section of conductor
- Effective resistance will be more $\implies R_{AC} > R_{DC}$
- More power loss

4.1 Limitations of HVAC Transmission

5. **Ferranti Effect**
   - At no-load/light load condition, $V_r > V_s$ due to capacitive charging
   - Line Reactors / Bus Reactors are used to nullify ferranti effect
6. Smooth power flow control / Reversal of power flow is not possible
   - FACTS devices can be used for power flow control in HVAC(But practical use started only during 1990's)

4.2 Advantages of HVDC Transmission

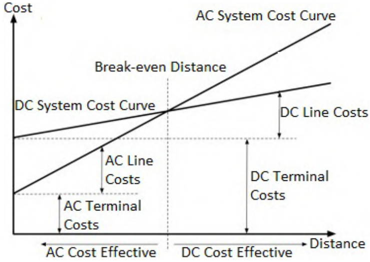
1. **No Reactive Power Loss**
    - L & C have no impact
2. **No Stability Problem**
    - HVAC →**Thermal Limit** & **Stability Limit**
    - HVDC → Only **Thermal Limit**(can load up to thermal limit)
3. **No Charging Current**
    - Long Transmission Line is possible
4. **No Skin Effect & Ferranti Effect**
5. **Smooth Power Flow Control is possible**
    - $P_{dc} = V_{dc} I_{dc}$
    - Usually I_{dc} is kept constant & V_{dc} is varied
    - **Two Quadrant Operation**($-V_{dc} \leftrightarrow 0 \leftrightarrow +V_{dc}$) & **Power Reversal**

4.2 Advantages of HVDC Transmission

6. **Less Space Requirement for Same Voltage Rating & Capacity**
   - $V_{max} \rightarrow$ Insulation requirement
   - $V_{rms} \rightarrow$ Power
   - HVDC Tower requires less space for same P & V
7. **Ground can be used as return conductor**
   - **Monopolar**
     - Reduce cost of conductor
     - Ground current may cause communication interference, corrosion, safety problems etc.
   - **Bipolar**
     - Commonly used
     - During fault conditions, operation as monopolar with 50% power transfer capability
8. **Less Corona Loss & Radio Interference**
   - $P_{corona\ loss} \propto (f + 25)$
   - Negligible for HVDC system

4.2 Advantages of HVDC Transmission

9. **Cheaper for Long Distance Transmission**



- HVDC requires many costly terminal equipments(converter, filter, smoothing reactor etc.)
- **Break-even Distance**
- For transmission distance < Break-even distance → HVAC is cheaper
- For transmission distance > Break-even distance → HVDC is cheaper
    - For long distance transmission, HVAC becomes more costlier due to huge charging reactive power. Intermediate compensating devices are required for controlling voltage profile
- Break-even Distance ≈ 600km

4.2 Advantages of HVDC Transmission

10. **Asynchronous Operation is possible**
    - Two different frequency regions can be interconnected through HVDC Link
11. **No Switching Transients**
    - Energy storage elements(L & C) cause switching transients
    - Switching transient magnitude depends on values of L & C and their distribution
    - No switching transients in HVDC system
    - Smoothing reactors are present only during switching

4.2 Advantages of HVDC Transmission

12. **No Transmission of Short Circuit Power**
    - Fault Level
    - **HVAC**
        - Adding additional line to the bus increases fault level
        - May require even to change circuit breaker
    - **HVDC**
        - HVDC link will not increase fault level
        - DC Line converter control is very very fast
        - No transmission of short-circuit power from one side to the other
13. **Low Short Circuit Current**
    - HVDC Line doesn't contribute to fault current of bus
14. **No Compensation Problem**
    - **HVAC**
        - Distributed L & C parameters
        - Compensation devices → good voltage profile
    - **HVDC**
        - No compensation is required

4.2 Advantages of HVDC Transmission

⑮ **Fast Fault Clearing Time**

- **HVAC**
  - Fault → Relay → Circuit Breaker(Mechanical device) → Fault Clearing
  - Slow fault clearing operation
- **HVDC**
  - Power Electronic Converter Control → Very fast control
  - Fast fault clearing operation

4.3 Disadvantages of HVDC Transmission

1. **Cost of Terminal Equipments is High**
    - Auxiliary equipments
    - Inverter, Converter, Cooling System, Filter, Smoothing Reactor etc.
2. **Introduction of Harmonics**
    - Conventional Power Converters
    - **Characteristic Harmonics**
        - $np \pm 1$ (n=integer, p=pulse number)
        - 6 pulse converter → 5, 7, 11, 13.... etc.
    - **Uncharacteristic Harmonics**
        - Mainly due to overlapping
    - Injection of harmonics into the AC system will cause problems
    - Harmonic filtering
3. **Blocking of Reactive Power(Q)**
    - **HVAC**
        - Q should be compensated locally
        - In case of emergency, AC line allows transfer of Q from one region to other
    - HVDC Line blocks the transfer of reactive power

4.3 Disadvantages of HVDC Transmission

4. **Point to Point Transmission**
   - Constant Current Control
   - Tapping of power in between sending end & receiving end is not allowed to keep I constant
   - Communication between terminal converters is necessary
   - **Multi-terminal HVDC System** → Power tapping in between sending end & receiving end → intermediate converter station → communication between all converters → complex & costly
5. **Limited Overload Capacity**
   - Use of power electronic converters
   - Power electronic devices rated for certain voltage & current
   - Overloading is not possible
6. **Huge Reactive Power Requirements at Converter Terminals**
   - No reactive power is involved in HVDC transmission line
   - Power flow control → V_dc control(ie, constant I_dc) → firing angle(α) control
   - $Cos\Phi = Cos\alpha$
   - Requires compensating devices at terminal converter stations

DC Power System

1. **Bulk Power Transmission**
    - Bulk power transfer from one region to other
    - No tapping of power in between
    - **Bulk Power** over **Long Transmission Line**
2. **Back to Back HVDC System**
    - Nearby regions connected through back to back converter
    - Monitoring power flow from one region to other
    - Disturbance in one region can't propagate to other
    - **Power Flow Control**
3. **Modulation of AC-DC System**
    - Weak AC line → Line power oscillations → may cause instability
    - Parallel DC line can support weak AC line
    - **Improvement of Stability**

Comparison of AC & DC Transmission

- **Economics of Power Transmission**
- **Technical Performance**
- **Reliability**
  - **Energy Availability** $= (1 - \frac{Equivalent\ \ Outage\ \ Time}{TotalTime}) \times 100\ \%$

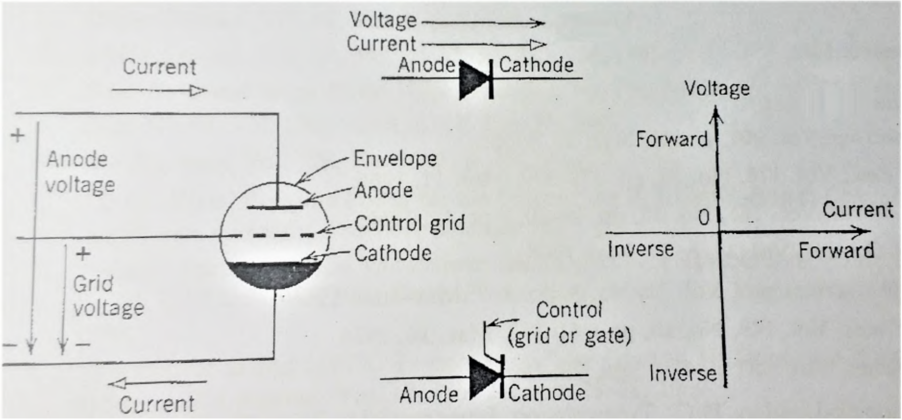
    Equivalent Outage Time = Actual Outage Time × Fraction of system Capacity Lost due to outage
  - **Transient Reliability** = (No of times HVDC system performed as designed)/(No of recordable AC faults)× 100 %
  - For HVDC system, reliability indices are $> 95\ \%$
  - Average failure rate of thyristors $< 0.6\%$ per operating year

5. Converter Circuits

- Mercury Arc Valve with Control Grid
- Thyristor Converter

1. Single Phase Converters
    - Half-wave Rectifier
    - Full-wave Rectifier
    - Bridge Rectifier
2. Three Phase Converters
    - Three Phase One-Way Rectifier
    - Three Phase Two-way Bridge Rectifier
3. Cascade of Two Three-phase Rectifiers
4. Parallel Connections with Interphase Transformer
5. Six-phase Diametrical Connection
6. Cascade of Three Single-phase Full-wave Rectifier
7. Twelve Pulse Cascade of Two Bridges

Valve Characteristics



Valve Characteristics

- Valve - Unidirectional Current Flow(from Anode to Cathode)
- Forward Voltage drop(20 - 50V for mercury arc valve)
- Inverse Voltage & Inverse leakage current(milliampere)

Characteristics

1. Positive(Forward) Current at Zero Voltage
2. Negative(Inverse) Voltage at Zero Current

Properties of Converter Circuits

- Waveform of V & I
- Magnitudes of DC Voltage(V_d) & DC Current(I_d)
- Calculation of VA rating of Valves & Transformers
- **VA rating of Valve = Average Current × Peak Inverse Voltage(PIV)**
- **Rating of Transformer = RMS Voltage × RMS Current**

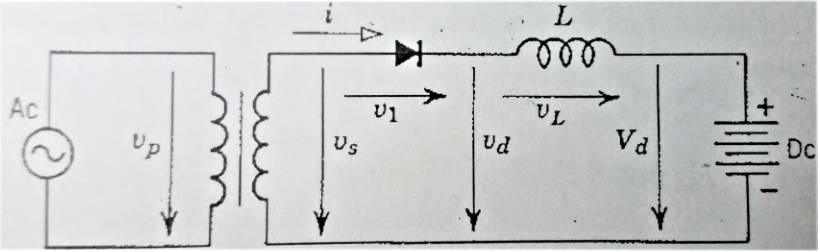
Assumptions

Ideal Conditions

- **Valve**
    - No control grids for valves
    - Converters operate as only rectifiers with no ignition delay
- **AC Source**
    - No impedance
    - Constant Voltage of sinusoidal waveform
    - Constant Frequency
    - Balanced Voltages in case of Polyphase system
- **Transformers**
    - No leakage impedance & exciting admittance
- **DC Load**
    - Infinite inductance($\Longrightarrow$ I_d is constant)
    - No ripple current but DC voltage on the valve side of smoothing reactor has ripple
    - DC Load → reactor in series with an EMF of constant voltage(Average value of ripple voltage)

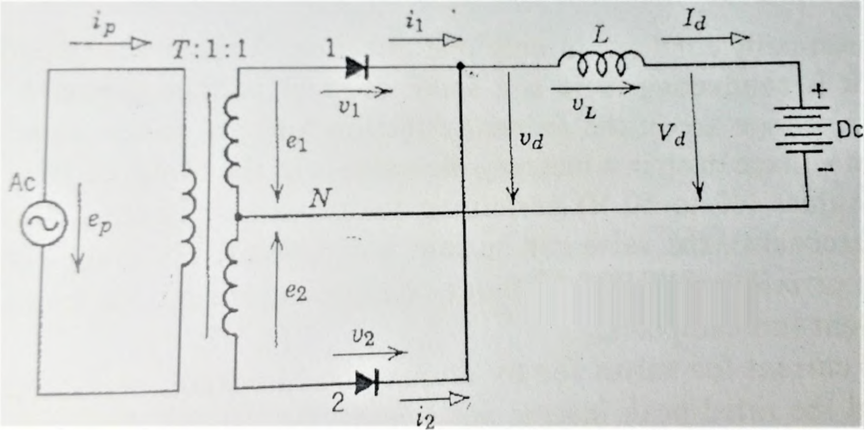
Single Phase Converters

Half-wave Rectifier

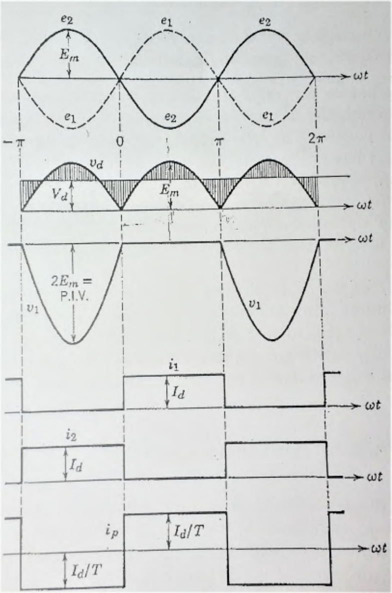


- Simplest Rectifier with One valve
- Current is inherently intermittent → I_d & V_d pulsate at same frequency of AC
- Direct current through transformer may saturate core → excessive primary current → Heating
- Only for very small power use

Full-wave Rectifier



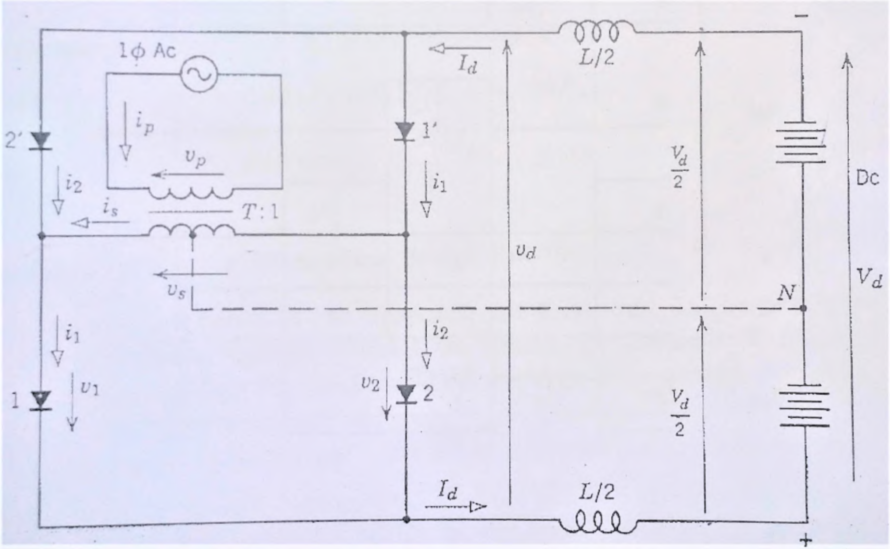
Full-wave Rectifier



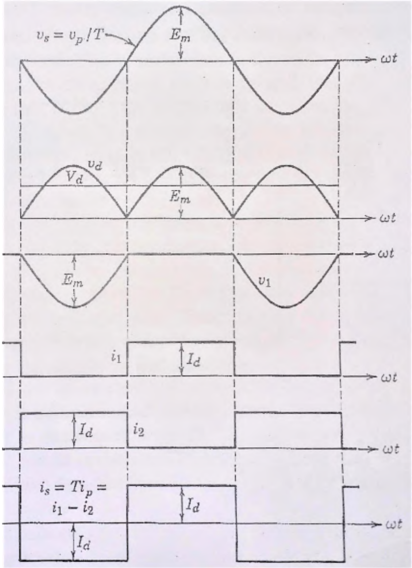
Full-wave Rectifier

- Two valves, Transformer with center-tapped 2^o winding
- Average Voltage $V_d = 0.637E_m$
- $E_m = 1.571V_d$
- Peak Inverse Voltage(PIV) $= 2E_m = 3.142V_d$
- E_1(RMS of e_1) $= 0.707E_m = 1.111V_d$
- E_p(RMS of e_p) $= 0.707\mathrm{T}E_m = 1.111\mathrm{T}V_d$
- Peak value of current in each valve $= I_d$
- Average value of current in each valve $= I_d/2$
- RMS value of current in each valve $= 0.707I_d$
- Aggregate VA rating of valve $= 2 \times 3.142V_d \times I_d/2 = 3.142V_dI_d = 3.142P_d$
- VA rating of 2^o winding $= 2 \times 1.111V_d \times 0.707I_d = 1.571P_d$
- VA rating of 1^o winding $= 1.111\mathrm{T}V_d \times I_d/T = 1.111P_d$

Bridge Rectifier



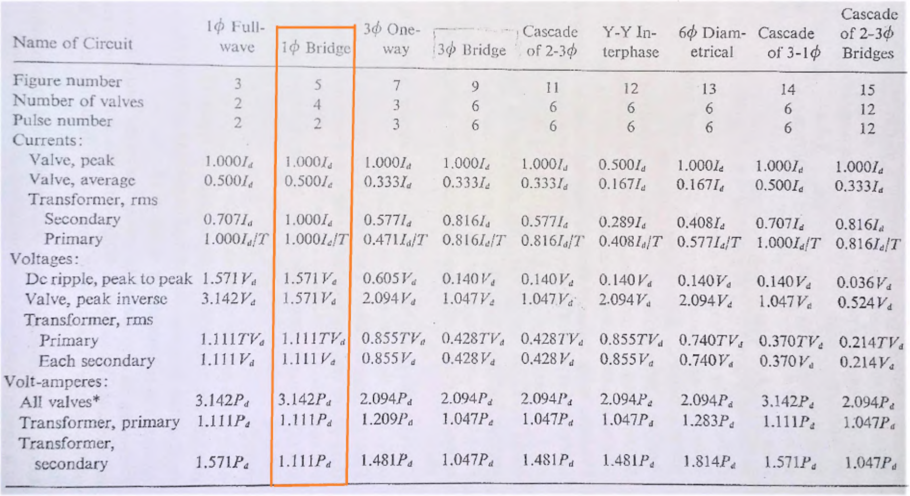
Bridge Rectifier



Bridge Rectifier

- **Two-way Circuit**
- N → Common neutral point
- Three-wire DC System
- If currents on positive & negative sides were equal $\implies$ No neutral current
- On comparison with full-wave rectifier
  - No of valves, V_d, P_d became double
  - Valves 1 & 1' conduct in series for one-half cycle and 2 & 2' in next half cycle
  - No change in valve current & Load current
  - Transformer 1^o current is doubled
  - Transformer 2^o winding is more effectively used(High Power Converters)
  - PIV of each valve became half for a given DC voltage → High Voltage Converters

Bridge Rectifier

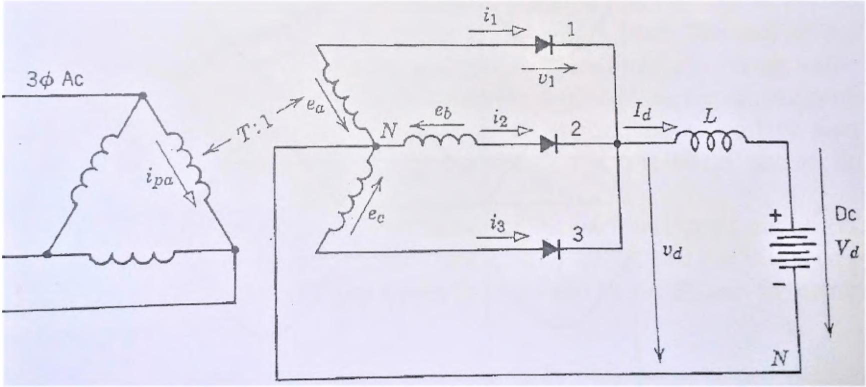


Name of Circuit	1ϕ Full-wave	1ϕ Bridge	3ϕ One-way	3ϕ Bridge	Cascade of 2-3ϕ	Y-Y Interphase	6ϕ Diametrical	Cascade of 3-1ϕ	Cascade of 2-3ϕ Bridges
Figure number	3	5	7	9	11	12	13	14	15
Number of valves	2	4	3	6	6	6	6	6	12
Pulse number	2	2	3	6	6	6	6	6	12
Currents:									
Valve, peak	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$0.500I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$
Valve, average	$0.500I_d$	$0.500I_d$	$0.333I_d$	$0.333I_d$	$0.333I_d$	$0.167I_d$	$0.167I_d$	$0.500I_d$	$0.333I_d$
Transformer, rms									
Secondary	$0.707I_d$	$1.000I_d$	$0.577I_d$	$0.816I_d$	$0.577I_d$	$0.289I_d$	$0.408I_d$	$0.707I_d$	$0.816I_d$
Primary	$1.000I_d/T$	$1.000I_d/T$	$0.471I_d/T$	$0.816I_d/T$	$0.816I_d/T$	$0.408I_d/T$	$0.577I_d/T$	$1.000I_d/T$	$0.816I_d/T$
Voltages:									
Dc ripple, peak to peak	$1.571V_d$	$1.571V_d$	$0.605V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.036V_d$
Valve, peak inverse	$3.142V_d$	$1.571V_d$	$2.094V_d$	$1.047V_d$	$1.047V_d$	$2.094V_d$	$2.094V_d$	$1.047V_d$	$0.524V_d$
Transformer, rms									
Primary	$1.111TV_d$	$1.111TV_d$	$0.855TV_d$	$0.428TV_d$	$0.428TV_d$	$0.855TV_d$	$0.740TV_d$	$0.370TV_d$	$0.214TV_d$
Each secondary	$1.111V_d$	$1.111V_d$	$0.855V_d$	$0.428V_d$	$0.428V_d$	$0.855V_d$	$0.740V_d$	$0.370V_d$	$0.214V_d$
Volt-amperes:									
All valves*	$3.142P_d$	$3.142P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$3.142P_d$	$2.094P_d$
Transformer, primary	$1.111P_d$	$1.111P_d$	$1.209P_d$	$1.047P_d$	$1.047P_d$	$1.047P_d$	$1.283P_d$	$1.111P_d$	$1.047P_d$
Transformer, secondary	$1.571P_d$	$1.111P_d$	$1.481P_d$	$1.047P_d$	$1.481P_d$	$1.481P_d$	$1.814P_d$	$1.571P_d$	$1.047P_d$

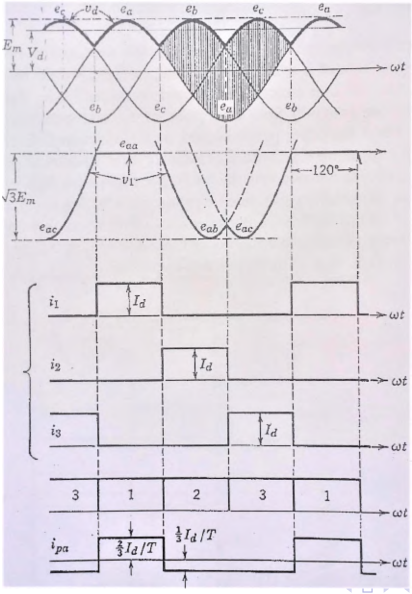
Polyphase Converters

- Polyphase converters
    - Smaller DC ripple magnitude
    - Higher DC ripple frequency
    - Easy to filter

Three-phase One-way Rectifier



Three-phase One-way Rectifier



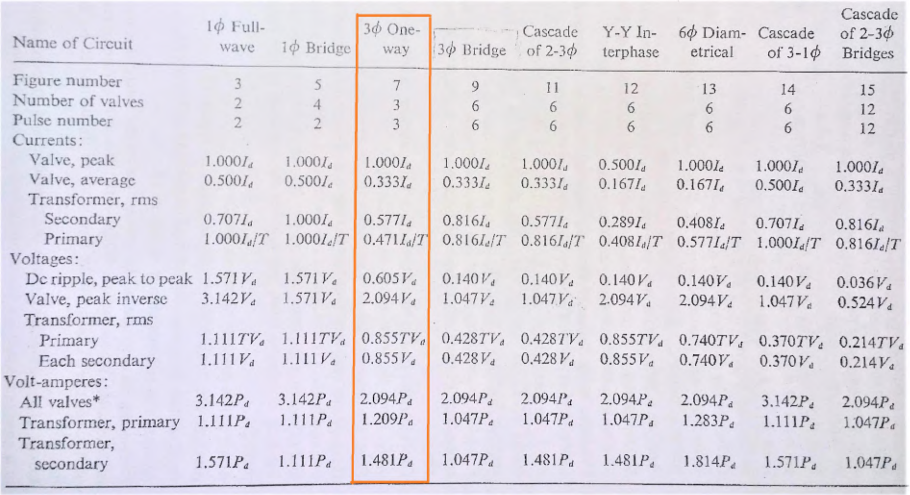
Three-phase One-way Rectifier

- Simplest three-phase converter
- DC current in 2^o saturates transformer core($\therefore$ use **zig-zag connection** instead of star-connection)
- e_a, e_b, e_c $\rightarrow$ Balance three-phase secondary voltages
- v_d = upper envelope of e_a, e_b & e_c
- $V_d = 0.827E_m$
- $E_m = 1.209V_d$
- Peak to peak ripple $= E_m(1\text{-}\cos 60) = 0.605V_d$
- Peak Inverse Voltage(PIV) $= \sqrt{3}E_m = 2.094V_d$

Three-phase One-way Rectifier

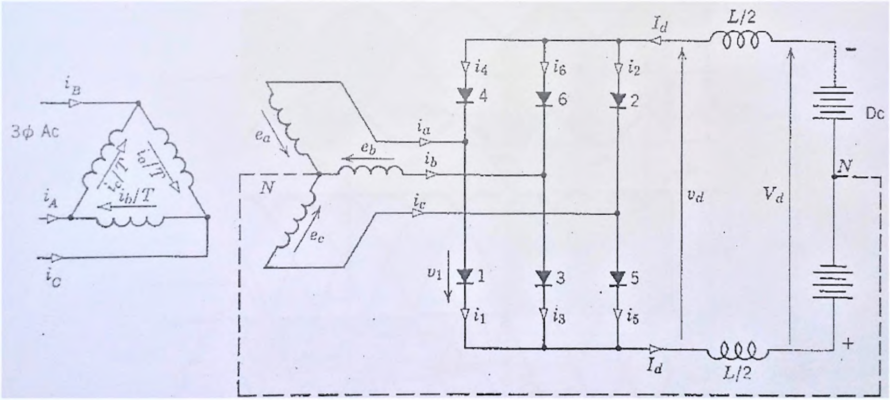
- Each valve conducts for one-third cycle
- Valve current(average) $= I_d/3$
- Valve current(rms) $= I_d/\sqrt{3} = 0.577 I_d$
- Transformer 2^o current $=$ valve current
- Transformer 1^o current has no DC component(average current $= 0$)
- Transformer 1^o current(rms) $= 0.471(I_d/T)$
- Aggregate valve rating $= 3\times\ 2.094 V_d \times 0.333 I_d = 2.094 P_d$
- VA rating of Transformer(2^o) $= 3\times\ 0.855 V_d \times 0.577 I_d = 1.481 P_d$
- VA rating of Transformer(1^o) $= 3\times 0.855 TV_d \times 0.471(I_d/T) = 1.209 P_d$

Three-phase One-way Rectifier

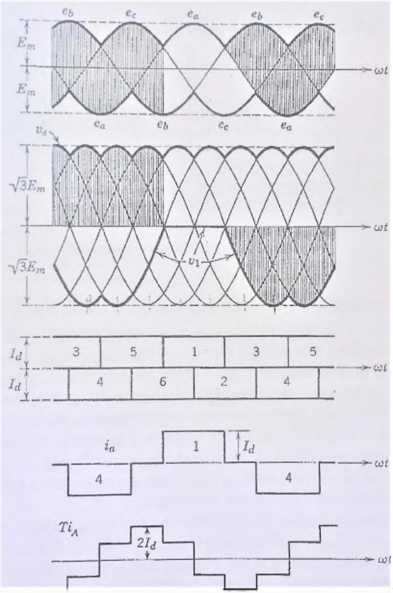


Name of Circuit	1ϕ Full-wave	1ϕ Bridge	3ϕ One-way	3ϕ Bridge	Cascade of 2-3ϕ	Y-Y Interphase	6ϕ Diametrical	Cascade of 3-1ϕ	Cascade of 2-3ϕ Bridges
Figure number	3	5	7	9	11	12	13	14	15
Number of valves	2	4	3	6	6	6	6	6	12
Pulse number	2	2	3	6	6	6	6	6	12
Currents:									
Valve, peak	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$0.500I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$
Valve, average	$0.500I_d$	$0.500I_d$	$0.333I_d$	$0.333I_d$	$0.333I_d$	$0.167I_d$	$0.167I_d$	$0.500I_d$	$0.333I_d$
Transformer, rms									
Secondary	$0.707I_d$	$1.000I_d$	$0.577I_d$	$0.816I_d$	$0.577I_d$	$0.289I_d$	$0.408I_d$	$0.707I_d$	$0.816I_d$
Primary	$1.000I_d/T$	$1.000I_d/T$	$0.471I_d/T$	$0.816I_d/T$	$0.816I_d/T$	$0.408I_d/T$	$0.577I_d/T$	$1.000I_d/T$	$0.816I_d/T$
Voltages:									
Dc ripple, peak to peak	$1.571V_d$	$1.571V_d$	$0.605V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.036V_d$
Valve, peak inverse	$3.142V_d$	$1.571V_d$	$2.094V_d$	$1.047V_d$	$1.047V_d$	$2.094V_d$	$2.094V_d$	$1.047V_d$	$0.524V_d$
Transformer, rms									
Primary	$1.111TV_d$	$1.111TV_d$	$0.855TV_d$	$0.428TV_d$	$0.428TV_d$	$0.855TV_d$	$0.740TV_d$	$0.370TV_d$	$0.214TV_d$
Each secondary	$1.111V_d$	$1.111V_d$	$0.855V_d$	$0.428V_d$	$0.428V_d$	$0.855V_d$	$0.740V_d$	$0.370V_d$	$0.214V_d$
Volt-amperes:									
All valves*	$3.142P_d$	$3.142P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$3.142P_d$	$2.094P_d$
Transformer, primary	$1.111P_d$	$1.111P_d$	$1.209P_d$	$1.047P_d$	$1.047P_d$	$1.047P_d$	$1.283P_d$	$1.111P_d$	$1.047P_d$
Transformer, secondary	$1.571P_d$	$1.111P_d$	$1.481P_d$	$1.047P_d$	$1.481P_d$	$1.481P_d$	$1.814P_d$	$1.571P_d$	$1.047P_d$

Three-phase Bridge Rectifier



Three-phase Bridge Rectifier



Three-phase Bridge Rectifier

Three-phase Two-way Rectifier / Graetz Circuit

- Three-wire DC system
- No neutral current if loads are balanced
- Six valves
  - Upper Group → 2, 4 & 6
  - Lower Group → 1, 3 & 5
- Instantaneous DC Voltage(v_d) → Upper envelop of line to line voltages
- On comparison with three-phase single-way rectifier
  - V_d & P_d are doubled for a given AC input voltage
  - PIV became half in terms of V_d
  - No DC current in transformer windings
  - Transformer winding current(rms) $<$ twice that of three-phase single-way rectifier
  - More efficient usage of transformer windings
  - DC Voltage ripple frequency $=$ 6f(twice that of three-phase single-way rectifier)
  - DC Voltage ripple magnitude is less
- Suitable for **High DC Voltage & High Power** applications

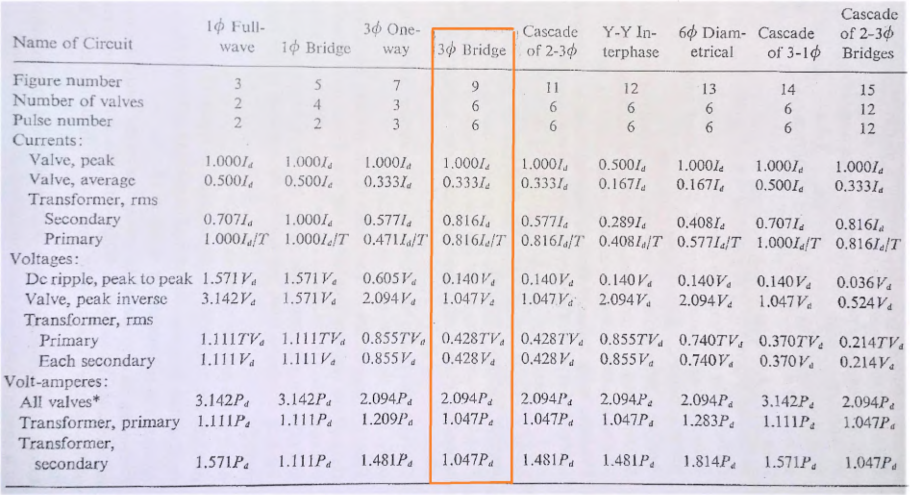
Three-phase Bridge Rectifier

- Load current is always carried by two valves in series(One from upper group & other from lower group)
- Each valve conducts for $(1/3)^{rd}$ cycle
- Commutation occurs at every $(1/6)^{th}$ cycle(60^o)
- Valves are numbered in the order they begin to conduct
- Commutation : 1 to 3 $\rightarrow$ 2 to 4 $\rightarrow$ 3 to 5 $\rightarrow$ 4 to 6 $\rightarrow$ 5 to 1 $\rightarrow$ 6 to 2
- $i_a = i_1$ - i_4
- Average DC Voltage$(V_d) = 1.654E_m$
- $E_m = 0.605V_d$
- Peak Inverse Voltage(PIV) $= \sqrt{3}E_m = 1.047V_d$
- Peak to peak ripple voltage $= \sqrt{3}E_m(1 - cos30) = 0.14V_d$
- Transformer 2^o voltage(line to neutral $\implies$ phase voltage, rms) $= E_m/\sqrt{2} = 0.428V_d$
- Transformer 2^o current(rms) $= 0.816I_d$

Three-phase Bridge Rectifier

- Aggregate valve rating $= 6 \times 1.047V_d \times I_d/3 = 2.094P_d$
- Aggregate VA rating of transformer 2^o windings $= 3 \times 0.428V_d \times 0.816I_d = 1.047P_d$
- Aggregate VA rating of transformer 1^o windings $= 1.047P_d$

Three-phase Bridge Rectifier



Name of Circuit	1ϕ Full-wave	1ϕ Bridge	3ϕ One-way	3ϕ Bridge	Cascade of 2-3ϕ	Y-Y Interphase	6ϕ Diametrical	Cascade of 3-1ϕ	Cascade of 2-3ϕ Bridges
Figure number	3	5	7	9	11	12	13	14	15
Number of valves	2	4	3	6	6	6	6	6	12
Pulse number	2	2	3	6	6	6	6	6	12
Currents:									
Valve, peak	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$0.500I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$
Valve, average	$0.500I_d$	$0.500I_d$	$0.333I_d$	$0.333I_d$	$0.333I_d$	$0.167I_d$	$0.167I_d$	$0.500I_d$	$0.333I_d$
Transformer, rms									
Secondary	$0.707I_d$	$1.000I_d$	$0.577I_d$	$0.816I_d$	$0.577I_d$	$0.289I_d$	$0.408I_d$	$0.707I_d$	$0.816I_d$
Primary	$1.000I_d/T$	$1.000I_d/T$	$0.471I_d/T$	$0.816I_d/T$	$0.816I_d/T$	$0.408I_d/T$	$0.577I_d/T$	$1.000I_d/T$	$0.816I_d/T$
Voltages:									
Dc ripple, peak to peak	$1.571V_d$	$1.571V_d$	$0.605V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.036V_d$
Valve, peak inverse	$3.142V_d$	$1.571V_d$	$2.094V_d$	$1.047V_d$	$1.047V_d$	$2.094V_d$	$2.094V_d$	$1.047V_d$	$0.524V_d$
Transformer, rms									
Primary	$1.111TV_d$	$1.111TV_d$	$0.855TV_d$	$0.428TV_d$	$0.428TV_d$	$0.855TV_d$	$0.740TV_d$	$0.370TV_d$	$0.214TV_d$
Each secondary	$1.111V_d$	$1.111V_d$	$0.855V_d$	$0.428V_d$	$0.428V_d$	$0.855V_d$	$0.740V_d$	$0.370V_d$	$0.214V_d$
Volt-amperes:									
All valves*	$3.142P_d$	$3.142P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$3.142P_d$	$2.094P_d$
Transformer, primary	$1.111P_d$	$1.111P_d$	$1.209P_d$	$1.047P_d$	$1.047P_d$	$1.047P_d$	$1.283P_d$	$1.111P_d$	$1.047P_d$
Transformer, secondary	$1.571P_d$	$1.111P_d$	$1.481P_d$	$1.047P_d$	$1.481P_d$	$1.481P_d$	$1.814P_d$	$1.571P_d$	$1.047P_d$

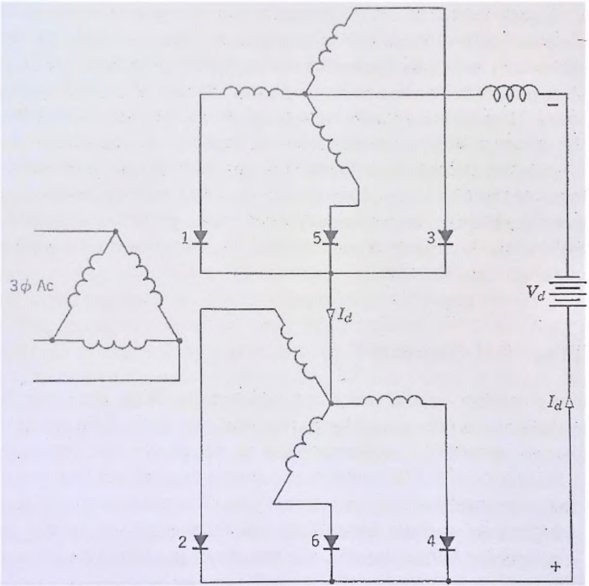
Pulse Number(p)

Pulse Number(p) = Number of pulsations(cycles of ripple) of DC voltage per cycle of alternating voltage

Circuit	Pulse Number(p)
1Φ Half-wave	1
1Φ Full-wave	2
1Φ Bridge	2
3Φ One-way	3
3Φ Two-way	6

- Harmonic orders in DC Voltage = pq where q = integer
- Harmonic orders in AC = $pq \pm 1$
- For Higher the pulse number
    - Higher the lowest frequencies of harmonics
    - Lower peak to peak ripple voltage
    - Higher DC ripple frequency
    - Easy filtering
    - But increased complexity of transformer connections

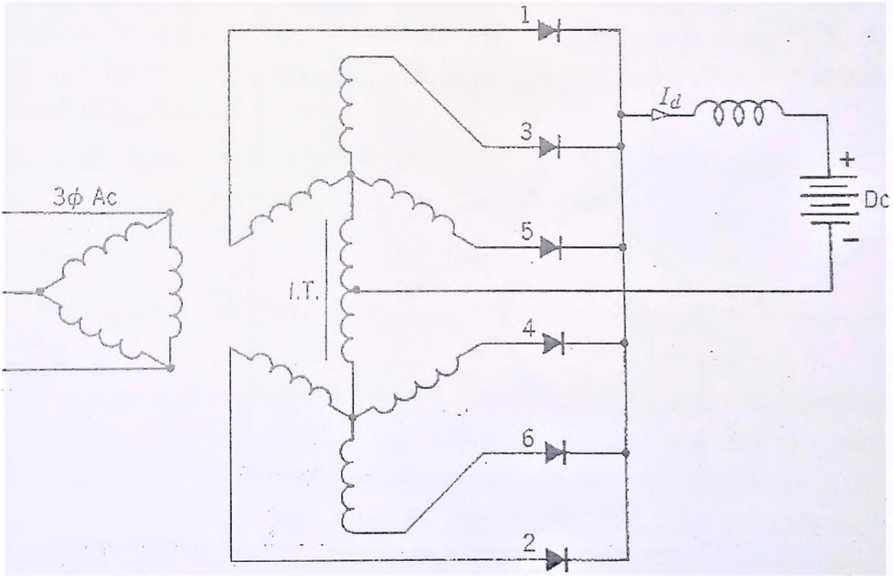
Cascade of Two Three-phase Rectifiers



Cascade of Two Three-phase Rectifiers

- Two three-phase groups of valves are in **series on DC side**
- Each group has common cathode connection
- Transformer 2^o windings are connected in double star with 180^o phase difference
- Each valve conducts for $(1/3)^{th}$ cycle
- More complex connection
- Greater aggregate VA rating of transformer 2^o windings
- Special case : One mercury-pool cathode in glass tube with three anodes

Parallel Connections with Interphase Transformer



Parallel Connections with Interphase Transformer

- Two three-phase groups of valves
- Double star-connected 2^o windings & Interphase Transformer
- Two valve groups are in **parallel on DC side**
- One DC pole of one group is directly connected to the like pole of other group & to one pole of DC line($\implies$ all cathodes are connected together and to the pole of DC line)
- Opposite poles are connected to opposite ends of interphase transformer (autotransformer)
- Center tap of interphase transformer is connected to other pole of DC line
- **Single-cathode six-anode valves**
- Instantaneous center tap voltage = average of instantaneous voltages of two ends of the winding
- Instantaneous DC line voltage(v_d) = average of voltages of two three-phase groups
- DC voltage has six-pulse ripple

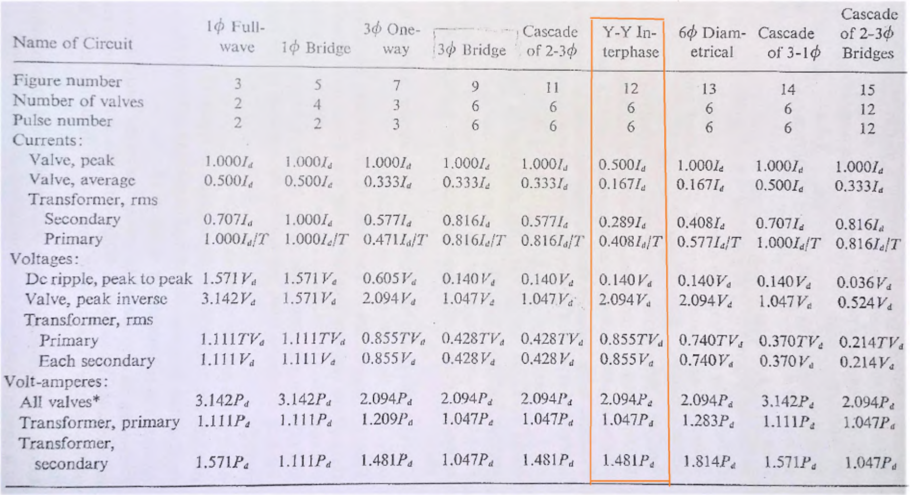
Parallel Connections with Interphase Transformer

- Each valve conducts for $(1/3)^{th}$ cycle

Demerits

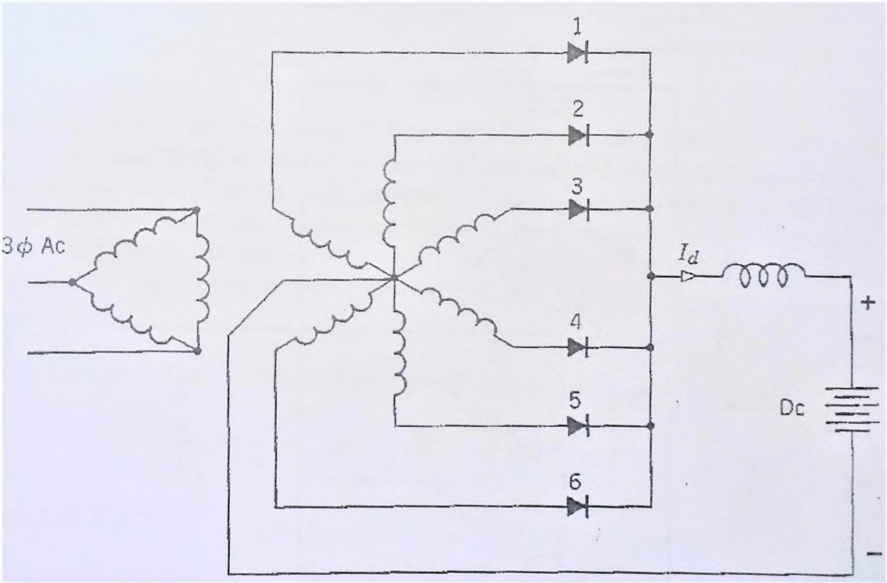
- Complex connection
- Greater aggregate VA rating of transformer 2^{o} windings
- Requires interphase transformer
- Lower DC voltage

Parallel Connections with Interphase Transformer



Name of Circuit	1ϕ Full-wave	1ϕ Bridge	3ϕ One-way	3ϕ Bridge	Cascade of 2-3ϕ	Y-Y Interphase	6ϕ Diametrical	Cascade of 3-1ϕ	Cascade of 2-3ϕ Bridges
Figure number	3	5	7	9	11	12	13	14	15
Number of valves	2	4	3	6	6	6	6	6	12
Pulse number	2	2	3	6	6	6	6	6	12
Currents:									
Valve, peak	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$0.500I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$
Valve, average	$0.500I_d$	$0.500I_d$	$0.333I_d$	$0.333I_d$	$0.333I_d$	$0.167I_d$	$0.167I_d$	$0.500I_d$	$0.333I_d$
Transformer, rms									
Secondary	$0.707I_d$	$1.000I_d$	$0.577I_d$	$0.816I_d$	$0.577I_d$	$0.289I_d$	$0.408I_d$	$0.707I_d$	$0.816I_d$
Primary	$1.000I_d/T$	$1.000I_d/T$	$0.471I_d/T$	$0.816I_d/T$	$0.816I_d/T$	$0.408I_d/T$	$0.577I_d/T$	$1.000I_d/T$	$0.816I_d/T$
Voltages:									
Dc ripple, peak to peak	$1.571V_d$	$1.571V_d$	$0.605V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.036V_d$
Valve, peak inverse	$3.142V_d$	$1.571V_d$	$2.094V_d$	$1.047V_d$	$1.047V_d$	$2.094V_d$	$2.094V_d$	$1.047V_d$	$0.524V_d$
Transformer, rms									
Primary	$1.111TV_d$	$1.111TV_d$	$0.855TV_d$	$0.428TV_d$	$0.428TV_d$	$0.855TV_d$	$0.740TV_d$	$0.370TV_d$	$0.214TV_d$
Each secondary	$1.111V_d$	$1.111V_d$	$0.855V_d$	$0.428V_d$	$0.428V_d$	$0.855V_d$	$0.740V_d$	$0.370V_d$	$0.214V_d$
Volt-amperes:									
All valves*	$3.142P_d$	$3.142P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$3.142P_d$	$2.094P_d$
Transformer, primary	$1.111P_d$	$1.111P_d$	$1.209P_d$	$1.047P_d$	$1.047P_d$	$1.047P_d$	$1.283P_d$	$1.111P_d$	$1.047P_d$
Transformer, secondary	$1.571P_d$	$1.111P_d$	$1.481P_d$	$1.047P_d$	$1.481P_d$	$1.481P_d$	$1.814P_d$	$1.571P_d$	$1.047P_d$

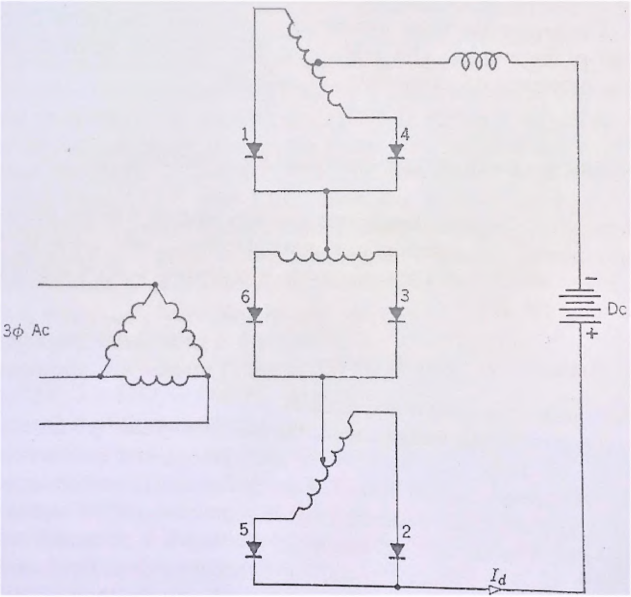
Six-phase Diametrical Connection



Six-phase Diametrical Connection

- Neutral points of star-connected secondary windings are solidly connected
- One center tapped winding per core instead of two separate windings per core
- Each valve conducts for $(1/6)^{th}$ cycle $\implies$ poor transformer utilization
- **Single-cathode six-anode valves**

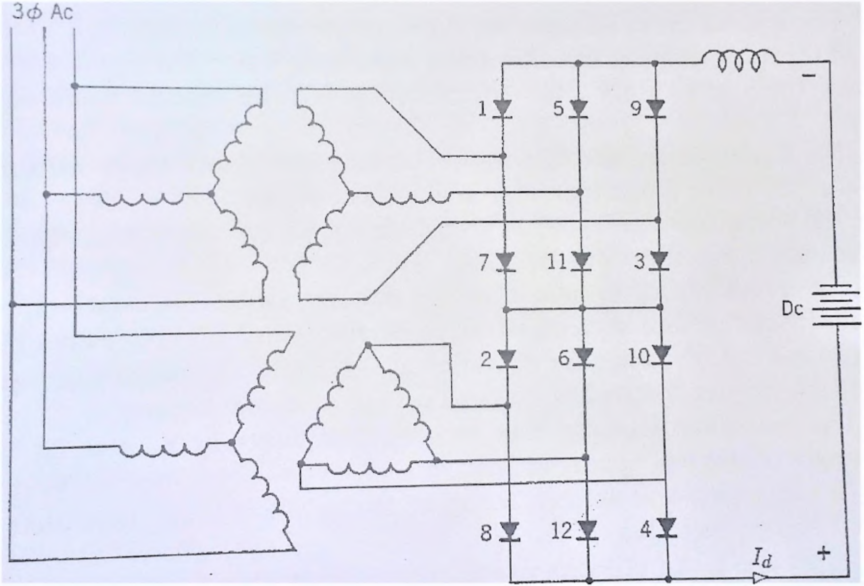
Cascade of Three Single-phase Full-wave Rectifier



Cascade of Three Single-phase Full-wave Rectifier

- Lesser DC Voltage for a given PIV on valve than bride circuit & cascade of two three-phase rectifiers
- Poor transformer utilization

Twelve-pulse Cascade of Two Bridges



Twelve-pulse Cascade of Two Bridges

- AC ports are in parallel $\implies$ AC current is doubled
- DC ports of two bridges are in series $\implies$ DC voltage is doubled
- Transformer banks $\rightarrow$ star-star & star-delta $\rightarrow$ 12-pulse DC converter
- Under balanced condition
  - Lowest harmonic on DC side $= 12^{th}$ harmonic
  - Lowest pair of harmonics on AC side $= 11^{th}$ and 13^{th} harmonics
- Complex transformer connection

6. Choice of Best Circuit for HVDC Converter

- Best converter → **Three-phase Bridge Rectifier**

Advantages

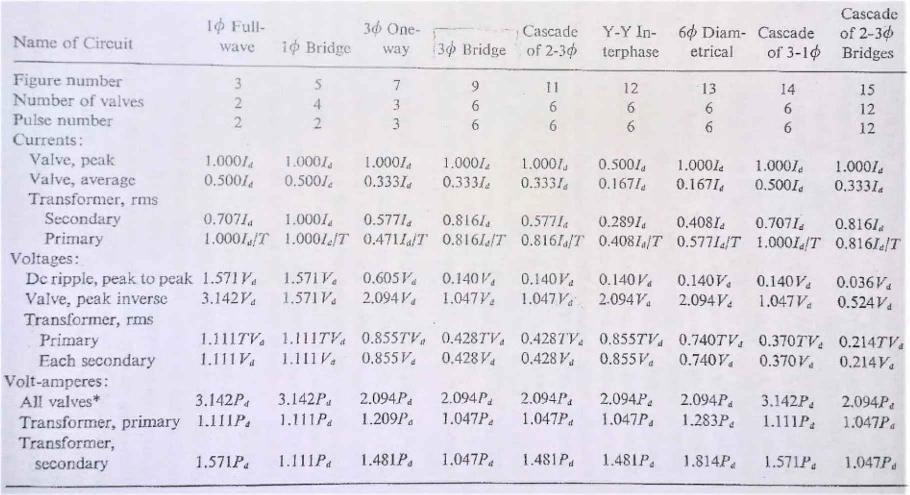
1. For given DC voltage, **PIV of valve is half** that of any other six-pulse converters except cascade of two three-phase rectifiers & cascade of three single-phase full-wave rectifiers
2. For given PIV, **DC voltage** V_d **is twice** that of other circuits
3. For a given power throughput, **VA rating of transformer** 2^o **winding is less** that in any other circuit
4. **VA rating of transformer** 1^o **winding is equal or less** than that of other circuits
5. Simplest transformer connections
6. Double or center tapped 2^o windings are not required
7. 2^o windings may be connected in either star or in delta
8. **Aggregate VA rating valve is lower** than that of cascade of three single-phase full-wave rectifiers and equal to that of the rest

6. Choice of Best Circuit for HVDC Converter

9. Bridge connection → Inherent protection against **Arcback**
    - Two valves in series across DC line
    - Two valves in series opposition across each pair of AC terminals
    - If all valves except malfunctioning valve are blocked by grid control, malfunctioning valve has no circuit through which current can be furnished $\implies$ arcback is prevented

Three-phase Bridge Rectifier(Graetz Circuit) is universally used for **High Power HV AC-DC Converters**

6. Choice of Best Circuit for HVDC Converter



Name of Circuit	1ϕ Full-wave	1ϕ Bridge	3ϕ One-way	3ϕ Bridge	Cascade of 2-3ϕ	Y-Y Interphase	6ϕ Diametrical	Cascade of 3-1ϕ	Cascade of 2-3ϕ Bridges
Figure number	3	5	7	9	11	12	13	14	15
Number of valves	2	4	3	6	6	6	6	6	12
Pulse number	2	2	3	6	6	6	6	6	12
Currents:									
Valve, peak	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$	$0.500I_d$	$1.000I_d$	$1.000I_d$	$1.000I_d$
Valve, average	$0.500I_d$	$0.500I_d$	$0.333I_d$	$0.333I_d$	$0.333I_d$	$0.167I_d$	$0.167I_d$	$0.500I_d$	$0.333I_d$
Transformer, rms									
Secondary	$0.707I_d$	$1.000I_d$	$0.577I_d$	$0.816I_d$	$0.577I_d$	$0.289I_d$	$0.408I_d$	$0.707I_d$	$0.816I_d$
Primary	$1.000I_d/T$	$1.000I_d/T$	$0.471I_d/T$	$0.816I_d/T$	$0.816I_d/T$	$0.408I_d/T$	$0.577I_d/T$	$1.000I_d/T$	$0.816I_d/T$
Voltages:									
Dc ripple, peak to peak	$1.571V_d$	$1.571V_d$	$0.605V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.140V_d$	$0.036V_d$
Valve, peak inverse	$3.142V_d$	$1.571V_d$	$2.094V_d$	$1.047V_d$	$1.047V_d$	$2.094V_d$	$2.094V_d$	$1.047V_d$	$0.524V_d$
Transformer, rms									
Primary	$1.111TV_d$	$1.111TV_d$	$0.855TV_d$	$0.428TV_d$	$0.428TV_d$	$0.855TV_d$	$0.740TV_d$	$0.370TV_d$	$0.214TV_d$
Each secondary	$1.111V_d$	$1.111V_d$	$0.855V_d$	$0.428V_d$	$0.428V_d$	$0.855V_d$	$0.740V_d$	$0.370V_d$	$0.214V_d$
Volt-amperes:									
All valves*	$3.142P_d$	$3.142P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$2.094P_d$	$3.142P_d$	$2.094P_d$
Transformer, primary	$1.111P_d$	$1.111P_d$	$1.209P_d$	$1.047P_d$	$1.047P_d$	$1.047P_d$	$1.283P_d$	$1.111P_d$	$1.047P_d$
Transformer, secondary	$1.571P_d$	$1.111P_d$	$1.481P_d$	$1.047P_d$	$1.481P_d$	$1.481P_d$	$1.814P_d$	$1.571P_d$	$1.047P_d$

Converter Circuits

1. Three Phase One-Way Rectifier
2. Twelve Pulse Cascade of Two Bridges
3. Cascade of Three Single-phase Full-wave Rectifier
4. Three Phase Two-way Bridge Rectifier
5. Parallel Connections with Interphase Transformer
6. Single Phase Bridge Rectifier
7. Single Phase Full-wave Rectifier
8. Six-phase Diametrical Connection
9. Cascade of Two Three-phase Rectifiers

References

1. E. W. Kimbark, *'Direct Current Transmission-Vol.1'*, Whley Interscience, New York 1971
2. J. Arrilage, *'High Voltage Direct Current Transmission'*, Peter Pereginver Ltd., London U.K. 1983
3. K. R. Padiyar, *'HVDC Transmission Systems'*, Wiley Eastern Ltd., New Delhi 1992

Thank You

*for private circulation only

HVDC Transmission Systems

(05EE 6034)

Module 2 - Overview

Bridge Converters - Analysis and Control

1. Analysis of Bridge Converter with Gate Control
    - Bridge Converter with Gate Control(No Overlap)
    - Bridge Converter with Gate Control(Overlap $< 60^o$)
2. Operation of Inverters
3. Means of Control
4. Power Reversal
5. Desired Features of Control
6. Actual Control Characteristics

1. Analysis of Bridge Converter with Gate Control

- Analysis of three-phase bridge converter with **grid control** and **overlap**

Assumptions

1. Source with balanced sinusoidal emf's of constant voltage and frequency
2. Constant ripple free direct current
3. Valves with no forward resistance and infinite inverse resistance
4. Ignition of valves at equal intervals of one-sixth cycle(60^o)

1. Analysis of Bridge Converter with Gate Control

- Instantaneous line-to-neutral(ie, phase) emf's

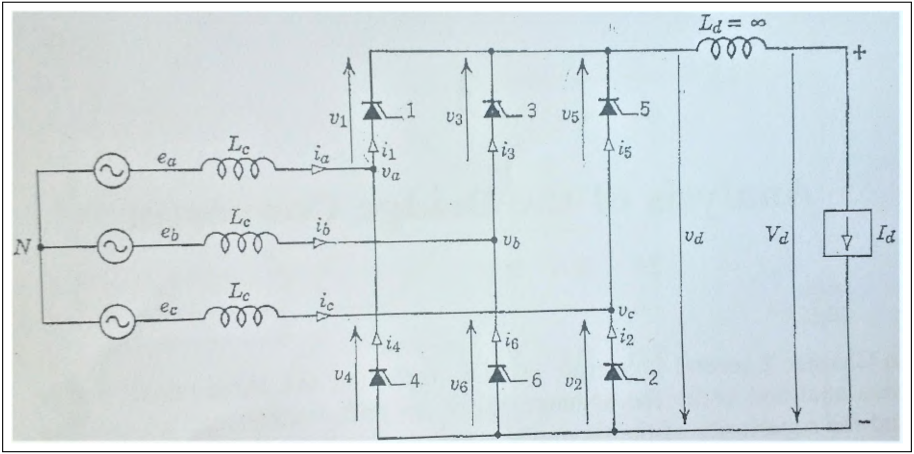
$$\begin{aligned} e_a &= E_m cos(\omega t + 60) \\ e_b &= E_m cos(\omega t - 60) \\ e_c &= E_m cos(\omega t - 180) \end{aligned}$$

- Instantaneous line-to-line emf's

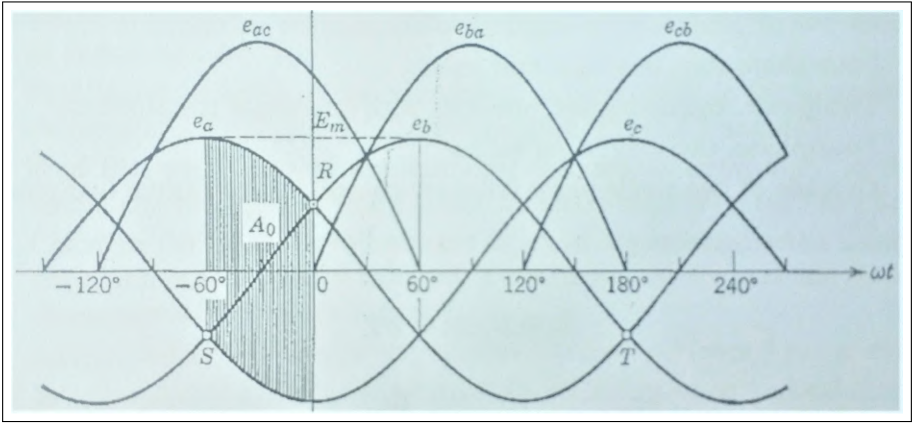
$$\begin{aligned} e_{ac} &= e_a - e_c = \sqrt{3} E_m cos(\omega t + 30) \\ e_{ba} &= e_b - e_a = \sqrt{3} E_m cos(\omega t - 90) = \sqrt{3} E_m sin \omega t \\ e_{cb} &= e_c - e_b = \sqrt{3} E_m cos(\omega t + 150) \end{aligned}$$

- Converter circuit with valves is *piecewise linear*

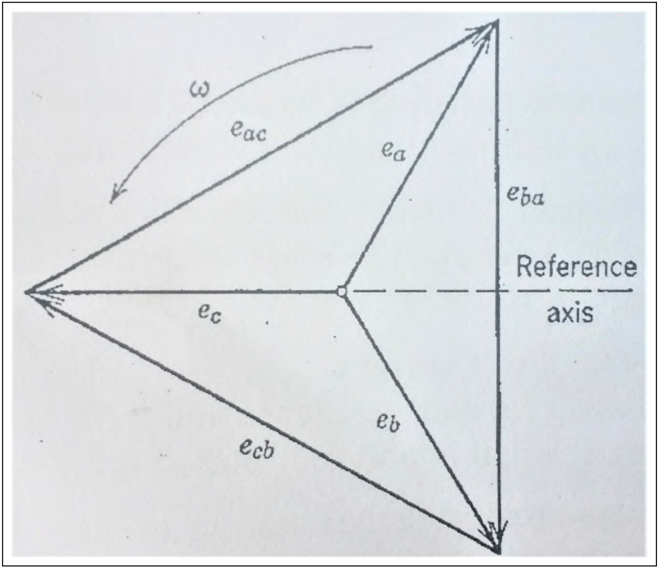
1. Analysis of Bridge Converter with Gate Control



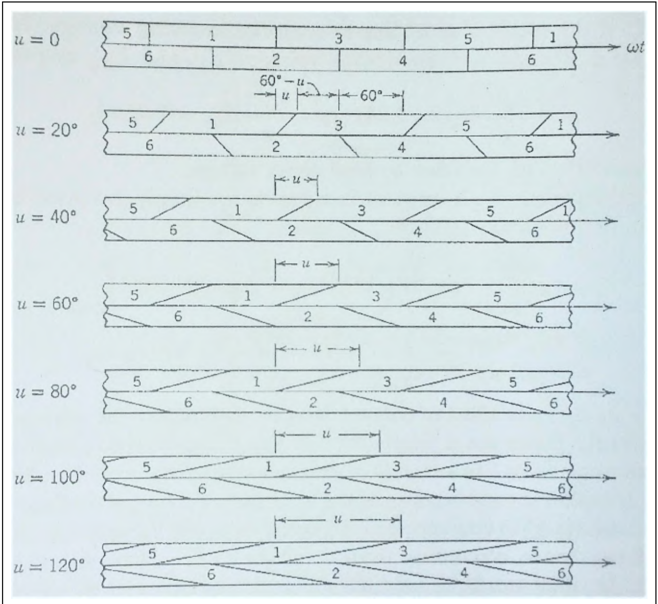
1. Analysis of Bridge Converter with Gate Control



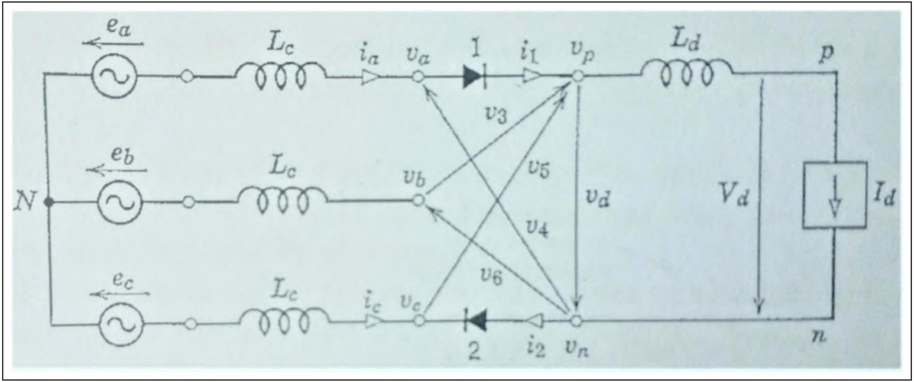
1. Analysis of Bridge Converter with Gate Control



1. Analysis of Bridge Converter with Gate Control



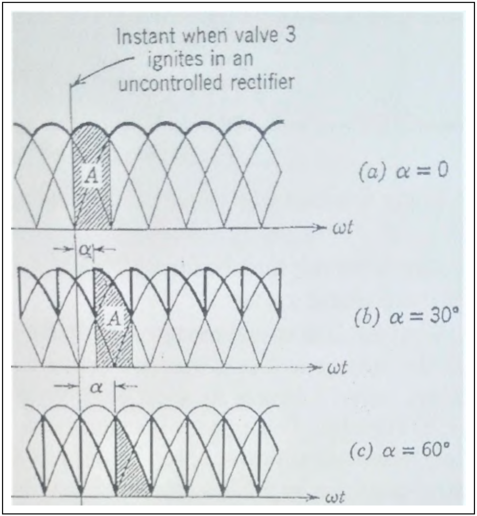
1. Analysis of Bridge Converter with Gate Control



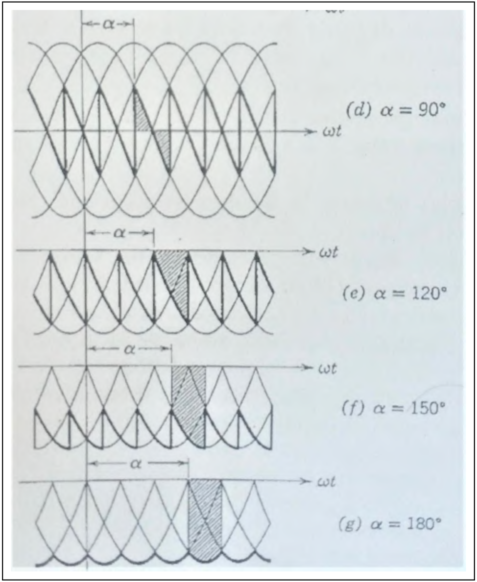
1.1 Bridge Converter with Gate Control(No Overlap)

- $i_a = i_1 = i_2 = -i_c = I_d$
- $i_b = i_3 = i_4 = i_5 = i_6 = 0$
- $v_a = v_p = e_a = E_m cos(\omega t + 60)$
- $v_b = e_b = E_m cos(\omega t - 60)$
- $v_c = v_n = e_c = E_m cos(\omega t - 180)$
- $v_d = v_p$ - $v_n = e_a - e_c = e_{ac} = \sqrt{3} E_m cos(\omega t + 30)$
- $v_1 = v_2 = 0$
- $v_3 = e_{ba} = \sqrt{3} E_m sin(\omega t)$
- $v_4 = v_5 = -v_d = \sqrt{3} E_m cos(\omega t - 150)$
- $v_6 = e_{cb} = \sqrt{3} E_m cos(\omega t + 150)$

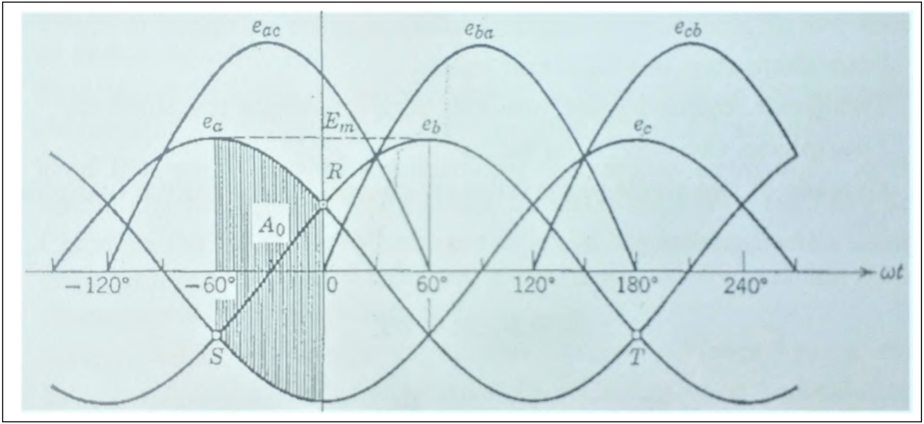
1.1 Bridge Converter with Gate Control(No Overlap)



1.1 Bridge Converter with Gate Control(No Overlap)



1.1 Bridge Converter with Gate Control(No Overlap)



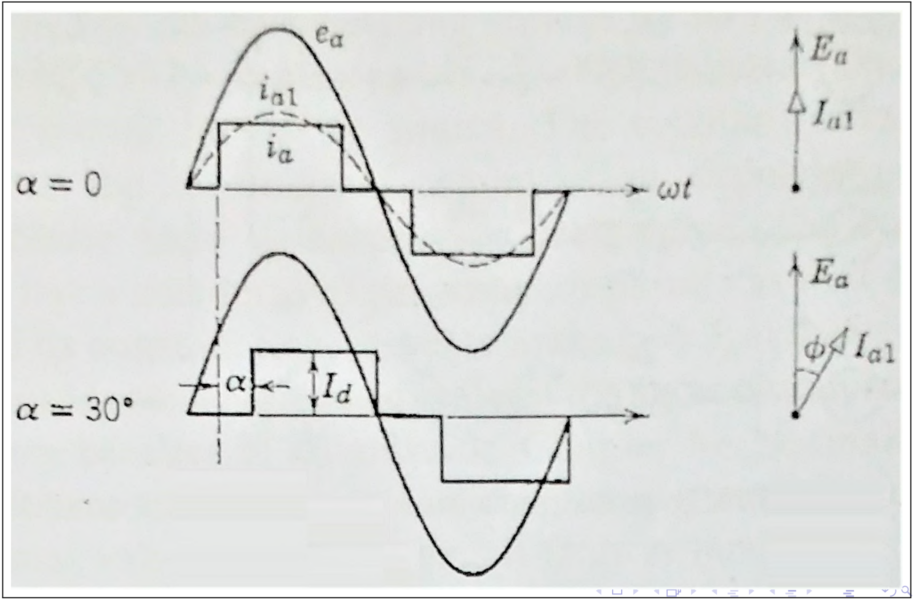
1.1 Bridge Converter with Gate Control(No Overlap)

- $V_{do} = 1.65E_m = \frac{3\sqrt{6}}{\pi}E_{LN} = 2.34E_{LN} = \frac{3\sqrt{2}}{\pi}E_{LL} = 1.35E_{LL}$
- $V_d = V_{do}cos\alpha$
- α : 0 $\rightarrow$ 180
- $cos\alpha$: -1 $\rightarrow$ +1
- **Rectification** and **Inversion**
- Ripple and Harmonics in direct voltage increase with delay up to 90^o and then decrease from 90^o to 180^o
- If losses are neglected,

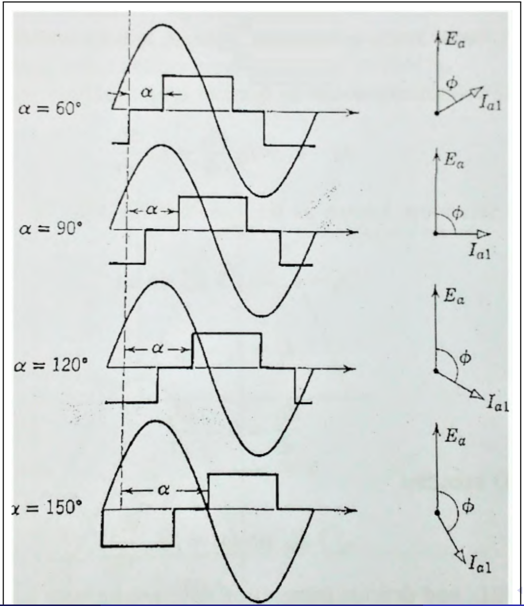
$$3E_{LN}I_{L1}cos\Phi = V_dI_d = I_dV_{do}cos\alpha$$

- I_{L1} = rms value of fundamental component of alternating current
- Line current has +ve and -ve rectangular pulses of height I_d & width $\frac{2\pi}{3}$

1.1 Bridge Converter with Gate Control(No Overlap)



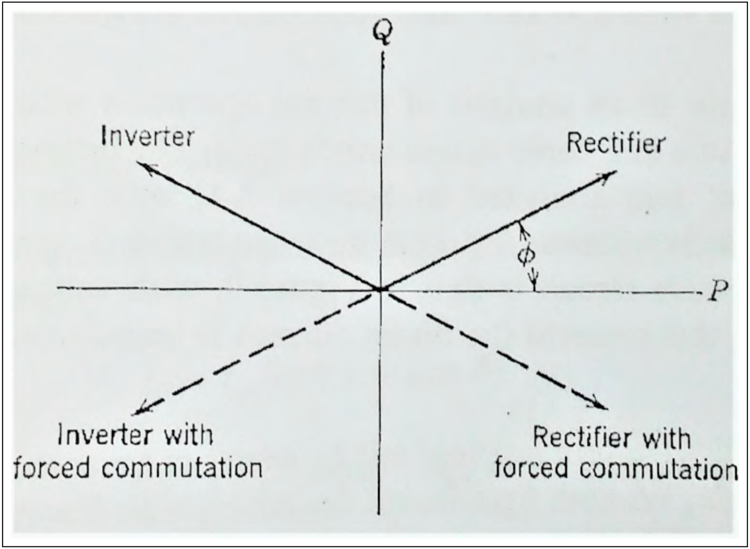
1.1 Bridge Converter with Gate Control(No Overlap)



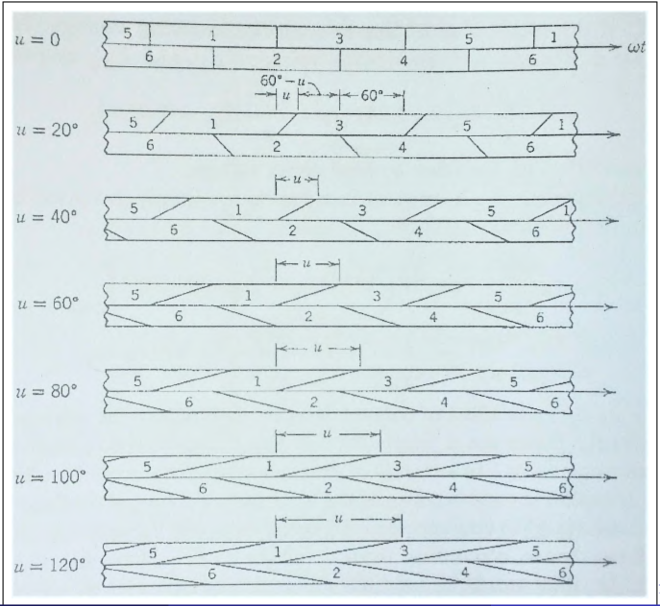
1.1 Bridge Converter with Gate Control(No Overlap)

- $I_L = \frac{\sqrt{6}}{\pi} I_d = 0.78 I_d$
- $cos\Phi = cos\alpha$
- $cos\Phi =$ **Displacement Factor** or **Vector Power Factor**
- $\Phi =$ Angle by which fundamental line current lags line-to-neutral source voltage
- Converter operates like a **transformer** with **fixed current ratio** but **voltage ratio that varies with ignition delay imposed by grid control**
- Ignition delay(α) shifts current wave and its fundamental component by angle $\Phi = \alpha \implies$ converter draws reactive power from the AC system

1.1 Bridge Converter with Gate Control(No Overlap)



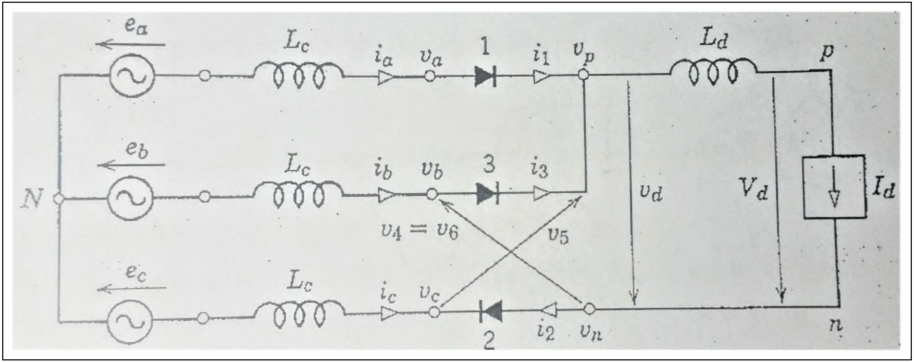
1.2 Bridge Converter with Gate Control(Overlap<60^o)



1.2 Bridge Converter with Gate Control(Overlap<60^o)

- Inductance of AC source & Transformer → Inductance → Finite rate of current change → **Commutation Time** or **Overlap Time**
- Commutation Time = $\frac{u}{\omega}$
- Usually u < 60^o (20^o to 25^o)
- For u < 60^o
  - During commutation → 3 valves conduct simultaneously → for 'u' degrees
  - Between commutation → 2 valves conduct → for (60^o - u) degrees
- At every 60^o, new commutation begins & lasts for overlap angle(u)
- Sequence of conducting valves : **12** → **123** → **23** → **234** →**34** → **345** → **45** → **456** → **56** → **561** → **61** → **612**
- If u = 60^o : **123** → **234** → **345** → **456** → **561** → **612**

1.2 Bridge Converter with Gate Control(Overlap$<60^o$)



1.2 Bridge Converter with Gate Control(Overlap<60^o)

- **12** conduct → Analysis is done
- **123** conduct : Direct current is transferred from **1** to **3**
  - At beginning($\omega t = \alpha$) : $i_1 = I_d$ & $i_3 = 0$
  - At end($\omega t = \alpha + u = \delta$) : $i_1 = 0$ & $i_3 = I_d$
- **Extinction Angle(δ)** $= \alpha + u$
- Consider loop **N31N** → Commutating EMF

$$e_b - e_a = L_c \frac{di_3}{dt} - L_c \frac{di_1}{dt} = \sqrt{3} E_m sin\omega t$$

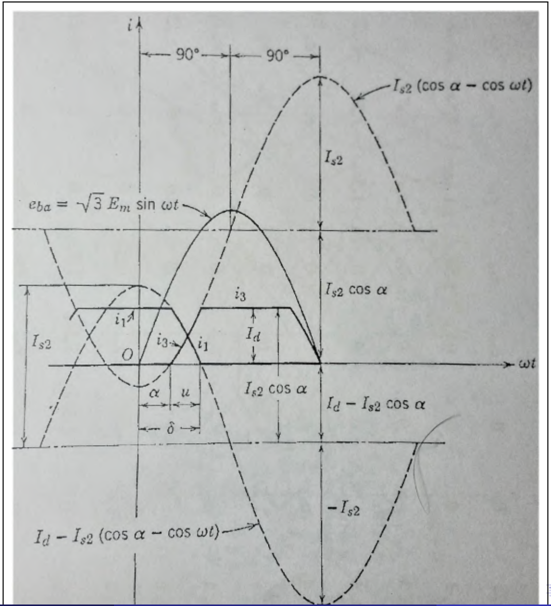
$$i_1 = I_d - i_3$$

$$\sqrt{3} E_m sin\omega t = 2L_c \frac{di_3}{dt}$$

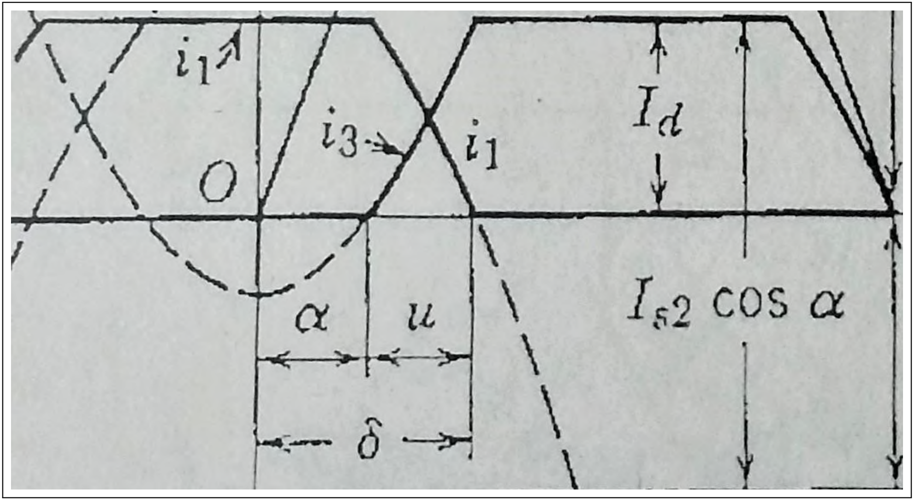
$$\frac{\sqrt{3} E_m}{2L_c} \int_{\alpha/\omega}^{t} sin\omega t dt = \int_0^{i_3} di_3$$

$$I_{s2} \left(cos\alpha - cos\omega t \right) = i_3 = I_d - i_1 \quad where \quad I_{s2} = \frac{\sqrt{3} E_m}{2\omega L_c}$$

1.2 Bridge Converter with Gate Control(Overlap$<60^o$)



1.2 Bridge Converter with Gate Control(Overlap<60°)



1.2 Bridge Converter with Gate Control(Overlap<60^o)

- i_3 → two terms → Constant DC term & sinusoidal term
- Sinusoidal term lags commutating voltage by 90^o
- I_{s2} → current in a line-to-line short circuit on AC source
- Constant term $= I_{s2} cos\alpha$
- During commutation : line-to-line voltage of short circuited phase is zero & line-to-neutral voltages are equal and is the average of correspondin open circuit voltages

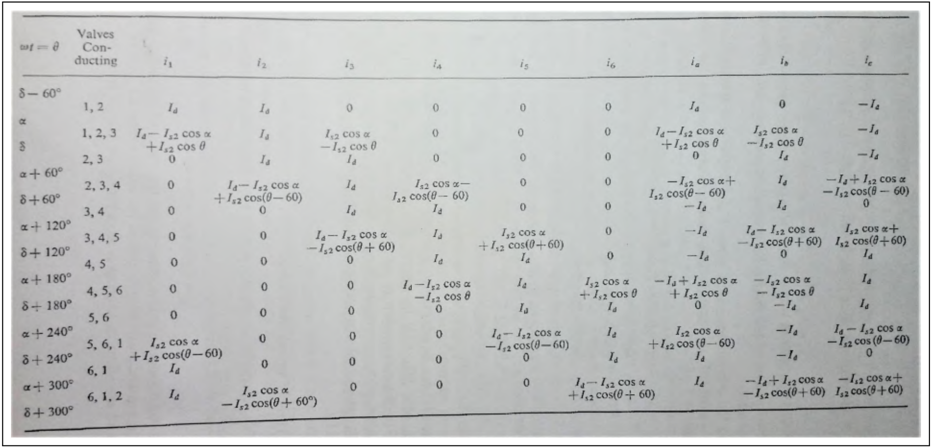
$$v_a = v_b = \frac{e_a + e_b}{2} = \frac{E_m}{2} cos\omega t = \frac{-e_c}{2}$$

1.2 Bridge Converter with Gate Control(Overlap<60^o)

During overlap interval of valves **1** and **3** :

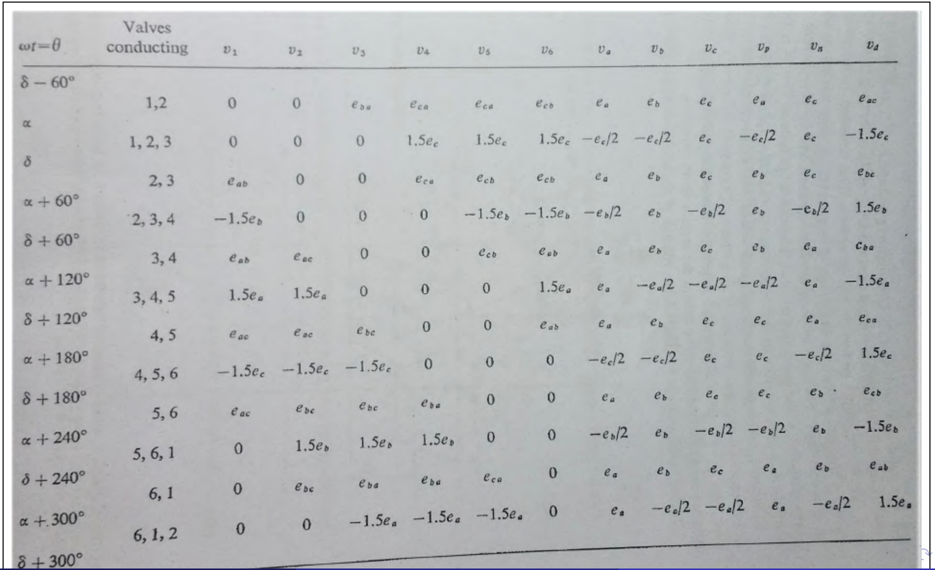
- $i_a = i_1 = I_d$ - $I_{s2}\left(cos\alpha - cos\omega t\right)$
- $i_b = i_3 = I_{s2}\left(cos\alpha - cos\omega t\right)$
- $i_c = -i_2 = -I_d$
- $i_4 = i_5 = i_6 = 0$
- $v_a = v_b = v_p = -0.5e_c = 0.5E_m cos\omega t$
- $v_c = v_n = e_c = -E_m cos\omega t$
- $v_d = v_p$ - $v_n = 1.5E_m cos\omega t$
- $v_1 = v_2 = v_3 = 0$
- $v_4 = v_5 = v_6 = -v_d = -1.5E_m cos\omega t$

1.2 Bridge Converter with Gate Control(Overlap$<60^o$)



$\omega t=\theta$	Valves Conducting	i_1	i_2	i_3	i_4	i_5	i_6	i_a	i_b	i_c
$\delta-60^\circ$										
	1, 2	I_d	I_d	0	0	0	0	I_d	0	$-I_d$
α										
	1, 2, 3	$I_d-I_{s2}\cos\alpha$ $+I_{s2}\cos\theta$	I_d	$I_{s2}\cos\alpha$ $-I_{s2}\cos\theta$	0	0	0	$I_d-I_{s2}\cos\alpha$ $+I_{s2}\cos\theta$	$I_{s2}\cos\alpha$ $-I_{s2}\cos\theta$	$-I_d$
δ										
	2, 3	0	I_d	I_d	0	0	0	0	I_d	$-I_d$
$\alpha+60^\circ$										
	2, 3, 4	0	$I_d-I_{s2}\cos\alpha$ $+I_{s2}\cos(\theta-60)$	I_d	$I_{s2}\cos\alpha-$ $I_{s2}\cos(\theta-60)$	0	0	$-I_{s2}\cos\alpha+$ $I_{s2}\cos(\theta-60)$	I_d	$-I_d+I_{s2}\cos\alpha$ $-I_{s2}\cos(\theta-60)$
$\delta+60^\circ$										
	3, 4	0	0	I_d	I_d	0	0	$-I_d$	I_d	0
$\alpha+120^\circ$										
	3, 4, 5	0	0	$I_d-I_{s2}\cos\alpha$ $-I_{s2}\cos(\theta+60)$	I_d	$I_{s2}\cos\alpha$ $+I_{s2}\cos(\theta+60)$	0	$-I_d$	$I_d-I_{s2}\cos\alpha$ $-I_{s2}\cos(\theta+60)$	$I_{s2}\cos\alpha+$ $I_{s2}\cos(\theta+60)$
$\delta+120^\circ$										
	4, 5	0	0	0	I_d	I_d	0	$-I_d$	0	I_d
$\alpha+180^\circ$										
	4, 5, 6	0	0	0	$I_d-I_{s2}\cos\alpha$ $-I_{s2}\cos\theta$	I_d	$I_{s2}\cos\alpha$ $+I_{s2}\cos\theta$	$-I_d+I_{s2}\cos\alpha$ $+I_{s2}\cos\theta$	$-I_{s2}\cos\alpha$ $-I_{s2}\cos\theta$	I_d
$\delta+180^\circ$										
	5, 6	0	0	0	0	I_d	I_d	0	$-I_d$	I_d
$\alpha+240^\circ$										
	5, 6, 1	$I_{s2}\cos\alpha$ $+I_{s2}\cos(\theta-60)$	0	0	0	$I_d-I_{s2}\cos\alpha$ $-I_{s2}\cos(\theta-60)$	I_d	$I_{s2}\cos\alpha$ $+I_{s2}\cos(\theta-60)$	$-I_d$	$I_d-I_{s2}\cos\alpha$ $-I_{s2}\cos(\theta-60)$
$\delta+240^\circ$										
	6, 1	I_d	0	0	0	0	I_d	I_d	$-I_d$	0
$\alpha+300^\circ$										
	6, 1, 2	I_d	$I_{s2}\cos\alpha$ $-I_{s2}\cos(\theta+60^\circ)$	0	0	0	$I_d-I_{s2}\cos\alpha$ $+I_{s2}\cos(\theta+60)$	I_d	$-I_d+I_{s2}\cos\alpha$ $-I_{s2}\cos(\theta+60)$	$-I_{s2}\cos\alpha+$ $I_{s2}\cos(\theta+60)$
$\delta+300^\circ$										

1.2 Bridge Converter with Gate Control(Overlap$<60^o$)



$\omega t=\theta$	Valves conducting	v_1	v_2	v_3	v_4	v_5	v_6	v_a	v_b	v_c	v_p	v_n	v_d
$\delta-60°$													
	1,2	0	0	e_{ba}	e_{ca}	e_{ca}	e_{cb}	e_a	e_b	e_c	e_a	e_c	e_{ac}
α													
	1, 2, 3	0	0	0	$1.5e_c$	$1.5e_c$	$1.5e_c$	$-e_c/2$	$-e_c/2$	e_c	$-e_c/2$	e_c	$-1.5e_c$
δ													
	2, 3	e_{ab}	0	0	e_{ca}	e_{cb}	e_{cb}	e_a	e_b	e_c	e_b	e_c	e_{bc}
$\alpha+60°$													
	2, 3, 4	$-1.5e_b$	0	0	0	$-1.5e_b$	$-1.5e_b$	$-e_b/2$	e_b	$-e_b/2$	e_b	$-e_b/2$	$1.5e_b$
$\delta+60°$													
	3, 4	e_{ab}	e_{ac}	0	0	e_{cb}	e_{ab}	e_a	e_b	e_c	e_b	e_a	e_{ba}
$\alpha+120°$													
	3, 4, 5	$1.5e_a$	$1.5e_a$	0	0	0	$1.5e_a$	e_a	$-e_a/2$	$-e_a/2$	$-e_a/2$	e_a	$-1.5e_a$
$\delta+120°$													
	4, 5	e_{ac}	e_{ac}	e_{bc}	0	0	e_{ab}	e_a	e_b	e_c	e_c	e_a	e_{ca}
$\alpha+180°$													
	4, 5, 6	$-1.5e_c$	$-1.5e_c$	$-1.5e_c$	0	0	0	$-e_c/2$	$-e_c/2$	e_c	e_c	$-e_c/2$	$1.5e_c$
$\delta+180°$													
	5, 6	e_{ac}	e_{bc}	e_{bc}	e_{ba}	0	0	e_a	e_b	e_c	e_c	e_b	e_{cb}
$\alpha+240°$													
	5, 6, 1	0	$1.5e_b$	$1.5e_b$	$1.5e_b$	0	0	$-e_b/2$	e_b	$-e_b/2$	$-e_b/2$	e_b	$-1.5e_b$
$\delta+240°$													
	6, 1	0	e_{bc}	e_{ba}	e_{ba}	e_{ca}	0	e_a	e_b	e_c	e_a	e_b	e_{ab}
$\alpha+300°$													
	6, 1, 2	0	0	$-1.5e_a$	$-1.5e_a$	$-1.5e_a$	0	e_a	$-e_a/2$	$-e_a/2$	e_a	$-e_a/2$	$1.5e_a$
$\delta+300°$													

1.2 Bridge Converter with Gate Control(Overlap<60^o)

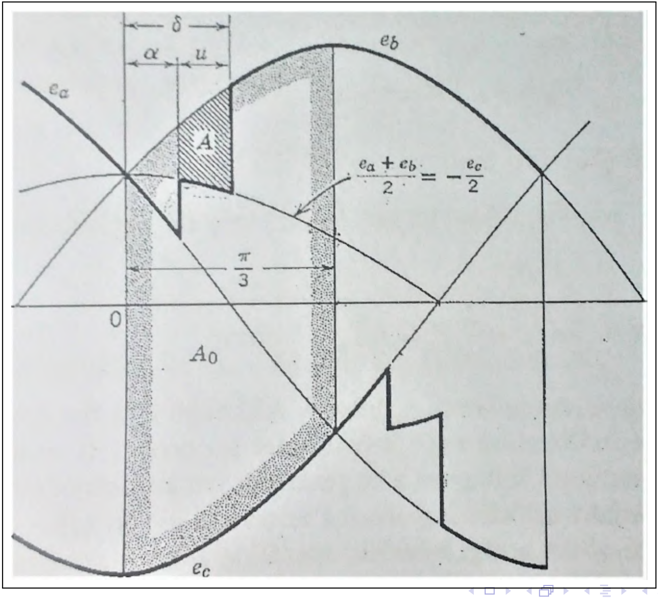
- At the end of commutation period

$$I_d = I_{s2}\left(cos\alpha - cos\delta\right)$$

- $V_{do} = \frac{1}{\pi/3}A_o \implies A_o = \frac{\pi}{3}V_{do}$
- A $= \frac{\pi}{3}\Delta V_d$
- Voltage drop(ΔV_d) due to overlap

$$\begin{aligned} A &= \int_{\alpha}^{\delta}\left(e_b - \frac{e_a + e_b}{2}\right) d\theta \\ &= \int_{\alpha}^{\delta}\left(\frac{e_b - e_a}{2}\right) d\theta \\ &= \frac{\sqrt{3}E_m}{2}\int_{\alpha}^{\delta} sin\theta d\theta \\ &= \frac{\sqrt{3}E_m}{2}\left(cos\alpha - cos\delta\right) \end{aligned}$$

1.2 Bridge Converter with Gate Control(Overlap$<60^o$)



1.2 Bridge Converter with Gate Control(Overlap<60^o)

$$\begin{aligned}
\Delta V_d &= \frac{1}{(\pi/3)} A \\
&= \frac{3\sqrt{3}E_m}{2\pi}\left(cos\alpha - cos\delta\right) \\
&= \frac{V_{do}}{2}\left(cos\alpha - cos\delta\right)
\end{aligned}$$

- With overlap, direct voltage

$$\begin{aligned}
V_d &= V_{do}cos\alpha - \Delta V_d \\
&= \frac{V_{do}\left(cos\alpha + cos\delta\right)}{2} \\
\frac{\Delta V_d}{V_{do}} &= \frac{I_d}{2I_{s2}} \\
V_d &= V_{do}\left(cos\alpha - \frac{I_d}{2I_{s2}}\right)
\end{aligned}$$

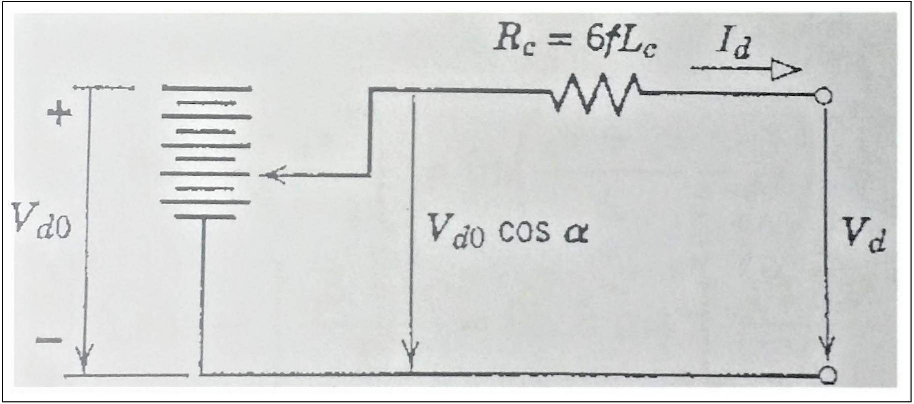
1.2 Bridge Converter with Gate Control(Overlap<60^o)

$$V_d = V_{do} cos\alpha - R_c I_d$$

where $R_c = \frac{3}{\pi}\omega L_c = \frac{3}{\pi}X_c = 6fL_c$

- **Commutating Resistance(R_c)**
- Equivalent circuit → Three-phase bridge rectifier operating at constant alternating voltage & ignition angle

1.2 Bridge Converter with Gate Control(Overlap$<60^o$)



1.2 Bridge Converter with Gate Control(Overlap<60^o)

Relation between AC and DC Quantities(u $<$ 60^o)

$$V_d = \frac{3\sqrt{6}}{\pi}\left(\frac{cos\alpha + cos\delta}{2}\right) E_{LN}$$

- With losses neglected, AC Power = DC Power

$$\begin{aligned} P_a &= P_d \\ \implies 3E_{LN}I_{L1}cos\phi &= V_d I_d \\ I_{L1}cos\phi &= \frac{\sqrt{6}}{\pi}\left(\frac{cos\alpha + cos\delta}{2}\right) I_d \\ I_{L1} &\approxeq \frac{\sqrt{6}}{\pi} I_d = I_{L1o} \quad if \quad u = 0 \end{aligned}$$

- If u = 60^o; error = 4.3%
- If u $\leq$ 30^o; error = 1.1%

1.2 Bridge Converter with Gate Control(Overlap$<60^o$)

- **Displacement Factor**

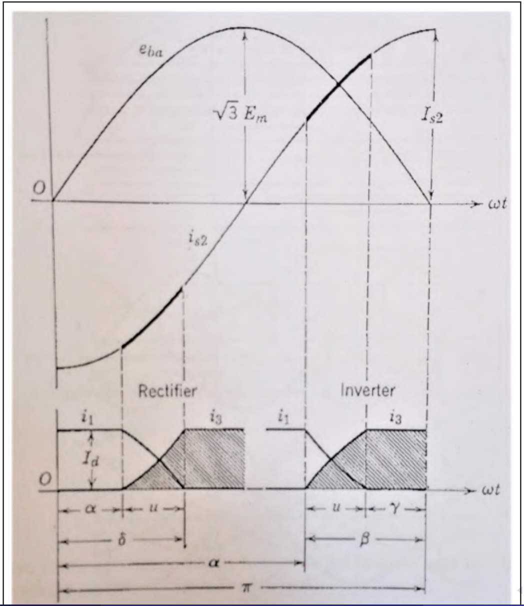
$$\begin{aligned} cos\phi &\approx \frac{cos\alpha + cos\delta}{2} \\ &= \frac{V_d}{V_{do}} \\ &= cos\alpha - \frac{R_c I_d}{V_{do}} \\ V_d &\approx \frac{3\sqrt{6}}{\pi} E_{LN} cos\phi \end{aligned}$$

- AC displacement factor depends on ignition delay angle(α) and load(I_d)
- Reactive power on AC side $= P_a tan\phi$

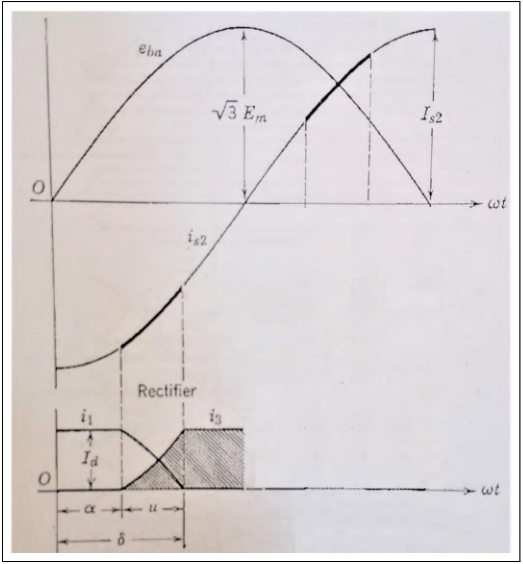
2. Operation of Inverters

- Valves → Unidirectional → I_d can't be reversed
- Power reversal → V_d can be reversed
- If u=0; V_d reverses at $\alpha = 90^o$
  - **Rectification** : $0 < \alpha < 90^o$
  - **Inversion** : $90^o < \alpha < 180^o$
- **Rectifier**
  - **Ignition Angle**(α) : Angle by which ignition is delayed from the instant ($\omega t = 0$ for valve 3) at which the commutating voltage (e_{ba} for valve 3) is zero and increasing
  - **Extinction Angle**(δ) : Delay(in terms of angle) from the instant ($\omega t = 0$ for valve 1)
- **Inverter**
  - **Ignition Angle**(β)
  - **Extinction Angle**(γ)

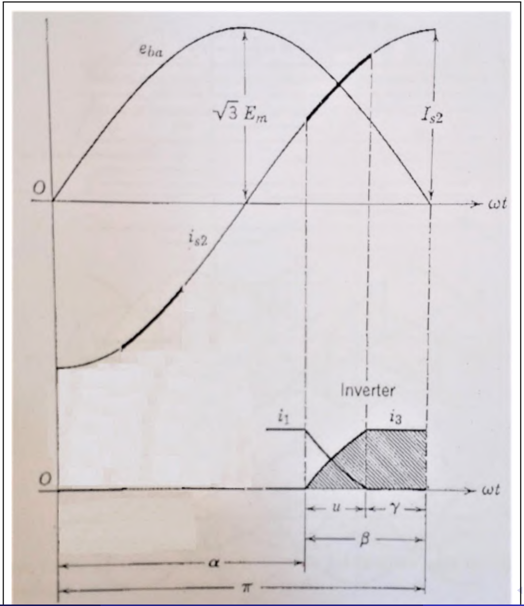
2. Operation of Inverters



2. Operation of Inverters



2. Operation of Inverters



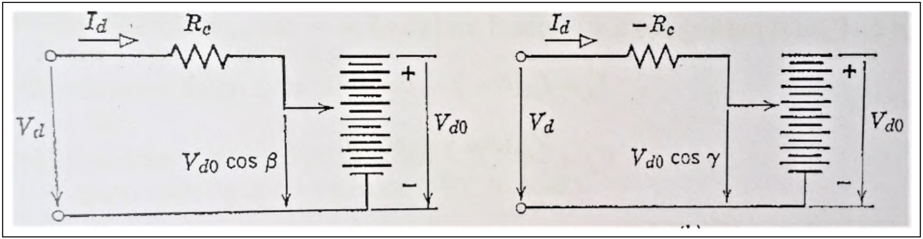
2. Operation of Inverters

$$\beta = \pi - \alpha$$
$$\gamma = \pi - \delta$$
$$u = \delta - \alpha = \beta - \gamma$$

- Rectifier to Inverter :
  - $V_d \rightarrow$ -V_d
  - cosα $\rightarrow$ - cosβ
  - cosδ $\rightarrow$ - cosγ

$$I_d = I_{s2}\left(cos\gamma - cos\beta\right)$$
$$V_d = \frac{V_{do}\left(cos\gamma + cos\beta\right)}{2}$$
$$V_d = V_{do}cos\beta + R_c I_d$$
$$V_d = V_{do}cos\gamma - R_c I_d$$

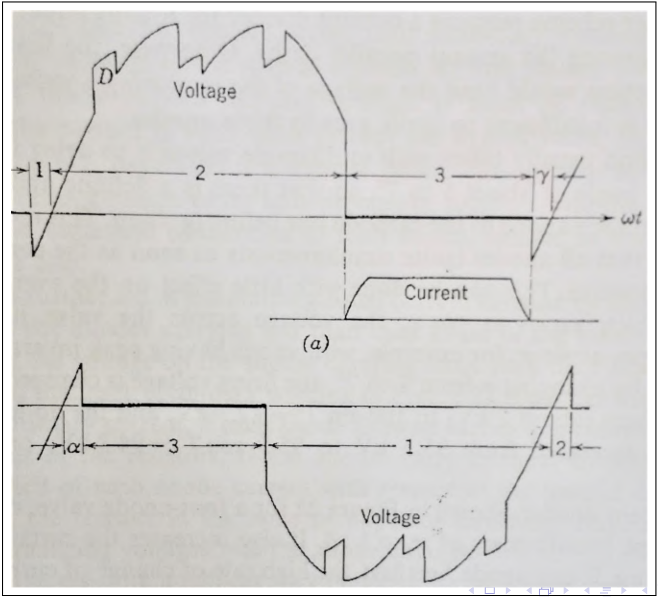
2. Operation of Inverters



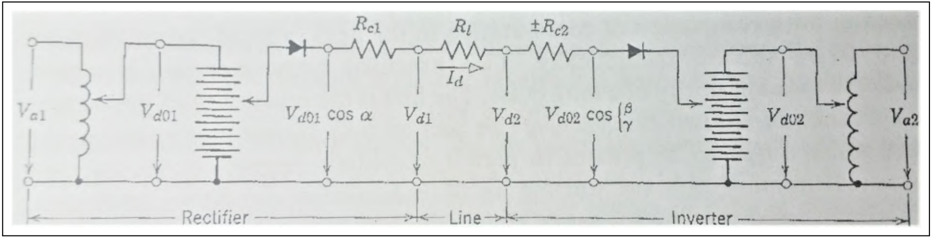
2. Operation of Inverters

- Average voltage across rectifier valve is -ve called as **inverse voltage**
- Average voltage across inverter valve is +ve(→ need for reliable grid control)
- Voltage across the valve is +ve just before conduction in both rectifier & inverter
    - +ve and shorter period in rectifier valve approaching zero as α approaches zero
    - +ve and longer period in inverter valve
- Voltage across the valve is -ve immediately after extinction of arc in both rectifier & inverter
    - -ve and shorter period in inverter valve
    - -ve and longer period in rectifier valve
- Abrupt changes in voltage across the valve occur at ignition and extinction
    - Voltage jump at ignition is greater in inverter than rectifier
    - Voltage jump at extinction is greater in rectifier than inverter

2. Operation of Inverters



3. Means of Control



3. Means of Control

- Ohm's Law

$$I_d = \frac{V_{do1} cos\alpha - V_{do2} cos\,(\beta \; or \; \gamma)}{R_{c1} + R_l \pm R_{c2}}$$

- $cos\beta$ & $+R_{c2}$ → if inverter is operated with constant ignition angle(β)
- $cos\gamma$ & $-R_{c2}$ → if inverter is operated with constant extinction angle(γ)
- $V_{a1} \rightarrow V_{do1} \rightarrow V_{do1} cos\alpha \rightarrow V_{d1}$
- Voltage drop due to overlap=Voltage across commutating resistance(R_{c1})
- I_d depends on
  - Voltage drop
  - Total resistance
- $I_d \propto$ difference of two internal voltages since resistance is fixed
- Each internal voltage can be controlled by
  - Grid control
  - Control of Alternating Voltage

3. Means of Control

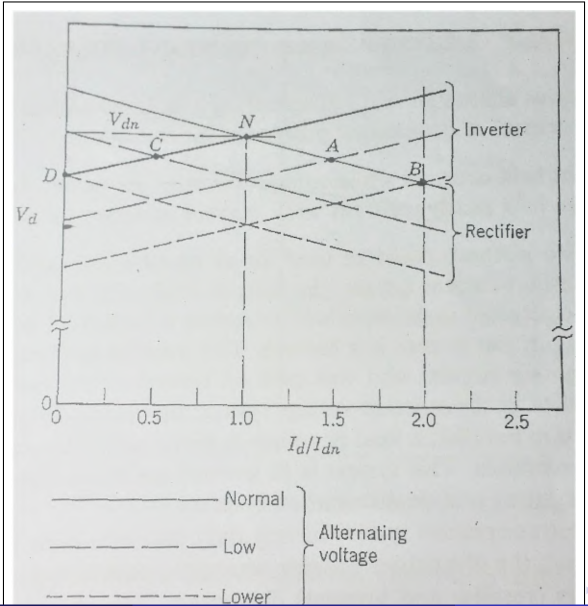
- Ideal $V_{do1} \propto$ Alternating Voltage
- Control of Alternating Voltage
  - **Tap changing on converter transformers**
  - Generator excitation control
- Grid control is rapid(1 to 10ms)
- Tap changing is slow(5 to 6s per step)
- Both controls are applied cooperatively at each terminal
- Grid control is initially used for rapid action followed by tap changing for restoring certain quantities(α in rectifier and β in inverter)

4. Power Reversal

To reverse the direction of power transmission

1. Polarity of direct voltages at both ends of the line must be reversed while maintaining the sign of their algebraic difference.
    - Station 2 becomes rectifier & station 1 inverter
    - Terminal voltage of rectifier is always greater in absolute value than that of inverter
2. Using reversing switches between each converter and line
    - No polarity reversal of conductor
3. By reversing current
    - Used in Low-voltage DC industrial application
    - Have two converters in parallel, one for each direction of current
    - Expensive

Limitations of Manual Control



Limitations of Manual Control

- Sudden variations of AC voltage
- Rapid grid control should restore the desired conditions on DC line as far as possible with available range of control
- **Rapid Automatic Control** Vs **Manual Control**
- Characteristic curve of voltage at midpoint versus current → straight line
- For Rectifier(left side) :
  - vertical axis intercept $= V_{do1} cos\alpha$
  - Slope $= -(R_{c1} + R_l/2)$

  For Inverter(right side) :
  - vertical axis intercept $= V_{do2} cos\beta$
  - Slope $= +(R_{c2} + R_l/2)$
- At point 'N'(intersection of two lines),
  - Rated Voltage → V_{dn}
  - Rated Current → I_{dn}
- Slope of the line is taken such that total voltage drop = 12.5% of V_{dn} $\Longrightarrow$ (Voltage drop due to commutation = 8% and Total line voltage drop = 9%)

Limitations of Manual Control

Let,

- AC voltage at inverter drops by 12.5% of V_{dn}(with no change in AC voltage at rectifier)
  - Inverter characteristic drops down and intersects with rectifier characteristic at **point A**
  - $I_d = 1.5I_{dn}$
- AC voltage at inverter drops by 25% of V_{dn}(with no change in AC voltage at rectifier)
  - Inverter characteristic drops down and intersects with rectifier characteristic at **point B**
  - $I_d = 2I_{dn}$

Limitations of Manual Control

Let,

- AC voltage at rectifier drops by 12.5% of V_{dn}(with no change in AC voltage at inverter)
  - Rectifier characteristic drops down and intersects with inverter characteristic at **point C**
  - $I_d = 0.5I_{dn}$
- AC voltage at rectifier drops by 25% of V_{dn}(with no change in AC voltage at inverter)
  - Rectifier characteristic drops down and intersects with inverter characteristic at **point D**
  - $I_d = 0$

Limitations of Manual Control

- **Dip in AC voltage produces a percentage change in I_d of four times the percentage change of voltage**
- Large fluctuations of current can't be tolerated
- High overcurrents may lead to **Arcback** of rectifier, **Commutation Failure** of inverter → Damage to valves
- $\Longrightarrow$ **Rapid control of current is essential**

Constant I Versus Constant V

- DC Transmission with Power Flow Control
    1. Current held constant while voltage varies as the power does
    2. Voltage held constant while current varies as power does
- Concern
    - Limitation of variation of current caused by variation of AC voltage or by faults on DC line or in converter → **Constant Current System**
    - The energy losses and efficiency → **Constant Voltage System**
- Automatic Control to combine best features of each

Desired Features of Control

1. Limitation of maximum current(→ Avoids damage to valves & other devices)
2. Limitation of fluctuation of current due to fluctuation of AC voltage
3. Prevention of **commutation failures** of the inverter
4. Prevention of **Arcback** of rectifier valves
5. In multianode valves, providing sufficient anode voltage before ignition occurs
6. Keeping sending end voltage constant at its rated value insofar as possible in order to minimize losses for a given power
7. Controlling power delivered or the frequency at one end
8. Keeping the power factor as high as possible

Desired Features of Control

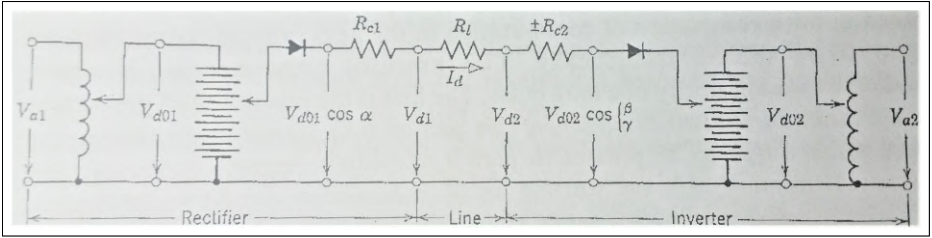
- **High Power Factor**
  - To keep the rated power of the converter as high as possible for given V & I ratings of valves & transformers as P $\propto V_d$
  - To reduce the stresses on the valves & damping circuits
  - Minimize required current rating & copper losses in AC lines
  - To minimize voltage drop at AC terminal of the converter as its loading increases
- For Rectifier

$$Cos\phi \approxeq \frac{V_d}{V_{do}} = \frac{Cos\alpha + Cos(\alpha + u)}{2}$$

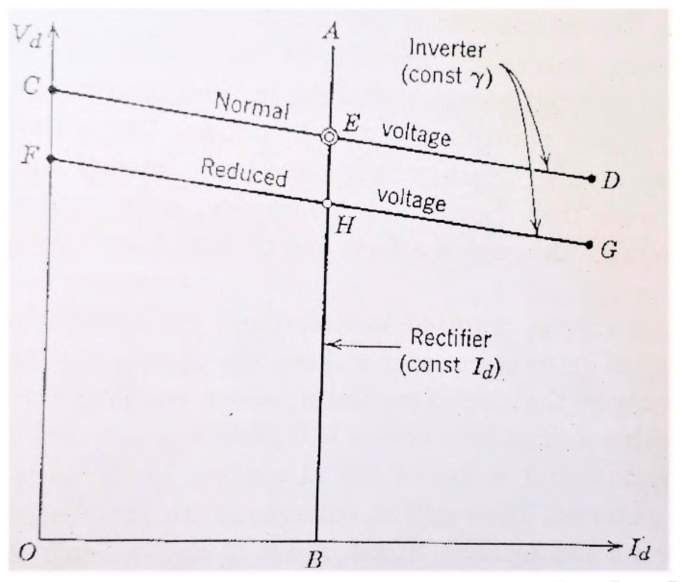
- For Inverter

$$Cos\phi \approxeq \frac{Cos\gamma + Cos(\gamma + u)}{2}$$

Actual Control Characteristics



Actual Control Characteristics



Actual Control Characteristics

Individual Characteristics of Rectifier & Inverter

- V_d versus I_d
- Consider sending end
- Rectifier with **Constant-Current Regulator** → Vertical Line **AB**
    - High negative slope
- Inverter with **Constant Extinction Angle(C.E.A) Regulator** → Line **CD**
    - Small negative slope

$$V_d = V_{do2} Cos\gamma + (R_l - R_{c2}) I_d$$

- Point **E** → Intersection of Rectifier & Inverter Characteristics

Actual Control Characteristics

- Rectifier Characteristic can be shifted horizontally by adjusting **Current command** to the current regulator
- Inverter Characteristic can be shifted raised or lowered
- Rectifier controls I_d
- Inverter controls V_d
- Inverter characteristic can be raised or lowered by means of **tap changer on transformer at inverter station**
- $V_{a1} \rightarrow V_{do1} \rightarrow V_{do1} Cos\alpha \rightarrow V_{d1} \rightarrow V_{d2} \rightarrow V_{do2} Cos\gamma \rightarrow V_{do2} \rightarrow V_{a2}$
- $I_d = \frac{V_{d1} - V_{d2}}{R_l}$

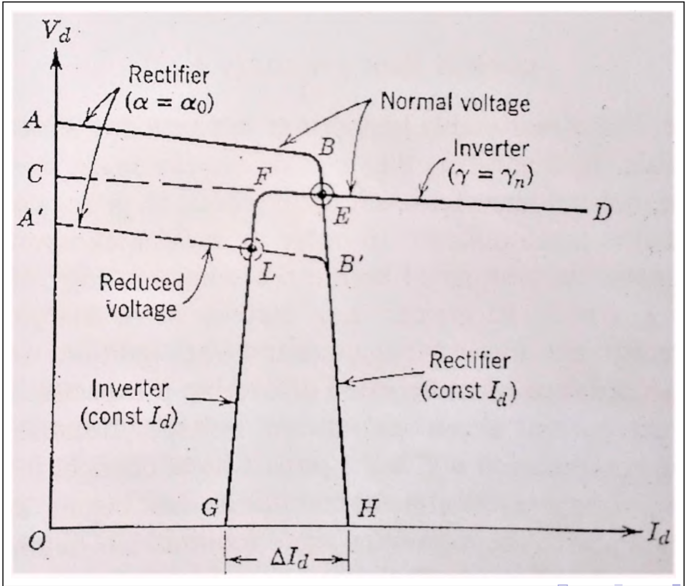
Actual Control Characteristics

1. If inverter voltage is raised, the rectifier voltage must be raised by an equal amount in order to keep the current constant
    - To increase V_{d1}, decrease α till 0(or α_o)
    - V_{d1} can be further increased by raising tapping on rectifier transformer
    - Rectifier tap changer is automatically adjusted to keep $10^o < \alpha < 20^o$ with a compromise between
        - Keeping pf high which required small α
        - Having a margin for quick increase in rectifier voltage which requires high α
2. Sudden reduction in inverter voltage
    - Inverter characteristic(**CD** is shifted downward to **FG**)
    - New operating point is **H** with reduced voltage and almost same current
    - Power is reduced in proportion to voltage
    - To restore the system, tap changer on inverter transformer is raised till V_d becomes normal or limit of tap changer is reached

Actual Control Characteristics

3. Decrease of Rectifier Voltage
   - $V_{a1} \downarrow$, $I_d \downarrow$
   - To increase I_d, increase V_{d1} by decreasing α to 0 or α_o(Constant Current Regulator)
   - $\alpha_o =$ Constant Minimum Ignition Angle
   - Rectifier Characteristic(**ABH**) has two segments
     1. Constant Minimum Ignition Angle Control(**AB**)
     2. Constant Current Control(**BH**)
4. Further big dip in Rectifier Voltage
   - Rectifier characteristic shifts to **A'B'H** which do not intersect with inverter characteristic
   - Consequently current & power drop to zero
   - To handle such the situation, inverter is also equipped with **Constant Current Regulator** in addition to **Constant Extinction Angle Controller**
   - Current setting of **C.C. Regulator** of Inverter $<$ Current setting of **C.C. Regulator** of Rectifier
   - Now inverter controls current & rectifier controls voltage
   - **Current Margin(ΔI_d)** $=$ % of rated current
   - New operating point is **L**

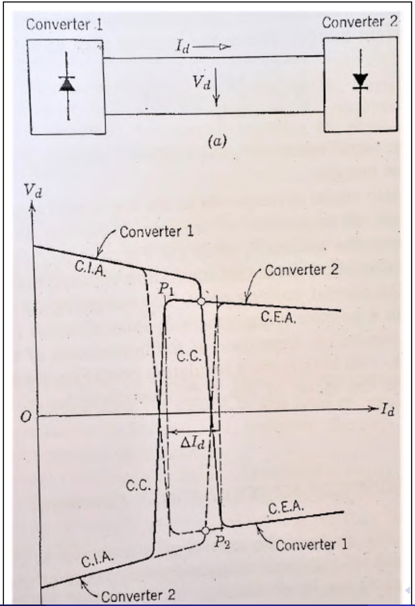
Actual Control Characteristics



Actual Control Characteristics

- Voltage dip at rectifier end reduces power more than does an equal dip at inverter end
- If the current is to be increased, the current setting is raised first at the rectifier and second at inverter
- If the current is to be decreased, the current setting at inverter is deceased first and then at rectifier

Combined Characteristics of Rectifier & Inverter



Combined Characteristics of Rectifier & Inverter

- Same current command is given to both stations. Then at the station which is designated as inverter, current margin(ΔI_d) is subtracted from the current command giving a smaller current setting

Constant Minimum Ignition Angle Control

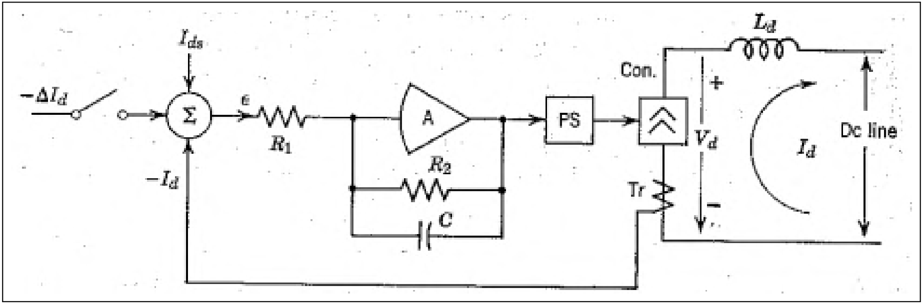
- Constant Minimum Ignition Angle
- Constant Current
- Constant Minimum Extinction Angle

Constant Current Control

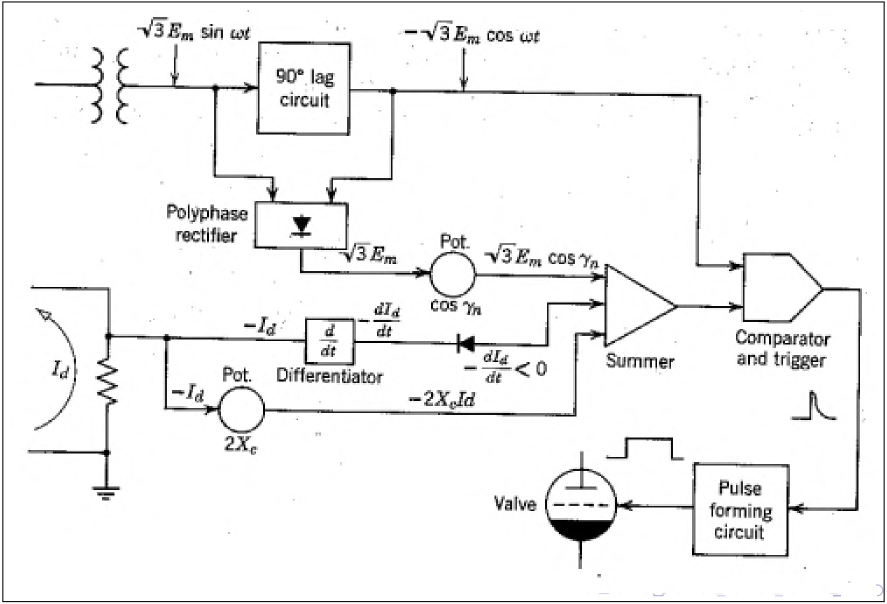
Constant Current Control involves

1. Measurement of Direct Current(I_d)
2. Comparison of I_d with set value I_{ds}(also called as reference value, current order or current current command)
3. Amplification of the difference ($I_{ds} - I_d$) called as error
4. Application of output signal of amplifier to phase shift circuit that alters the ignition angle α of the valves in the proper direction for reducing the error

Constant Current Regulator



Constant Extinction Angle Control



References

1. E. W. Kimbark, *'Direct Current Transmission-Vol.1'*, Whley Interscience, New York 1971
2. J. Arrilage, *'High Voltage Direct Current Transmission'*, Peter Pereginver Ltd., London U.K. 1983
3. K. R. Padiyar, *'HVDC Transmission Systems'*, Wiley Eastern Ltd., New Delhi 1992

Thank You

*for private circulation only

HVDC Transmission Systems

(05EE 6034)

Module 3 - Overview

Misoperation of Converters and Protection

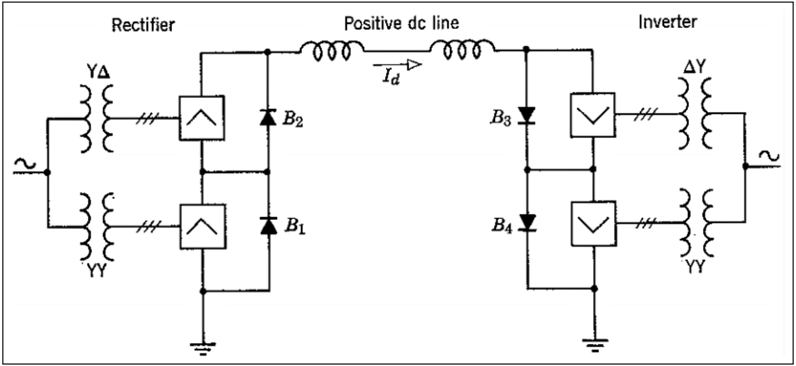
1. Malfunctions of Valves
2. Bypass Action
3. Commutation Failure
4. Protection of Converters
5. DC Reactors
6. Voltage Oscillations
7. Circuit Breaker
8. Over Voltage Protection

Malfunctions of Valves

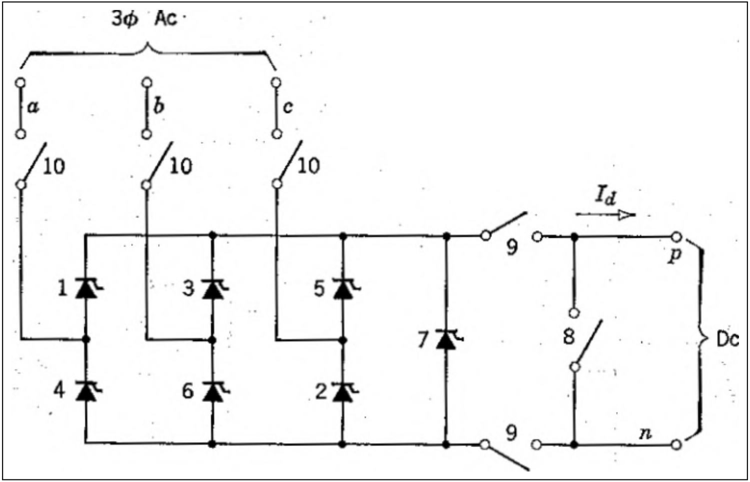
- Gate Control → **Control** as well as **Protection** of converter
- **Arcback(Backfire)** → Conduction in reverse direction
- **Arc-through(Fire-through/Shoot-through)** → Conduction during a scheduled blocking period
- **Quenching(Arc Quenching/Arc Chopping)** → Premature extinction of arc during a scheduled conducting period
- **Misfire** → Failure to ignite in spite of positive grid and anode voltages
- **Commutation Failure(Break-through)** → Failure to complete commutation before commutating emf reverses

Bypass Valves

- Non self-clearing faults in valves are cleared with the help of bypass valves
- Bypass valve → Seventh Valve



Bypass Valves

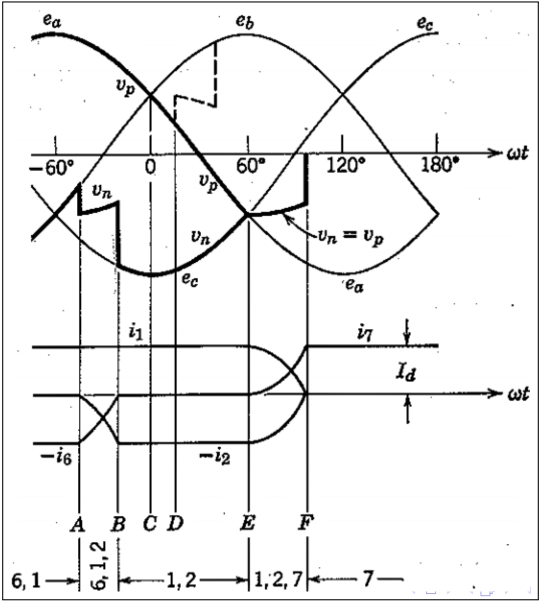


7 → Bypass Valve

8 → Bypass Switch

9 & 10 → Disconnecting Switches

Transfer of Current

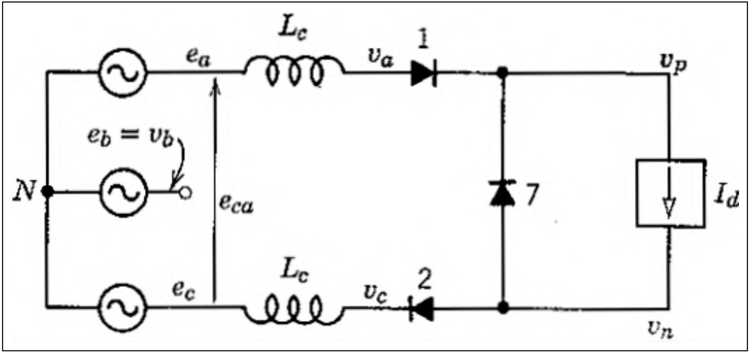


Transfer of Current

Transfer to Bypass Valve when the bridge is operating as Rectifier

- I_d is kept constant by DC reactor and constant current control
- Direct Voltage across bypass valve is normally negative
- At instant **'C'**
  - Valves 1 & 2 are conducting
  - All main valves are blocked
  - Bypass valve(Valve 7) is unblocked
  - Anode voltage of Valve 7 $= v_7 = -v_d = v_n - v_p$
  - Since v_7 is -ve, valve 7 can't be ignited
- At instant **'D'**
  - Valve 3 can't start conducting due to lack of grid pulse
  - Valves 1 & 2 continue to conduct
  - Direct voltage(v_d) declines
- At instant **'E'**
  - Direct voltage(v_d) $= 0$ and starts to reverse
  - Valve 7 ignites

Transfer of Current



Transfer of Current

- Voltage

$$e_{ca} = \sqrt{3}E_m Sin\omega t$$

- Bypass current

$$i_7 = I_{s2}(1 - Cos\omega t)$$

$$I_{s2} = \frac{\sqrt{3}E_m}{2\omega L_c}$$

- Main valve currents

$$i_1 = i_2 = I_d - i_7 = I_d - I_{s2}(1 - Cos\omega t)$$

- Commutation ends when $i_1 = i_2 = 0$

$$i_7 = I_d \;\; at \;\; \omega t = u_7$$

Transfer of Current

- Overlap Angle

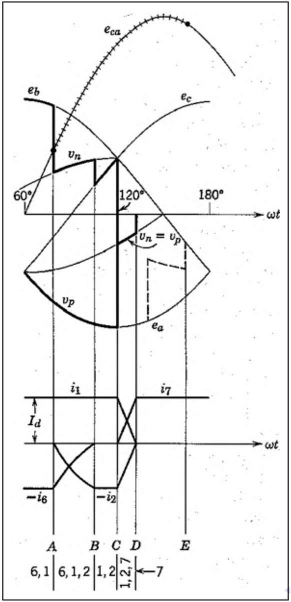
$$Cos(u_7) = 1 - \frac{I_d}{I_{s2}}$$

Transfer of Current

Transfer to Bypass Valve when the bridge is operating as Inverter

- Direct Voltage across bypass valve is normally positive
- **Bypass valve gets ignited as soon as it is unblocked**
- Commutation begins from conducting main valves to bypass valve immediately

Transfer of Current



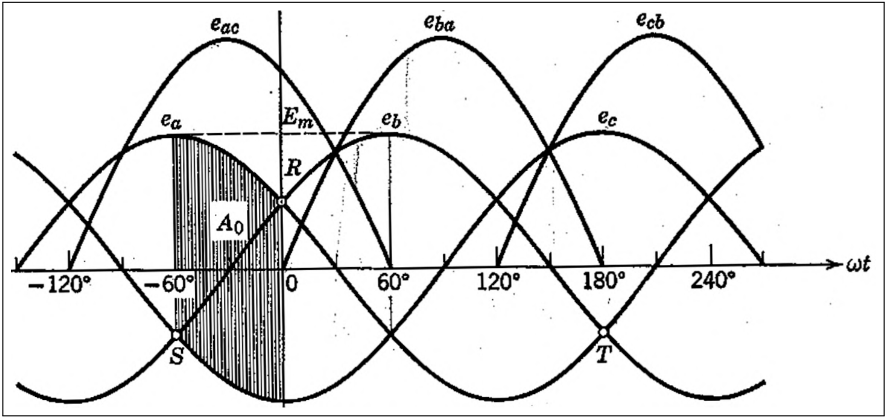
Commutation Failure

- **Commutation Failure(Breakthrough)** : Failure to complete commutation before the commutating emf reverses
- If commutation is not completed before the alternating commutation emf reverses, **current will be shifted back from incoming valve to the valve that was expected to go out**

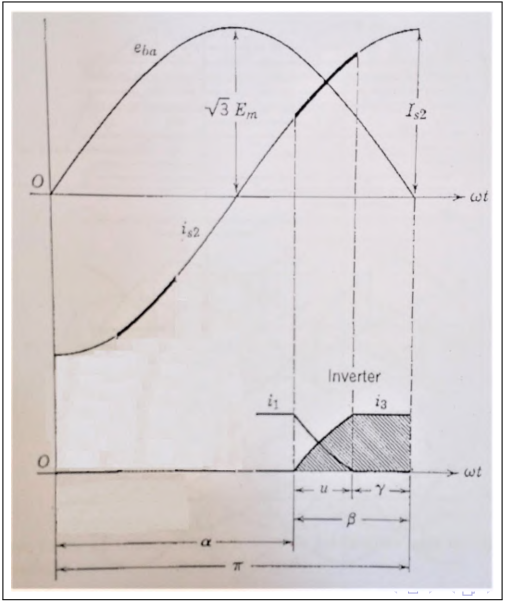
Causes

1. Conditions in the AC or DC circuits outside the bridge in which failure occurs
2. **Inadequate control of time of ignition**

Commutation Failure



Commutation Failure



Commutation Failure

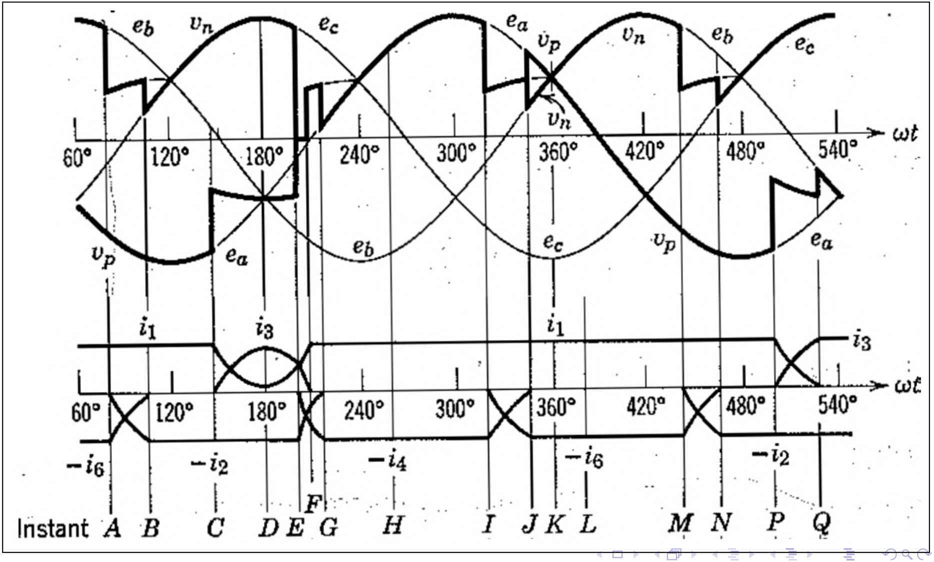
Analysis : Failure of commutation from valve 1 to valve 3

- Normal Extinction Angle $= 15^o$
- Ignition Angle $= 40^o$
- Late firing of valve 3

At instant $\mathbf{A}(\omega t = 80^o)$

- Normal commutation from valve 6 to valve 2

Commutation Failure



Commutation Failure

At instant $\mathbf{B}(\omega t = 105^o)$

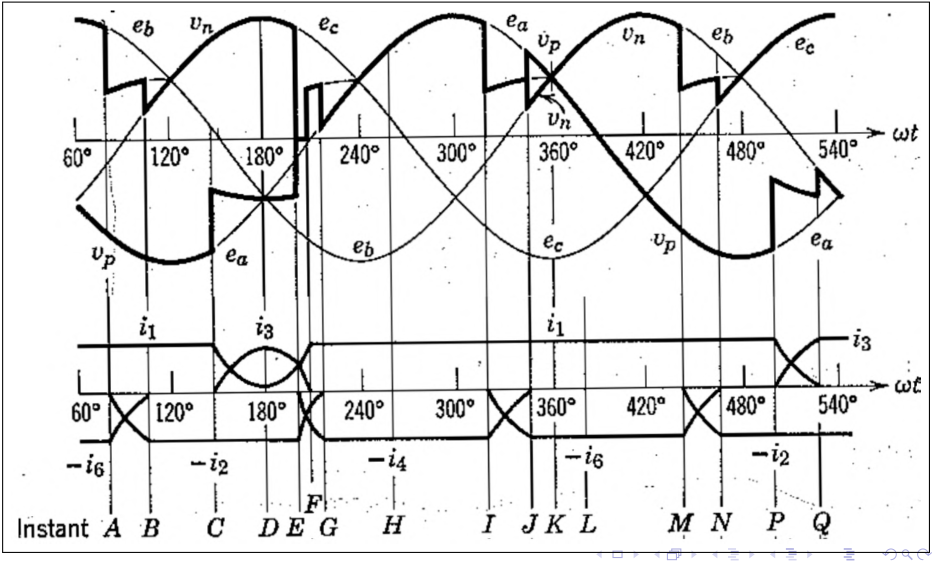
- Commutation from valve 6 to valve 2 is completed
- Valve 1 and 2 are conducting

Commutation Failure

At instant **C**$(\omega t = 145^o)$

- **Valve 3 fires** 5^o **late**
- Commutation begins from valve 1 to valve 3

Commutation Failure



Commutation Failure

At instant **D**$(\omega t = 180^o)$

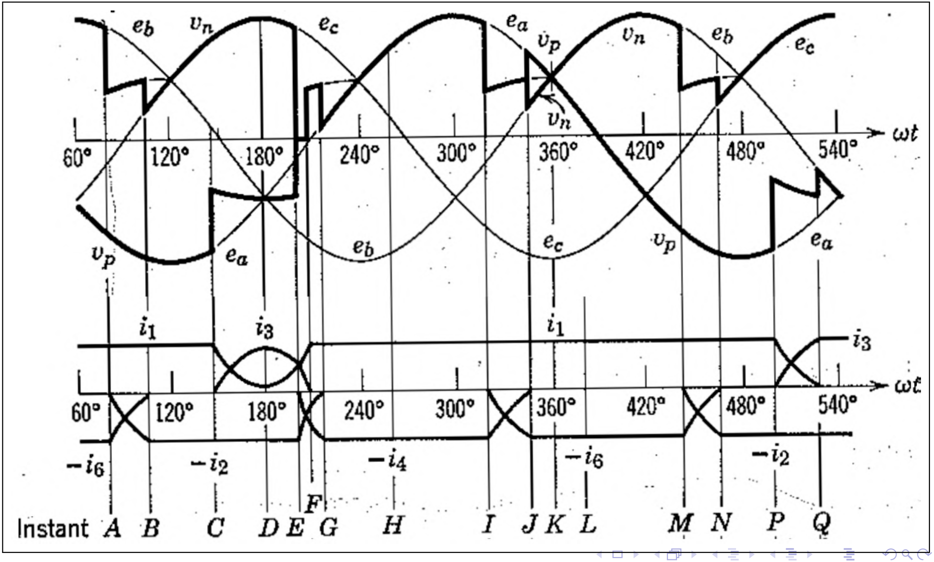
- **Commutating voltage(e_b - e_a) reverses before commutation is completed**
- Failure of commutation
- Reverse transfer of current begins

Commutation Failure

At instant $\mathbf{E}(\omega t = 200^o)$

- Before reverse commutation from valve 3 to valve 1 is completed, **valve 4 ignites**
- Commutation from valve 2 to valve 4 begins
- Valves 1, 2, 3 & 4 are conducting
- **Double overlap**
- **AC & DC terminals are short-circuited**
- All voltages are zero

Commutation Failure

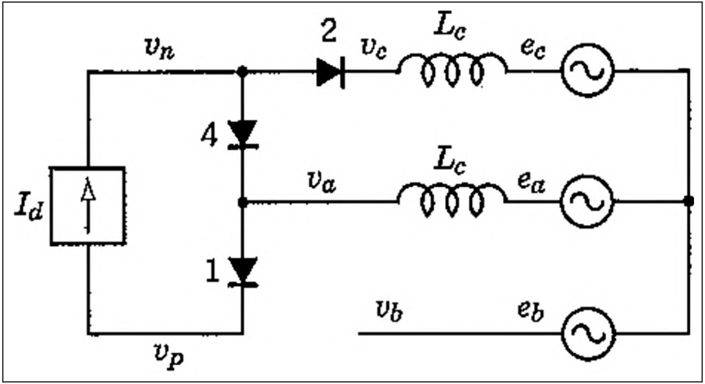


Commutation Failure

At instant **F**$(\omega t = 207.4^o)$

- Reverse commutation from valve 3 to valve 1 is completed
- Valves 1, 2 & 4 are conducting
- Commutation from valve 2 to valve 4 is going on
- **DC terminals are short circuited through valves 1 & 4**
- **AC terminals, 'a' & 'c' are short-circuited**

Commutation Failure

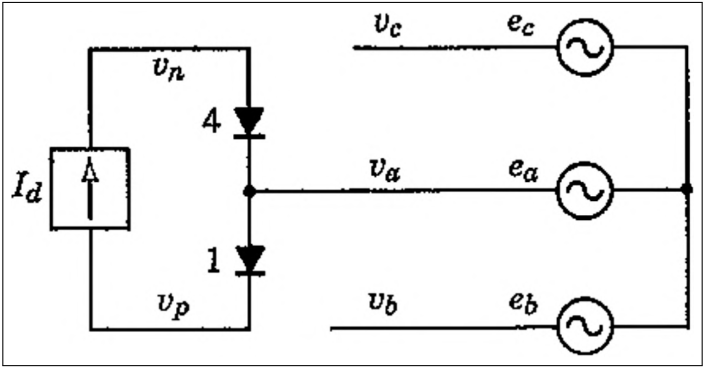


Commutation Failure

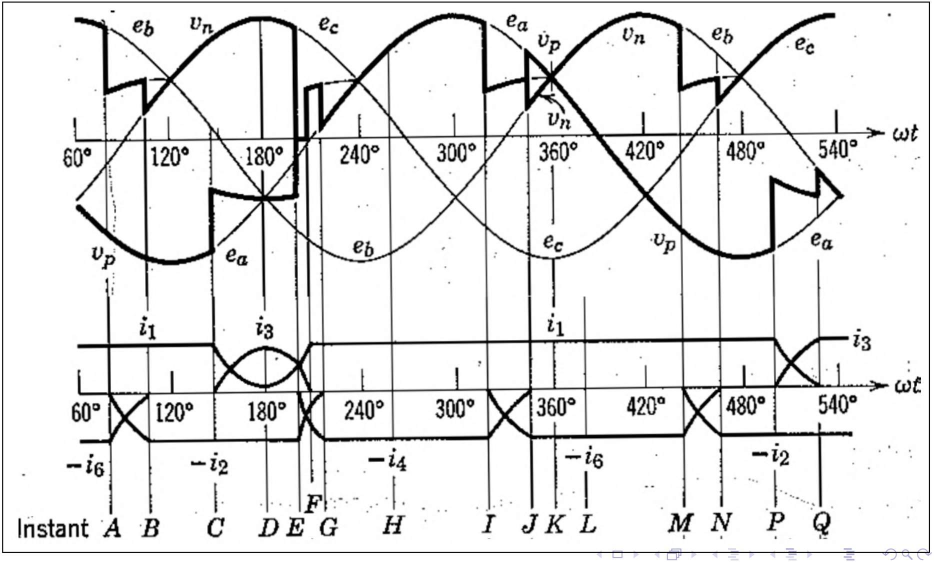
At instant **G**$(\omega t = 214.8^o)$

- Commutation from valve 2 to valve 4 is completed
- Valves 1 & 4 are conducting
- **DC terminals are short-circuited**
- No alternating current

Commutation Failure



Commutation Failure



Commutation Failure

At instant **H**$(\omega t = 260^o)$

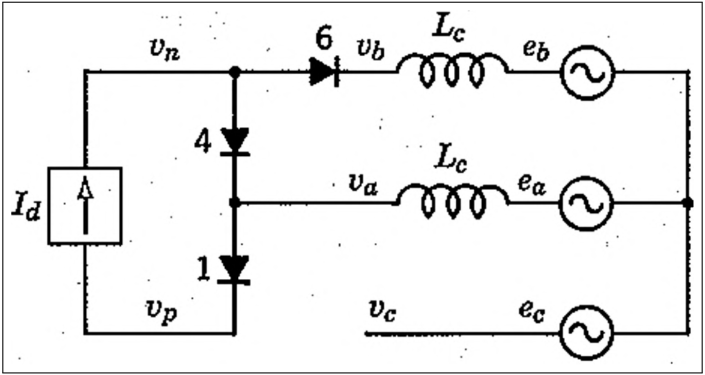
- Valve 5 is pulsed
- **Valve 5 can not ignite as voltage across it is negative**

Commutation Failure

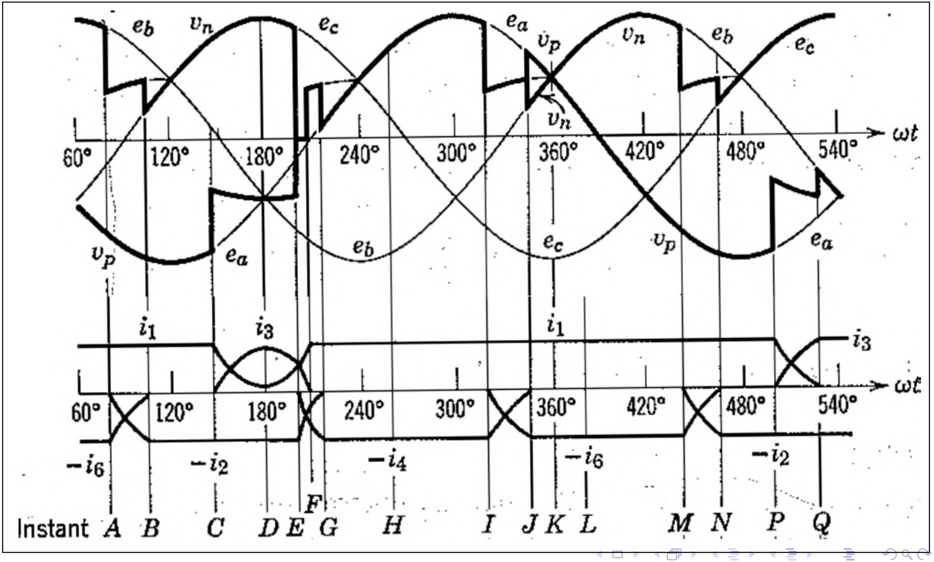
At instant **I**$(\omega t = 320^o)$

- **Valve 6 ignites**
- Commutation from valve 4 to valve 6 begins
- Valves 1, 4 & 6 are conducting
- DC terminals are still short-circuited through valves 1 & 4
- AC terminals **'a' & 'b'** are short-circuited through valves 4 & 6

Commutation Failure



Commutation Failure



Commutation Failure

At instant $\mathbf{J}(\omega t = 345^o)$

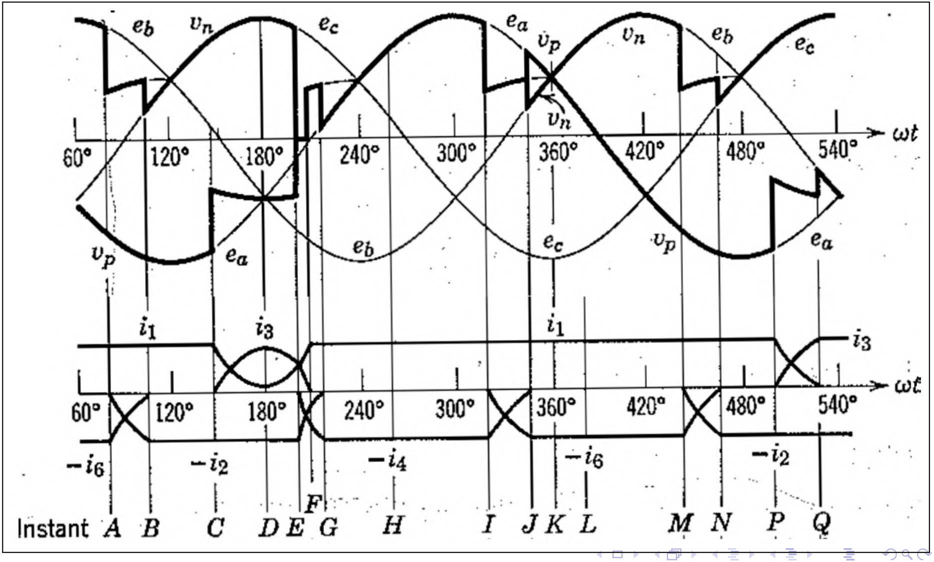
- Commutation from valve 4 to valve 6 is completed
- **DC short-circuit is removed**
- Valves 1 & 6 are still conducting

Commutation Failure

At instant $\mathbf{K}(\omega t = 360^o)$

- v_d **reverses & becomes negative**

Commutation Failure



Commutation Failure

At instant $\mathbf{L}(\omega t = 380^o)$

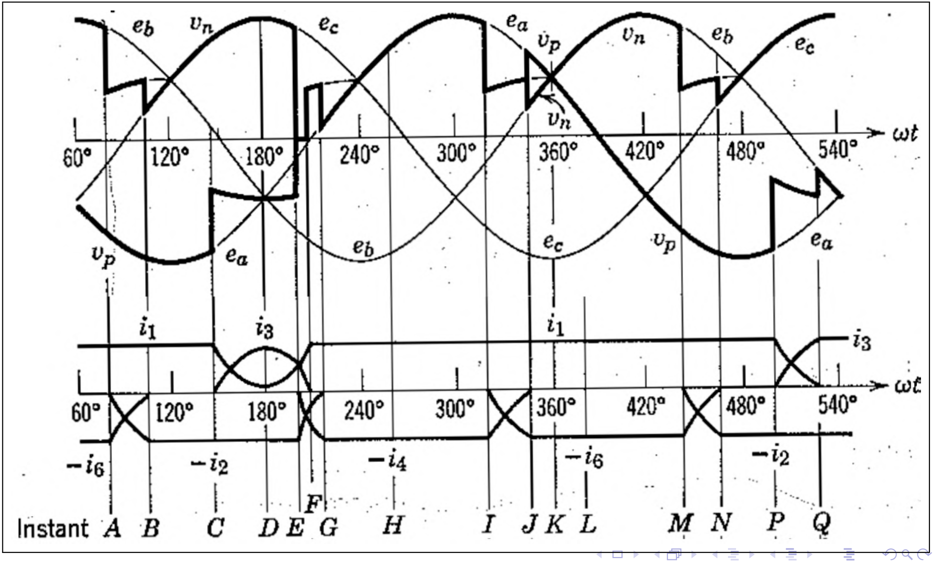
- **Valve 1 is pulsed but is already conducting**

Commutation Failure

At instant **M**$(\omega t = 440^o)$

- **Valve 2 ignites**
- Commutation from valve 6 to valve 2 starts

Commutation Failure



Commutation Failure

At instant **N**$(\omega t = 465^o)$

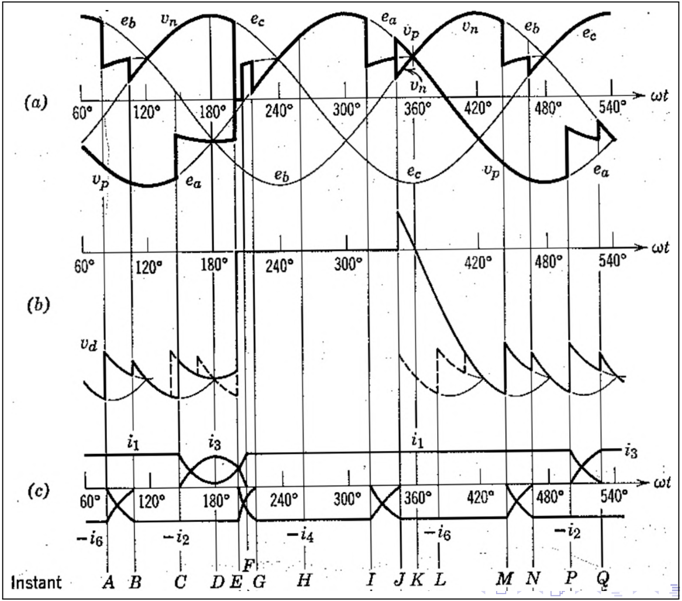
- Commutation from valve 6 to valve 2 is completed

Commutation Failure

At instant **P**$(\omega t = 500^o)$

- **Valve 3 ignites**
- Commutation from valve 1 to valve 3 begins

Commutation Failure



Commutation Failure

At instant $\mathbf{Q}(\omega t = 525^o)$

- **Valve 1 extinguishes**
- Commutation from valve 1 to valve 3 is completed
- **Inverter operates normally**

Commutation Failure

Symptoms

- DC Voltage is zero from instant **'E'** to **'J'**(a period of 145^o) since DC terminals are short-circuited
- For a period of 205^o after instant **'E'**, DC Voltage is below normal
- AC currents in all terminals are zero from instant **'G'** to **'I'**(a period of 105^o). ie, for this period DC current is greater than AC current

Remedy

- After the occurrence of commutation failure, succeeding commutation is initiated earlier by **C.E.A.(Constant Extinction Angle)** Control System
- If the cause of commutation failure is low AC voltage, then setting AC voltage back to its normal value will help to prevent further commutation failures

Protection of Converters

Protection of **AC System**

1. **Over Voltage Protection**
    - Overhead Shield Wires, Protective Gaps, Lightning Arresters etc.
2. **Over Current Protection**
    - Fuses, Circuit Breakers, Protective Relays, Current Limiting Reactors etc.

Protection of **HVDC System**

1. **Over Voltage Protection**
    - Overhead Shield Wires, Protective Gaps, Lighting Arresters etc.
2. **Over Current Protection**
    - by Control of Valves
3. **Damper Circuits**
4. **DC Reactors**

DC Reactors

- Reactors with inductances of 0.4H to 1H
- Connected in series with each pole of converter station

Functions

1. **Prevent consequent commutation failures in inverter by limiting the rate of increase of direct current** during commutation in one bridge when direct voltage of another bridge collapses
2. Decrease the incidence of commutation failures in inverter during dips in AC voltage
3. Decrease harmonic voltages and currents in DC line
4. Smooth the ripple in direct current sufficiently to prevent the current from becoming discontinuous or almost so at light loads

Prevention of Consequent Commutation Failures

- Inverter faults → collapse of DC voltage of a bridge
- Counter voltage of affected inverter poles falls to $\left(\frac{b-1}{b}\right)$ times normal value where b = number of bridges in series
- If 2 bridges per pole, voltage of affected pole drops to half of normal value
- I_d will increase such that
    - Transmission line voltage drop(IR) = Rectifier voltage - reduced inverter voltage
- Rise of current prolongs commutation → Commutation failure → Additional large decrease of inverter voltage → Further increase in rate of rise of I_d → Power transmitted decreases to half of its prefault value
- To avoid such disturbance, rise in I_d during commutation in one bridge caused by collapse of direct voltage in another bridge **must be limited to a value that does not cause commutation failure**

Prevention of Consequent Commutation Failures

Magnitude and Rate of rise of I_d depends on

- **DC reactor**
  - Inductance of DC reactor is the principal factor limiting the rate of rise of I_d

Prevention of Consequent Commutation Failures

To calculate the inductances required for sufficiently limiting the rise of I_d after the collapse of DC voltage of a bridge so that a commutation failure does not ensue, the following assumptions are made.

- V_d on line side of DC reactor remains constant at its initial value
- AC voltage at the inverter station remains constant
- The tap changer does not move
- Initially I_d has its normal value(I_{dn})
- Ignition is assumed to be late by 1^o due to error in C.E.A Control

Prevention of Consequent Commutation Failures

Let,

- Normal Extinction Angle(γ_n) $= 16^o$
- Minimum extinction angle(γ_m) to be permitted as a result of collapse of direct voltage $= 8^o$
- Normal ignition advance angle(β_n)

$$cos\beta_n = cos\gamma_n - \frac{I_{dn}}{I_{s2}}$$

- Greatest permissible current at the end of commutation($\gamma \to \gamma_m$)

$$\frac{I_{d\beta} + I_{d\gamma}}{2} = I_{s2}\left(cos\gamma - cos\beta\right)$$

$$\beta = \beta_n - 1^o$$

$$\gamma = \gamma_m$$

$$I_{d\beta} = I_{dn}$$

$$I_{d\gamma} = I_{dn} + \Delta I_d$$

Prevention of Consequent Commutation Failures

$$\begin{aligned}
\Delta I_d &= 2I_{s2}\left[cos\gamma_m - cos\left(\beta_n - 1^o\right)\right] - 2I_{dn} \\
\frac{dI_d}{dt} &= \frac{\Delta I_d}{\Delta t} = \frac{\Delta V_d}{L_d} \\
\implies L_d &= \frac{\Delta V_d . \Delta t}{\Delta I_d} \\
\Delta t &= \frac{\beta_n - 1^o - \gamma_m}{360^o f}
\end{aligned}$$

Prevention of Consequent Commutation Failures

1. Find the inductance of the DC reactor required to prevent consequent commutation failure in the inverter described below

Number of bridges = 2

Rated voltage per bridge = 200kV

Rated current = 1.8kA

I_{s2} = 10kA

Frequency = 60Hz

Ans:

$$\begin{aligned} cos\beta_n &= cos\gamma_n - \frac{I_{dn}}{I_{s2}} = cos16^o - 1.8/10 = 0.781 \\ \beta_n &= 37.6^o \\ \Delta I_d &= 2I_{s2}\left[cos\gamma_m - cos\left(\beta_n - 1^o\right)\right] - 2I_{dn} \\ &= 2 \times 10(cos8^o - cos37.6^o) - 2 \times 1.8 \\ &= 0.36kA(ie, 20\%) \end{aligned}$$

Prevention of Consequent Commutation Failures

$$\begin{aligned}\Delta t &= \frac{\beta_n - 1^o - \gamma_n}{360^o f} \\ &= \frac{37.6 - 8}{360 \times 60} = 1.37ms \\ L_d &= \frac{\Delta V_d.\Delta t}{\Delta I_d} = \frac{200 \times 1.37 \times 10^{-3}}{0.36} = 0.76H\end{aligned}$$

Prevention of Consequent Commutation Failures

2. Find the smallest fraction of normal value to which balanced alternating voltage at the inverter can fall suddenly without causing a commutation failure. Assume that the fall of voltage occurs immediately after the beginning of a commutation at $\beta = 37.6^o$ with $I_d = 1.8$kA. Assume also that a commutation failure occurs if $\gamma < 1^o$

Ripple in Direct Current

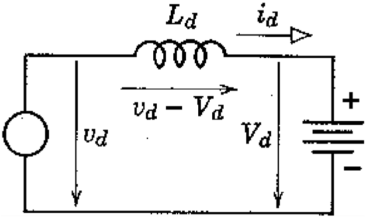
- Ripple in Direct Current may cause
    - Noise in telephone circuits
    - Ripple sets lowest average current at which the current is continuous
        - Current becomes discontinuous or intermittent if current is below that lowest value
        - In 12 pulse converter, current will be interrupted 12 times per cycle → high overvoltages$\left(L\frac{di}{dt}\right)$ will be induced in windings of converter transformer & DC reactor → this high voltage can't be accepted

Calculation of Ripple

Assumptions

1. Consider six-pulse operation of one bridge
    - Ripple will be more in six-pulse operation than twelve-pulse operation
2. Constant ripple-free direct voltage on the line side of DC reactor
    - Good filtering by DC reactor with or without tuned filters
3. No overlap
    - At light loads, overlap will be small
    - Small effect on the wave shape of direct current
4. Periodic variation of direct voltage on the valve side of DC reactor consisting of arcs of sine waves of power system frequency
5. Arbitrary ignition angle(α)
6. No resistance in DC reactor

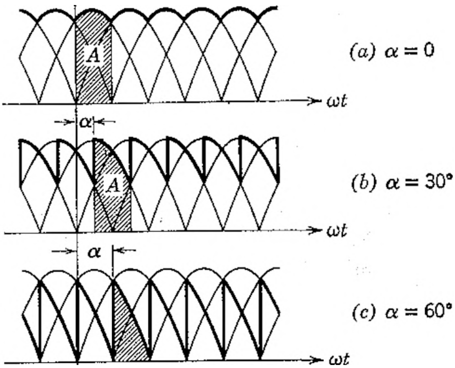
Calculation of Ripple



$$L_d \frac{di_d}{dt} = v_d - V_d$$

$$i_d = \frac{1}{L_d} \int (v_d - V_d)\, dt$$

Calculation of Ripple



- In six-pulse converter with no overlap, v_d consists of 60^o arcs of sine waves with amplitudes equal to peak line-to-line AC voltages

$$V_{do} = \frac{3\sqrt{3}E_m}{\pi} = 1.65E_m$$

Calculation of Ripple

- Equation of first arc after origin of time

$$v_d = \sqrt{3}E_m cos\left(\omega t - 30^o\right) \qquad for \;\; \alpha \leqq \omega t \leqq \alpha + 60^o$$

- If there is no overlap

$$V_d = V_{do} cos\alpha$$

- Voltage across the reactor in the specified time range

$$v_d - V_d = V_{do}\left[\frac{\pi}{3} cos\left(\omega t - 30^o\right) - cos\alpha\right]$$

- Instantaneous direct current(i_d)

$$i_d = \frac{V_{do}}{\omega L_d}\left\{\frac{\pi}{3}\left[sin\left(\omega t - 30^o\right) - sin\left(\alpha - 30^o\right)\right] - \left(\omega t - \alpha\right) cos\alpha\right\}$$

Calculation of Ripple

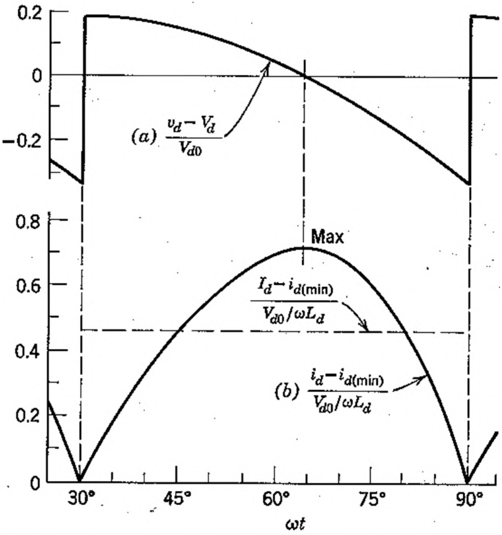


Figure 1 : (a) v_d (b) i_d for $\alpha = 30^o(\omega t = 30^o$ to $\omega t = 90^o)$

Calculation of Ripple

- Maxima and minima of i_d occur when $(v_d - V_d) = 0$
  - When $(v_d - V_d) > 0 \implies i_d$ increases
  - When $(v_d - V_d) < 0 \implies i_d$ decreases
- Zero of i_d has been taken as it's value at $\omega t = \alpha$
- Average value of ripple current

$$\begin{aligned} I_d &= \frac{3}{\pi}\int_{\alpha}^{\alpha+\pi/3} i_d d(\omega t) \\ &= \frac{V_{do}}{\omega L_d}\left[sin\alpha - \frac{\pi}{3}sin\left(\alpha - 30^o\right) - \frac{\pi}{6}cos\alpha\right] \\ \implies I_d &= \frac{V_{do}}{\omega L_d}\left(0.0931sin\alpha\right) \end{aligned}$$

Calculation of Ripple

- For all values of α except 0^o and 180^o,
  - $(v_d - V_d)$ has discontinuities at junctions between arcs at $\omega t = \alpha, \alpha + 60^o, \alpha + 120^o$ etc.
- For values $10.1^o < \alpha < 169.9^o$,
  - Zero of $(v_d - V_d)$ lies on this range
  - Minimum of i_d occurs at same time
- For $\alpha = 0^o$
  - Neither of the zeros of $(v_d - V_d)$ in a 60^o arc falls at $\omega t = \alpha$
  - Value of i_d at $\omega t = \alpha$ is not the minimum
- If $\alpha = 10.1^o$ or $\alpha = 169.9^o$
  - Zero of $(v_d - V_d)$ lies at one end of the discontinuity
- For twelve-pulse converter

$$I_d = \frac{V_{do}}{\omega L_d}(0.023 sin\alpha)$$

Calculation of Ripple

Q. Find the inductance of the DC reactor required to keep the direct current continuous when the given converter is operating with one bridge per pole at 5% of rated current and $\alpha = 90^o$

Number of bridges = 2

Rated voltage per bridge = 200kV

Rated current = 1.8kA

$I_{s2} = 10$kA

Frequency = 60Hz

Ans:

Six-pulse converter

$$L_d = \frac{V_{do} \times 0.0931 sin\alpha}{\omega i_{dm}}$$

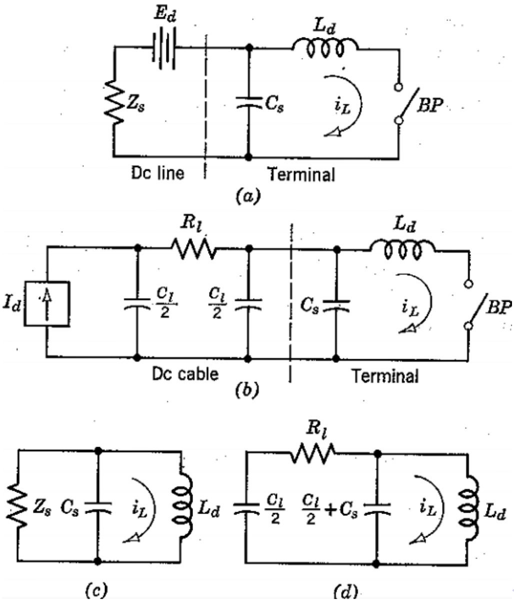
$$i_{dm} = 0.05 \times 1.8kA = 0.09kA$$

$$L_d = 0.49H$$

Discharge of Line through Bypass Valves

- At inverter station, bypass valves are of such polarity that the line can discharge through them
- If inverter bypass valves on one pole are unblocked accidentally, the line discharges through bypass valves
- Inverter station is represented by inductance of DC reactor & total shunt capacitance of the station
- A long overhead line can be represented by Thevenin equivalent circuit for transients comprising the open circuit voltage(E_d) and surge impedance
- DC cable can be represented by nominal T or π circuit with series resistance and charged shunt capacitance
- Rectifier may be represented by a constant current source
- Current thorough bypass valves consists of a steady state DC component and a transient component
- DC component during first round-trip wave-travel time is E_d/Z_s
- Transient current is a damped sinusoid

Discharge of Line through Bypass Valves



Discharge of Line through Bypass Valves

- Current through bypass valves

$$i_L = \frac{E_d}{Z_s}\left\{1 - \epsilon^{-\sigma t}\left[cos\omega t - \left(\frac{Z_s}{\omega L_d} - \frac{\sigma}{\omega}\right) sin\omega t\right]\right\}$$

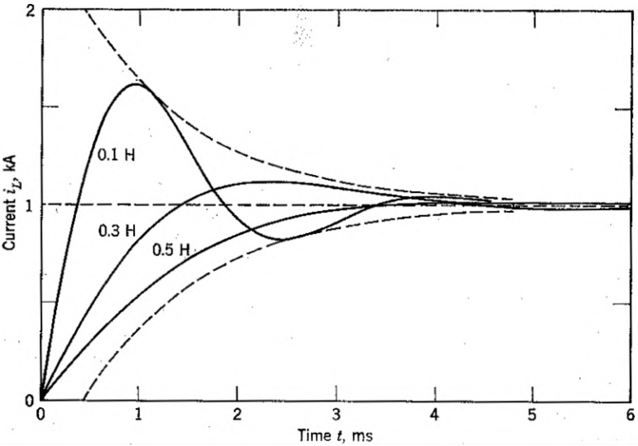
$$\sigma = \frac{1}{2Z_sC_s}$$

$$\omega = \sqrt{\omega_n^2 - \sigma^2}$$

$$\omega_n = \frac{1}{\sqrt{L_dC_s}}$$

- Transient current consists of a DC term with exponential decay and a damped sinusoidal term
- DC reactor limits the crest value of discharge current

Discharge of Line through Bypass Valves



- Discharge of overhead DC line as affected by the inductance of DC reactor
- Broken lines represent the envelope of i_L for $L_d = 0.1\text{H}$

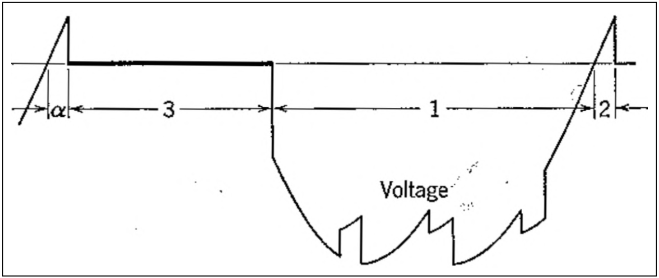
Voltage Oscillations

- To avoid frequent **arcbacks**,
  - **Rate of rise of inverse voltage** across mercury arc valves must be limited
  - **Peak inverse voltage** across mercury arc valves must be limited to value depending on valve design
- Damping circuits can be used

Voltage Oscillations

Waveform of Voltage across Valve

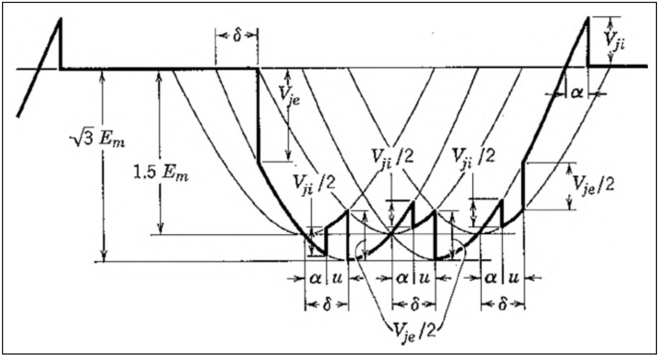
- Waveform across a **rectifier valve without damping circuits or stray capacitance**



Voltage Oscillations

Waveform of Voltage across Valve

- Waveform across a **rectifier valve without damping circuits or stray capacitance**



Voltage Oscillations

Waveform of Voltage across Valve

- Waveform across a rectifier valve without damping circuits or stray capacitance
- **Vertical discontinuity** or sudden voltage jump immediately after the extinction of arc

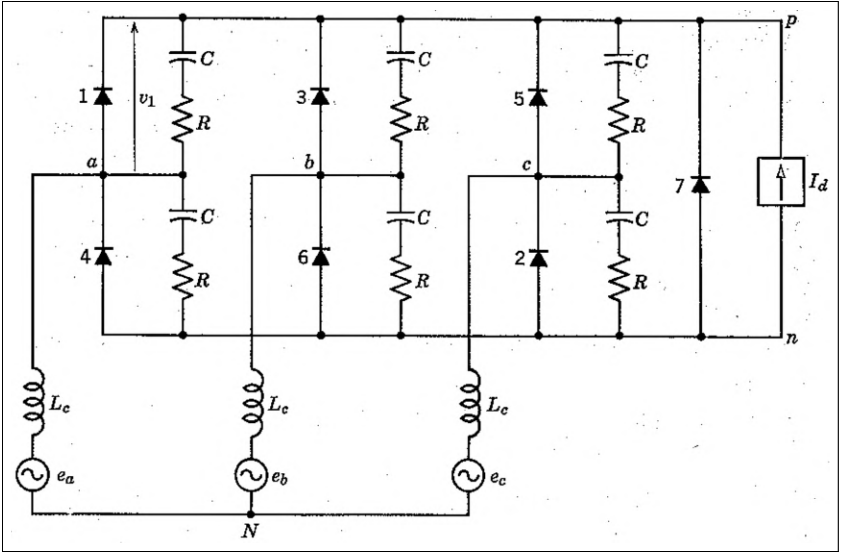
$$V_{je} = \sqrt{3}E_m sin\delta$$

- Stray capacitance across the valve causes rate of rise of inverse voltage to be finite but higher than the permissible rate
  - **Stray capacitance** across the valve in conjunction with leakage inductance of transformer causes voltage oscillations in frequency range **10 to 20kHz & overshoot approaching 100%**
- Low rate of rise of voltage can be obtained by connecting a **capacitor across each valve**
  - Voltage oscillation frequency is **1 to 2 kHz**
  - High overshoot

Voltage Oscillations

- Overshoot can be reduced by connecting **resistor in series with each capacitor**
    - Overshoot will be 10 to 25%
- Series RC combination connected across each valve to damp voltage oscillations is known as **valve damper**
- RC dampers also improve the transient voltage division between two or more bridges in series

Voltage Oscillations



Voltage Oscillations

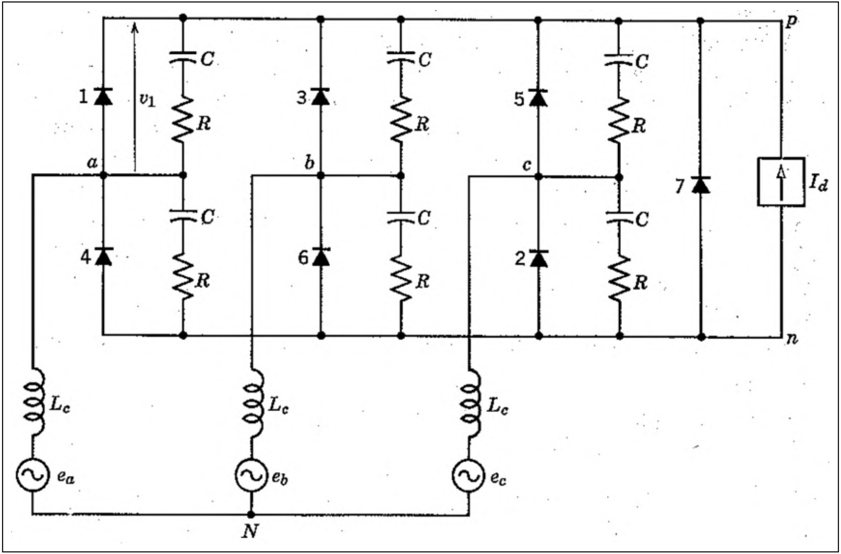
Calculation of Waveform of Voltage across Valve with Dampers

- Consider **voltage across valve 1 immediately after the end of commutation with valve 3**

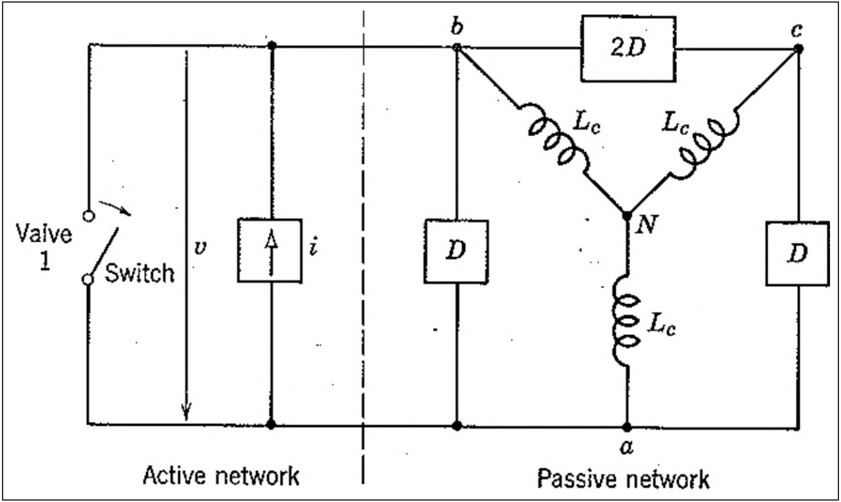
Circuit Simplification

1. During the time considered, **valves 2 & 3 are conducting** and short-circuiting their own dampers → these dampers & valves are replaced by solid connections
2. **Four non-conducting valves** are replaced by open circuits
3. Dampers across valves 5 & 6 are in parallel and may be combined to one of twice the admittance

Voltage Oscillations



Voltage Oscillations



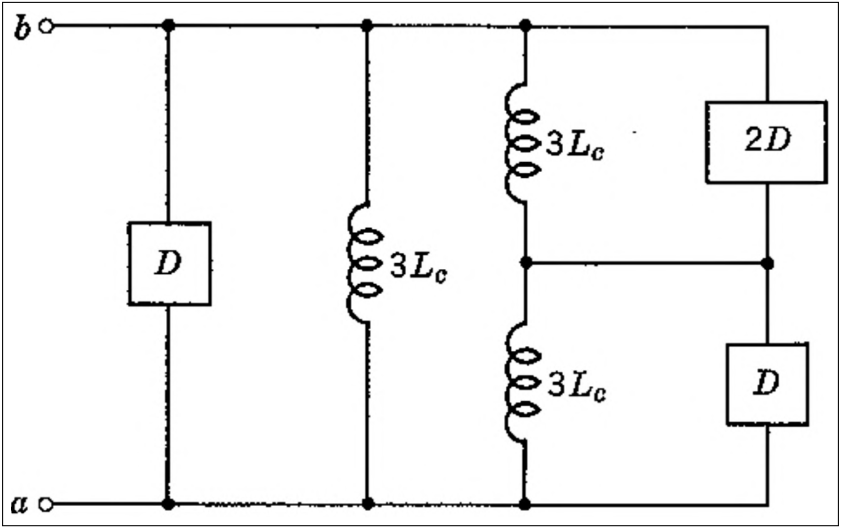
Voltage Oscillations

4. With respect to terminals a & b(across valve 1), the given circuit is equivalent to one in which internal sources are replaced by an external current source connected between those terminals(**Norton equivalent circuit**)
    - Internal sources are AC voltage sources(represented by short-circuits in Norton equivalent circuit) and a constant current source representing direct current(represented by open-circuit in Norton equivalent circuit)
    - When switch representing valve is closed, all current from the external source goes through the switch & there is no voltage across it
    - When switch is opened at t = 0, current of the external source goes through passive network and develops voltage across it equal to recovery voltage across the valve
5. During short time of consideration(say, one cycle of natural frequency), current source can be represented as a ramp

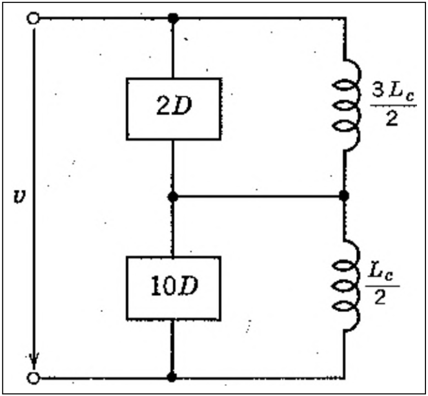
$$i_1 = \frac{V_{je}}{2L_c} t$$

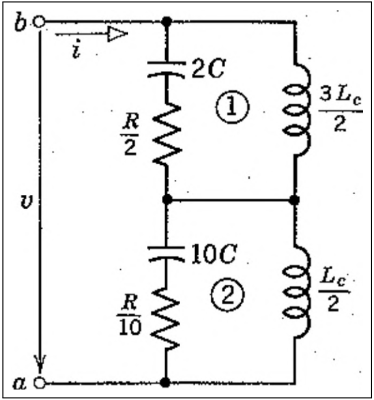
6. Three star-connected inductances can be replaced by an equivalent Δ-network which eliminates the node N

Voltage Oscillations



Voltage Oscillations





Voltage Oscillations

7. Equivalent impedance

$$Z_{ab}(s) = \frac{1}{6B+10D} + \frac{1}{2B+2D} = \frac{8B+12D}{(2B+2D)(6B+10D)}$$

where

$$B = 1/3L_c s = Admittance\ of\ inductance\ 3L_c$$
$$D = \frac{Cs}{RCs+1} = Admittance\ of\ one\ damper$$

Complex natural frequencies

$$s_1, s_3 = -\sigma_1 \pm j\omega_1, \quad s_2, s_4 = -\sigma_2 \pm j\omega_2$$

where

Voltage Oscillations

Damping Factors

$$\sigma_1 = \frac{R}{6L_c}, \;\; \sigma_2 = \frac{R}{10L_c} = 0.6\sigma_1$$

Undamped Natural Frequencies

$$\omega_{n1} = \frac{1}{\sqrt{3L_c C}}, \;\; \omega_{n2} = \frac{1}{\sqrt{5L_c C}} = 0.775\omega_{n1}$$

Actual Damped Natural Frequencies

$$\omega_1 = \sqrt{\omega_{n1}^2 - \sigma_1^2}, \;\; \omega_2 = \sqrt{\omega_{n2}^2 - \sigma_2^2}$$

Voltage Oscillations

- Voltage across passive network as a function of time can be found by taking **inverse Laplacian transform** of

$$V_1(s) = Z_{ab}(s)I_1(s)$$

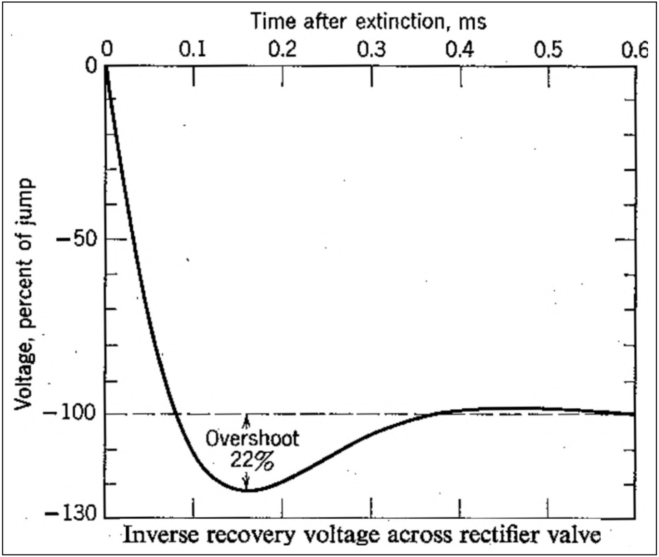
where

$$I_1(s) = \frac{V_j}{2L_c s^2}$$

Voltage across the valve

$$v_1(t)$$
$$= V_j\left[\frac{3}{4}\epsilon^{-\sigma_1 t}\left(cos\omega_1 t - \frac{\sigma_1}{\omega_1}sin\omega_1 t\right) + \frac{1}{4}\epsilon^{-\sigma_2 t}\left(cos\omega_2 t - \frac{\sigma_2}{\omega_2}sin\omega_2 t\right) - 1\right]$$

Voltage Oscillations



Voltage Oscillations

Q. Calculate the waveform of voltage across a valve and its associated damper in a given HVDC terminal converter. The damper parameters are R = 3500Ω and C = 25nF. The leakage reactance per phase of the converter transformers(Y-connected) calculated at f = 50Hz is $L_c =$ 56mH. Assume extinction voltage jump to be $V_j =$ 100kV

Current Oscillations

- If ignition of a valve is delayed, a positive voltage builds up across it which collapses when the valve is ignited
- Any stray capacitance across the valve is charged to this voltage & discharges through the valve as soon as the valve ignites
- Because of inductance in discharge circuit, the discharge is oscillatory
- Because of low resistance of discharge circuit, the oscillations(medium & high frequencies) are lightly damped
- Medium Frequency Band : 20 to 60kHz
- High Frequency Band : 0.5 to 10MHz

Effects of Current Oscillations

1. **Extinction of cathode spot** in the incoming valve with consequent misfire
2. Increased likelihood of **arcback** of the outgoing valve if the overlap is short
3. **Radio Interference**

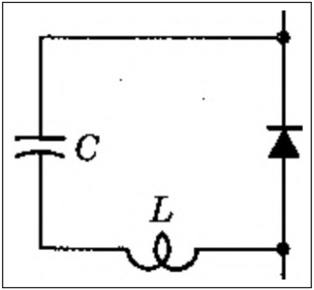
Current Oscillations

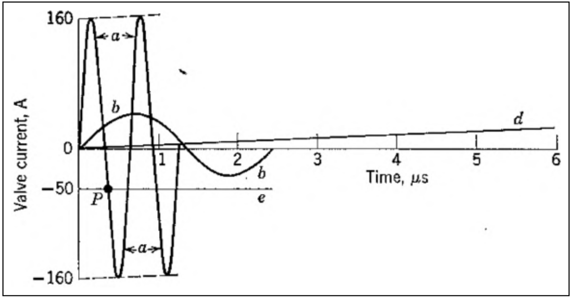
A. Extinction of Cathode Spot

- Mercury arc valves used in HVDC converters are the kind of **excitrons**
- In excitron, mercury vapour is kept ionized during non-conducting periods by means of arcs from one or more excitation anodes to the mercury pool cathode
- The arc terminate in a cathode spot which is the source of electrons
- The movement of electrons through the vapour constitutes the valve current
- If the net cathode current(sum of current from the main anodes and extinction anodes) becomes zero, cathode spot becomes unstable & could be extinguished.
- Thereafter the valve can't conduct again until the spot is re-established by the ignition electrode.
- Extinction would occur if, (during an oscillation) the main current goes negative by the amount of the extinction current
- The oscillations of the current of the incoming valve at the beginning of commutation can be determined by using simplified circuits

Current Oscillations

(i) With stray capacitance(C) and stray inductance(L) of valve

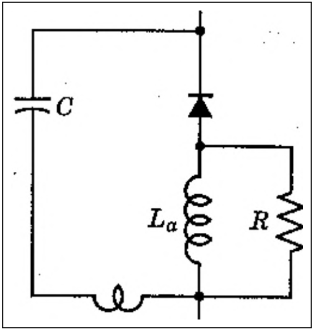


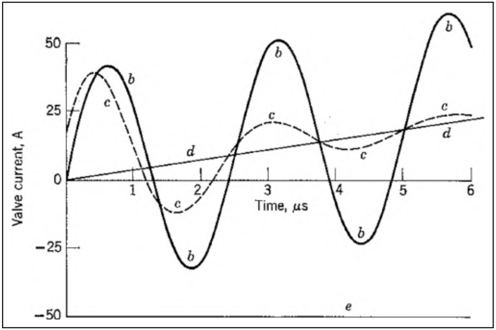


- Stray capacitance(C) is initially charged to voltage V_{ji}
- When valve is ignited, the capacitance discharges through stray inductance(L)
- High frequency oscillation occurs(curve-a)
- Negative main current greatly exceeds extinction current → spot extinction at point 'P'

Current Oscillations

(ii) With Stray Capacitance(C), Stray Inductance(L) of valve, Anode damper(L_a) & Resistor(R)





Current Oscillations

- Cathode spot extinction and Radio Interference is decreased
- Anode reactor(L_a) having inductance of 1 to 2.5mH is connected in series with valve
- Resistor(R) of 2 to 7kΩ is connected in parallel with the reactor
- Reactor lowers both the frequency and amplitude of the current oscillation(b)
- Resistor increases the damping of oscillation and further decreases reverse main current(curve-c)
- Reverse main current with crest value less than excitation current is harmless
- The combination of anode reactor(L_a) and resistor(R) is called as **anode damper**

Current Oscillations

B. **Arcback**

- Current oscillations occur in current of incoming and outgoing valves of the same commutating pair
- Current oscillation in the outgoing valve is caused by the capacitive coupling between the two valves
- Consider the commutation from valve 1 to 3

References

1. E. W. Kimbark, *'Direct Current Transmission-Vol.1'*, Whley Interscience, New York 1971
2. J. Arrilage, *'High Voltage Direct Current Transmission'*, Peter Pereginver Ltd., London U.K. 1983
3. K. R. Padiyar, *'HVDC Transmission Systems'*, Wiley Eastern Ltd., New Delhi 1992

Thank You

*for private circulation only

HVDC Transmission Systems

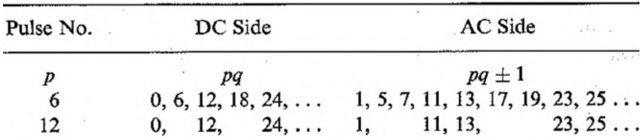
(05EE 6034)

Module 4 - Overview

1. Harmonics
   - Characteristic & Uncharacteristic Harmonics
   - Troubles due to Harmonics & Harmonic Filters
2. Converter Charts
   - Chart 1 with Rectangular Coordinates of Direct Current & Voltage
   - Chart 2 with Rectangular Coordinates of Active & Reactive Power
3. Interaction between AC & DC systems
   - Voltage Interaction & Harmonic Instabilities
   - DC Power Modulation
4. Design Considerations of Thyristor Converter
   - Converter Transformer
   - Overhead Lines
   - Cable Transmission
   - Earth Electrodes
5. Design of Back-to-Back Thyristor Converter System

Harmonics

- Harmonic voltages & currents on both AC & DC sides
- Converter with pulse number p generates harmonics of orders
  - h = pq on DC side
  - h = pq ± 1 on AC side



Pulse No.	DC Side	AC Side
p	pq	$pq \pm 1$
6	0, 6, 12, 18, 24, . . .	1, 5, 7, 11, 13, 17, 19, 23, 25 . . .
12	0, 12, 24, . . .	1, 11, 13, 23, 25 . . .

- Amplitude of harmonics decrease with increasing order
- Harmonics will cause
  - Overheating of capacitors & generators
  - Instability of converter control
  - Interference with telecommunication systems
  - Noise on telephones lines

Harmonics

- To eliminate harmonics
  - Increase the pulse number
  - Installation of filters
- Use of filters in HVDC converters is more economical than increasing pulse number beyond 12
- AC filters
  - Diminishes AC harmonics
  - Supply reactive power at fundamental frequency
- On DC side, DC reactor diminishes harmonics

Characteristic Harmonics

- **Pulse number** is the number of non-simultaneous commutations per cycle of fundamental AC voltage
- **Order of harmonic** is the ratio of its frequency to the fundamental(lowest frequency of a periodic wave
- Order of harmonic on DC side of a converter is defined with respect to the fundamental frequency on AC side
- **Characteristic harmonics** are those harmonic orders given by the equations $h = pq$ and $h = pq \pm 1$
- **Non-characteristic harmonics** are those of other orders

Characteristic Harmonics

Assumptions for deriving orders, magnitudes and phases of characteristic harmonics of 6 pulse converter

1. AC voltages are three-phase, sinusoidal, balanced and of positive sequence
2. Direct current is constant without ripple
3. Valves are ignited at equal time intervals of one-sixth cycle
4. Commutation inductances are equal in three phases

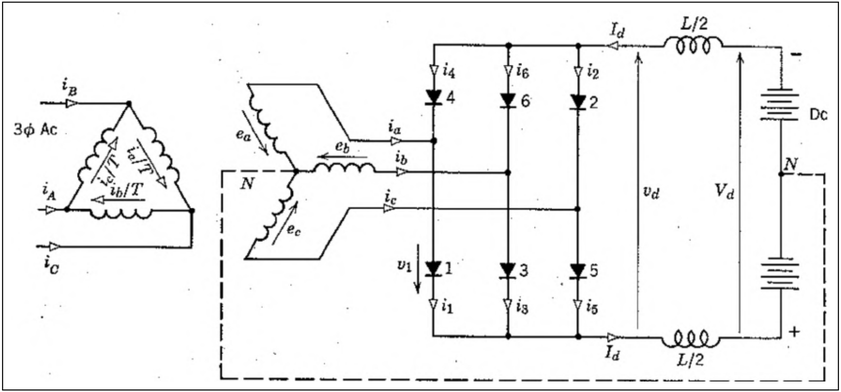
$\Longrightarrow$

1. AC voltage has no harmonics except fundamental
2. Direct current has no harmonics
3. There can be higher order harmonic currents on AC side and harmonic voltages on DC side
4. The overlap angle is same for every commutation
5. Ripple of direct voltage has a period of one-sixth of AC voltage
6. Harmonics of the DC voltage are of the order 6 and its multiples 12, 18, 24 etc
7. Alternating currents of three phases have same wave shape but are displaced by one-third cycle in time

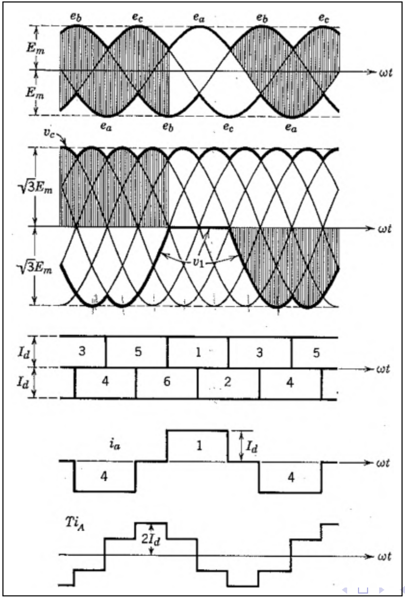
Characteristic Harmonics

- Alternating currents have positive and negative parts of same shape except that one is inverted $\implies$ no even harmonics in alternating current
- Phase difference for the h^{th} harmonic is h times that for the fundamental
- No characteristic harmonics of order 3q(triple harmonics) can exist

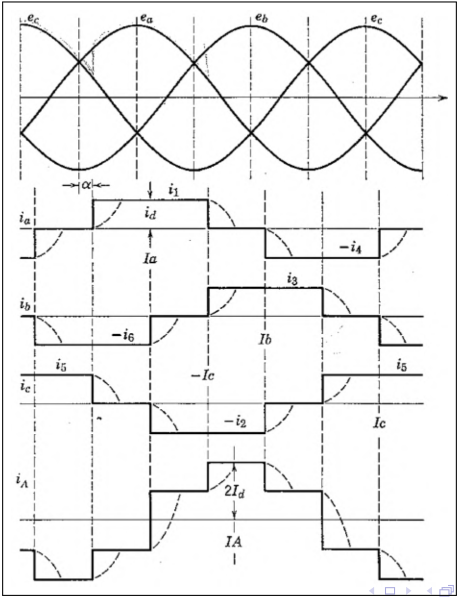
Three-phase Bridge Rectifier



Three-phase Bridge Rectifier

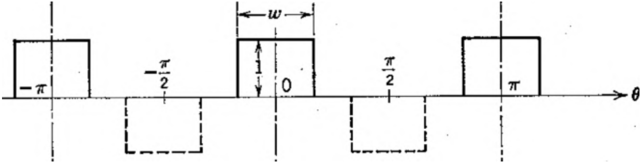


AC Harmonic at No-overlap



AC Harmonic at No-overlap

Valve Currents & Line Currents on Valve Side



- Fourier series

$$F(\theta) = \frac{A_0}{2} + \Sigma_{h=1}^{\infty}(A_h cosh\theta + B_h sinh\theta)$$

$$A_0 = \frac{1}{\pi}\int_0^{2\pi} F(\theta)d\theta$$

$$A_h = \frac{1}{\pi}\int_0^{2\pi} F(\theta)cosh\theta d\theta$$

$$B_h = \frac{1}{\pi}\int_0^{2\pi} F(\theta)sinh\theta d\theta$$

AC Harmonic at No-overlap

$$A_h - jB_h = C_h \angle \phi_h$$
$$C_h = \sqrt{A_h^2 + B_h^2}$$
$$\phi_h = tan^{-1}\left(\frac{-B_h}{A_h}\right)$$

- Since wave is even function, $B_h = 0$ for all h

$$A_h = \frac{1}{\pi}\int_0^{2\pi} F(\theta) cosh\theta d\theta$$
$$= \frac{1}{\pi}\int_{-\pi}^{\pi} cosh\theta d\theta$$
$$= \frac{1}{\pi}\int_{-w/2}^{w/2} cosh\theta d\theta$$

AC Harmonic at No-overlap

$$= \frac{1}{\pi h}\left[sin\left(\frac{hw}{2}\right) - sin\left(\frac{-hw}{2}\right)\right]$$

$$= \frac{2}{\pi h} sin\left(\frac{hw}{2}\right)$$

$$\frac{A_0}{2} = \frac{1}{2\pi}\int_{-w/2}^{w/2} d\theta = \frac{w}{2\pi}$$

- The series is

$$F_1(\theta) = \frac{2}{\pi}\left(\frac{w}{4} + sin\frac{w}{2}cos\theta + \frac{1}{2}sin\frac{2w}{2}cos2\theta + \frac{1}{3}sin\frac{3w}{2}cos3\theta + \frac{1}{4}sin\frac{4w}{2}cos4\theta \ldots\right)$$

AC Harmonic at No-overlap

- Series has constant term and cosine terms of every harmonic frequency
- For certain pulse widths, certain cosine terms vanish. This occurs if $\frac{hw}{2} = q\pi$ or $w = \frac{2q\pi}{h}$
- If pulses of valve current in three-phase bridge current have width $w = \frac{2\pi}{3}$
  - h = 3,6,9,.....3q
  - sin(hw/2) = sin($q\pi$) = 0
  - $\implies$ Third harmonic and its multiples(**triple harmonics**) are absent in the series
- If we consider the negative pulses only,

$$F_2(\theta)$$

$$= \frac{2}{\pi}\left(-\frac{w}{4} + sin\frac{w}{2}cos\theta - \frac{1}{2}sin\frac{2w}{2}cos2\theta + \frac{1}{3}sin\frac{3w}{2}cos3\theta - \frac{1}{4}sin\frac{4w}{2}cos4\theta...\right)$$

AC Harmonic at No-overlap

- Fourier series

$$F_3 = F_1 + F_2$$
$$= \frac{4}{\pi}\left(sin\frac{w}{2}cos\theta + \frac{1}{3}sin\frac{3w}{2}cos3\theta + \frac{1}{5}sin\frac{5w}{2}cos5\theta + ...\right)$$

- Constant term is vanished
- All even harmonics are eliminated
- With w $= 2\pi/3$ and height $= I_d$

$$i_a$$
$$= \frac{2\sqrt{3}}{\pi}I_d\left(cos\theta - \frac{1}{5}cos5\theta + \frac{1}{7}cos7\theta - \frac{1}{11}cos11\theta + \frac{1}{13}cos13\theta - \frac{1}{17}cos17\theta ..\right.$$

AC Harmonic at No-overlap

- This series contains only harmonics of orders 6q ± 1
- Peak value of fundamental frequency current

$$I_{10m} = \frac{2\sqrt{3}}{\pi} I_d = 1.103 I_d$$

- Effective or rms value of fundamental frequency current

$$I_{10} = \frac{I_{10m}}{\sqrt{2}} = \frac{\sqrt{6}}{\pi} I_d = 0.78 I_d$$

- Effective or rms value of h^{th} harmonic

$$I_{h0} = \frac{I_{10}}{h}$$

AC Harmonic at No-overlap

- Line Currents on Network side of Six-pulse group

Uncharacteristic Harmonics

- If the conditions mentioned earlier are not fulfilled, not only characteristic harmonics with slightly changed magnitudes and phases, but also uncharacteristic harmonics will be produced
- Low order uncharacteristic harmonics are much smaller than adjacent characteristic harmonics in the converter

Causes

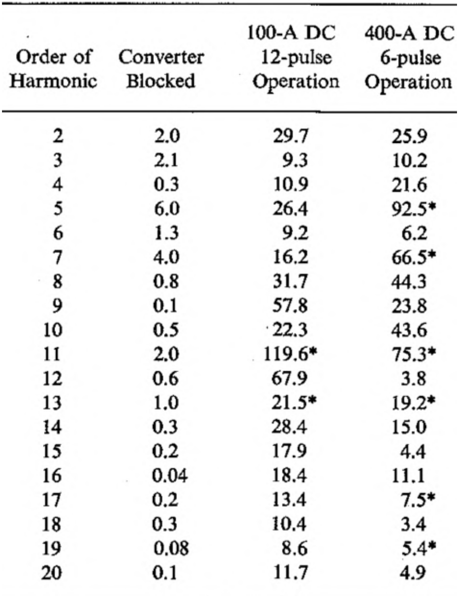
- Ignition delay is measured from a zero of the commutating voltage
- If three-phase voltages are unbalanced, their zeros are not equally spaced → valves are not fired at equal time intervals

Uncharacteristic Harmonics

Consequences

- Increase telephone interference
- May cause instability of Constant Current control

Uncharacteristic Harmonics



Order of Harmonic	Converter Blocked	100-A DC 12-pulse Operation	400-A DC 6-pulse Operation
2	2.0	29.7	25.9
3	2.1	9.3	10.2
4	0.3	10.9	21.6
5	6.0	26.4	92.5*
6	1.3	9.2	6.2
7	4.0	16.2	66.5*
8	0.8	31.7	44.3
9	0.1	57.8	23.8
10	0.5	22.3	43.6
11	2.0	119.6*	75.3*
12	0.6	67.9	3.8
13	1.0	21.5*	19.2*
14	0.3	28.4	15.0
15	0.2	17.9	4.4
16	0.04	18.4	11.1
17	0.2	13.4	7.5*
18	0.3	10.4	3.4
19	0.08	8.6	5.4*
20	0.1	11.7	4.9

Harmonics

- **Troubles due to Harmonics**
- **Harmonic Filters**

Converter Charts

- Converter charts show relationship among
  - DC Quantities
    - Direct Voltage(V_d)
    - Direct Current(I_d)
  - Converter Angles
    - Ignition Angle(α)
    - Extinction Angle(δ)
    - Overlap Angle(u)
  - AC Quantities
    - Active Power(P)
    - Reactive Power(Q)
    - Apparent Power(S)
    - Displacement Factor($cos\phi$)
    - Alternating Current(I_a)
- **Chart 1** : Rectangular coordinates x & y proportional to V_d & I_d
- **Chart 2** : Rectangular coordinates x & y proportional to P & Q
- Both charts uses per unit variables
- Rectifier & Inverter operations are represented by different regions of the charts

Converter Charts

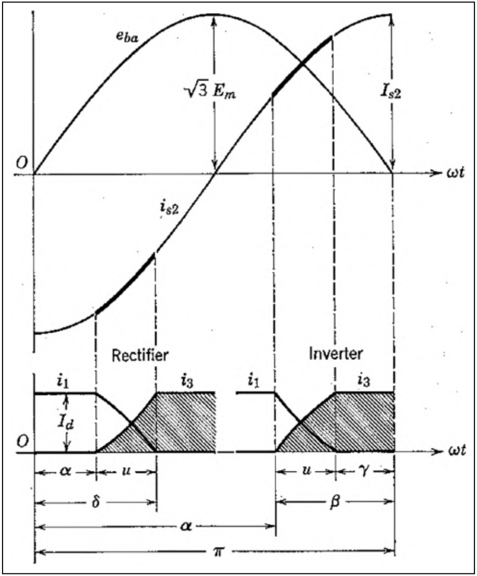


Chart 1 : with Rectangular Coordinates of V_d & I_d

- x is chosen as the ratio of I_d to crest value of symmetrical alternating current in a line-to-line short circuit

$$x = \frac{I_d}{I_{s2}} = I'_d = \frac{2\omega L_c I_d}{\sqrt{3}E_m}$$

- y is the ratio of V_d under general condition to its value with no load & no delay of ignition

$$y = \frac{V_d}{V_{do}} = V'_d = \frac{\pi V_d}{3\sqrt{3}E_m}$$

- x & y varies **inversely** as the AC voltage referred to valve side of transformer

Chart 1 : with Rectangular Coordinates of V_d & I_d

- **Upper Half Plane :**
  - with Positive I_d & V_d
  - represents **Rectification**
- **Lower Half Plane :**
  - with Positive I_d & negative V_d
  - represents **Inversion**

Chart 1 : with Rectangular Coordinates of V_d & I_d

Overlap Angle Less than $60^o (0 \leq u \leq 60^o)$

- Loci of Constant-α & Constant-δ
  - Coordinates x & y are related to ignition delay angle(α) & extinction angle(δ) as follows

$$I_d = I_{s2}(cos\alpha - cos\delta)$$

$$\implies x = cos\alpha - cos\delta$$

$$V_d = \frac{V_{do}(cos\alpha + cos\delta)}{2}$$

$$\implies 2y = cos\alpha + cos\delta$$

$$y = cos\alpha - \frac{x}{2} \tag{1}$$

$$y = cos\delta + \frac{x}{2} \tag{2}$$

Chart 1 : with Rectangular Coordinates of V_d & I_d

- Eqn. (1) $\rightarrow$
    - locus of constant ignition angle(α) in xy plane
    - It's a **straight line**
    - Slope is (-1/2)
    - Intercepts y axis at cosα
    - Intercepts x axis at 2cosα
    - Family of such parallel lines can be drawn for each value of α

Chart 1 : with Rectangular Coordinates of V_d & I_d

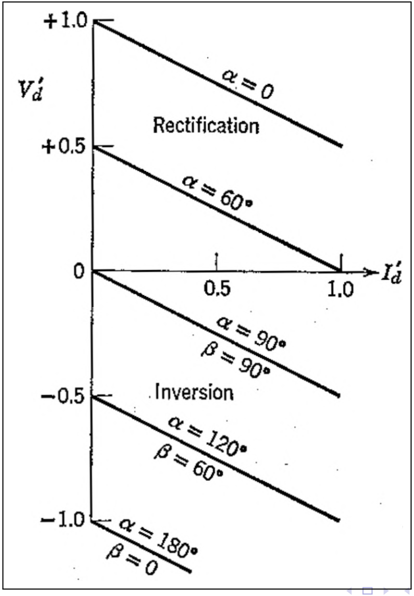


Chart 1 : with Rectangular Coordinates of V_d & I_d

- Eqn. (2) $\rightarrow$
  - locus of constant extinction angle(δ) in xy plane
  - It's a **straight line**
  - Slope is $(+1/2)$
  - Intercepts y axis at cosδ
  - Intercepts x axis at -2cosδ
  - Family of such parallel lines can be drawn for each value of δ

Chart 1 : with Rectangular Coordinates of V_d & I_d

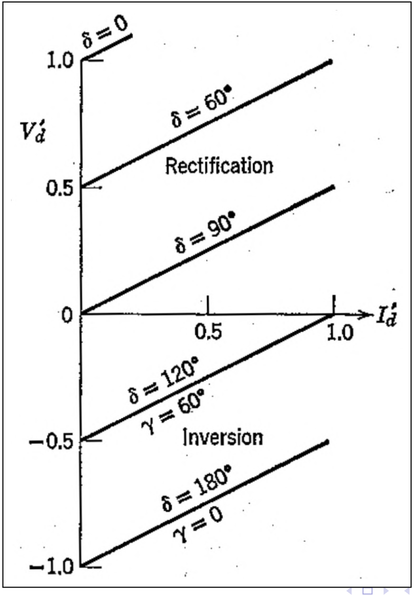


Chart 1 : with Rectangular Coordinates of V_d & I_d

- α & δ may range from 0 to 180^o
- since $(\beta = \pi - \alpha)$, the loci of constant-α are also loci of constant-β but numerical values of α & β differ from one another on the same locus
- since $(\gamma = \pi - \delta)$, the loci of constant-δ are also loci of constant-γ but numerical values of δ & γ differ from one another on the same locus
- For inverter operation, β & γ are used instead of α & δ

Chart 1 : with Rectangular Coordinates of V_d & I_d

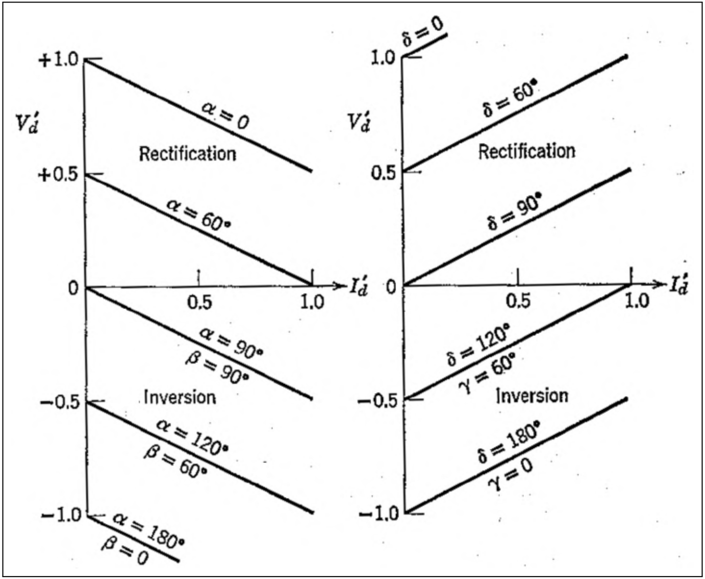


Chart 1 : with Rectangular Coordinates of V_d & I_d

- Loci of Constant u

$$u = \delta - \alpha$$

  - Locus of constant-u is a curve passing through the points of **intersection of constant-α lines and constant-δ lines** for which α & δ differ by a constant angle
  - Range of u : 0 to 60^o
  - Locus of u = 0 → **vertical axis**
  - Loci of other values of u → **elliptical**

Chart 1 : with Rectangular Coordinates of V_d & I_d

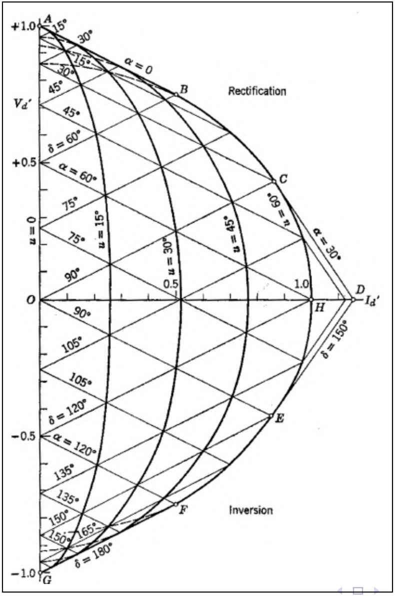


Chart 1 : with Rectangular Coordinates of V_d & I_d

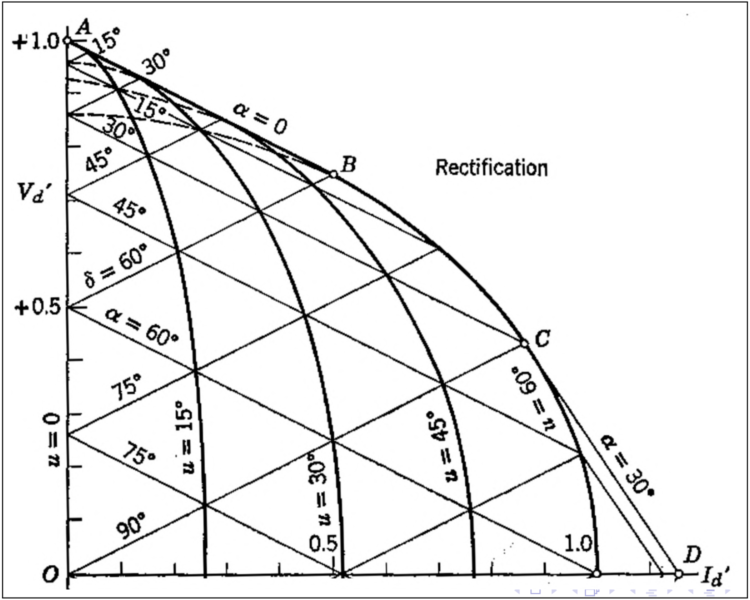


Chart 1 : with Rectangular Coordinates of V_d & I_d

$$\begin{aligned}
cos\delta + cos\alpha &= 2cos\left(\frac{\delta+\alpha}{2}\right) cos\left(\frac{\delta-\alpha}{2}\right) \\
cos\delta - cos\alpha &= 2sin\left(\frac{\delta+\alpha}{2}\right) sin\left(\frac{\delta-\alpha}{2}\right) \\
\delta + \alpha &= \lambda \\
2y &= 2cos\left(\lambda/2\right) cos\left(u/2\right) \\
-x &= 2sin\left(\lambda/2\right) sin\left(u/2\right) \\
cos\left(\lambda/2\right) &= \frac{y}{cos\left(u/2\right)} \\
sin\left(\lambda/2\right) &= \frac{-x}{2sin\left(u/2\right)} \\
sin^2\left(\lambda/2\right) + cos^2\left(\lambda/2\right) &= 1 \\
\left(\frac{-x}{2sin\left(u/2\right)}\right)^2 + \left(\frac{y}{cos\left(u/2\right)}\right)^2 &= 1
\end{aligned}$$

Chart 1 : with Rectangular Coordinates of V_d & I_d

- It is in the form standard equation of an ellipse with centre at origin, horizontal half axis a and vertical half axis b

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 = 1$$

$$a = 2sin\left(u/2\right)$$

$$b = cos\left(u/2\right)$$

Chart 1 : with Rectangular Coordinates of V_d & I_d

Loci of Constant AC Quantities

- The relationship between per unit AC & DC quantities are

$$
\begin{aligned}
P'_a = P'_d = P' &= V'_d I'_d = xy \\
I'_a &= T' I'_d = T' x \\
E'_a cos\phi &= \frac{V'_d}{T'} = \frac{y}{T'} \\
T' &= \left(\frac{Actual\ turns\ ratio}{Nominal\ turns\ ratio} \right) of\ converter\ transformer \\
cos\phi &= \frac{V_d}{V_{do}} = V'_d = y \\
E'_a &= \frac{1}{T'}
\end{aligned}
$$

- E'_a is the per unit alternating voltage on the network side of transformer
- E'_a is **independent** of direct current & voltage hence doesn't appear on the chart

Chart 1 : with Rectangular Coordinates of V_d & I_d

Loci of Constant Displacement Factor($cos\phi$)

- They are horizontal lines at ordinate y = cos ϕ
- They coincide with loci of constant direct voltage V_d'
- Independent of Transformer ratio

Loci of Constant Apparent Power(S')

$$S' = E_a' I_a' = \frac{1}{T'} T' x = x = I_d'$$

- The loci are vertical lines at abscissa x = S'
- They coincide with loci of constant direct current I_d'
- Independent of Transformer ratio

Chart 1 : with Rectangular Coordinates of V_d & I_d

Loci of Constant Reactive Power(Q')

$$Q' = \sqrt{(S')^2 - (P')^2} = \sqrt{x^2 - (xy)^2} = x\sqrt{1 - y^2}$$

$$x = \frac{Q'}{\sqrt{1 - y^2}} \implies y = \pm \left[1 - \left(\frac{Q'}{x}\right)^2\right]^{1/2}$$

- These curves are of the fourth degree & ar unnamed
- All values of Q' are positive except on the vertical axis where Q' = 0
- Independent of Transformer ratio

Chart 1 : with Rectangular Coordinates of V_d & I_d

Loci of Constant Active Power(P')

- The loci are rectangular hyperbolas given by

$$xy = P' \implies y = \frac{P'}{x}$$

- Those loci in first quadrant are for positive power(**Rectification**)
- Those loci in fourth quadrant are for negative power(**Inversion**)
- Locus for P' = 0 consists of y-axis & positive x-axis

Chart 1 : with Rectangular Coordinates of V_d & I_d

Loci of Constant Alternating Current(I'_a)

- These loci are vertical lines at abscissa

$$x = \frac{I'_a}{T'}$$

- At nominal ratio($T' = 1$), they coincide with loci of constant S' of the same numerical value
- For other values of T', they are shifted; corresponding loci don't appear in the charts

Chart 1 : with Rectangular Coordinates of V_d & I_d

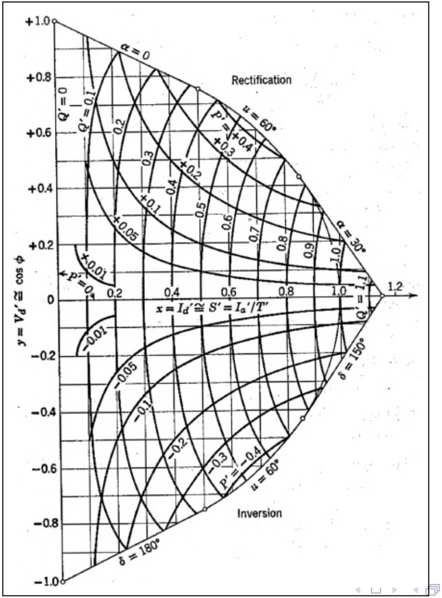


Chart 1 : with Rectangular Coordinates of V_d & I_d

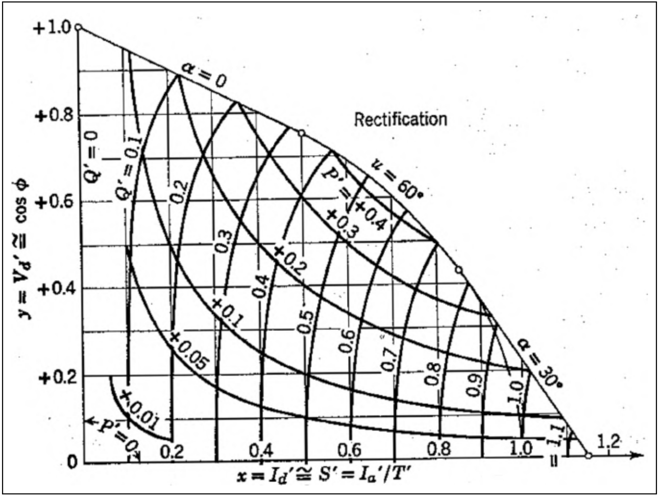


Chart 2 : with Rectangular Coordinates of P' & Q'

- Per unit active power

$$x = P' = \frac{P}{P_b}$$

$$P_b = V_{do} I_{s2} = \frac{9E_{LN}^2}{\pi X_c}$$

- Per unit reactive power

$$y = Q' = \frac{Q}{Q_b}$$

- P' & Q' together form complex power plane, (P' + jQ')

Chart 2 : with Rectangular Coordinates of P' & Q'

- In polar coordinates

$$r = S' = \frac{S}{P_b}$$

- Angle ϕ is measured counter clockwise from $+$ve x-axis representing the phase angle by which the fundamental alternating current(I_1') lags behind the alternating source voltage(E)
- Those loci with constant ϕ are labelled with values of displacement factor(cosϕ) in the figure

Chart 2 : with Rectangular Coordinates of P' & Q'

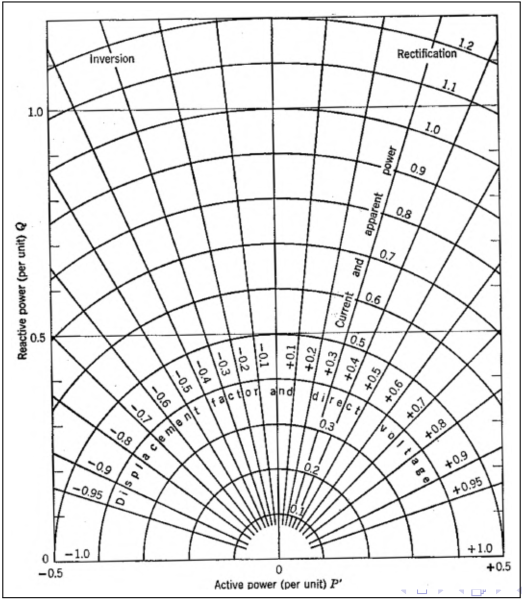


Chart 2 : with Rectangular Coordinates of P' & Q'

- Loci of Constant Overlap Angle(u)
- Loci of Constant Ignition Angle(α)
- Loci of Constant Extinction Angle(δ)
- Loci of Constant Direct Current & Voltage

Relationship between the Chart 1 & Chart 2

- Every point on chart-1 and chart-2 represents specific values of all the variables $(I'_d, V'_d, \alpha, \delta, u, I'_a/T', P', Q', S' \ and \ cos\phi)$
- For every point on chart-1, there is a corresponding point on chart-2 such that the set of values denoted by the point on chart-1 is identical to the set denoted by point on chart-2
- Every point on one chart could be moved to the position of the corresponding point on the other chart
- The origin on chart-2 does not transform to a single point on chart-1 but, instead becomes the whole vertical axis
- The transformation is not conformal

Design Considerations of HVDC System

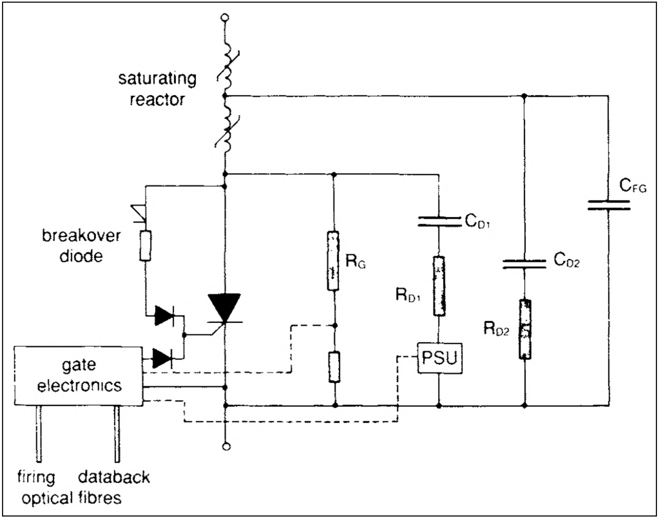
- **Design steps** of HVDC transmission scheme are
  - Identify the main **operational objectives** to be met, i.e. energy considerations, MW loading requirements and maintenance.
  - Identify any **technical constraints** which may have to be accepted, e.g. the maximum voltage and current ratings of submarine cables, limitations of earth return etc.
  - **Adopt voltage and current ratings**
  - Decide the **overall control requirements**, e.g. constant-power control, short-term overload, damping characteristics, constant extinction-angle control, constant ideal(noload) direct voltage, etc.
  - Develop **converter-station arrangements**.
  - Design the **transmission line**.
  - Assess the **capital equipment cost, the operating costs and the cost of losses**
- Design layout of the converter plant is greatly influenced by the switching-device technology.

Thyristor Valves

(a) Electrical consideration

- Limited voltage rating of the individual thyristors many of them must be connected in series to constitute an HVDC valve.
- The series connection of thyristors requires **additional passive components** to distribute the OFF state voltage uniformly between them and to protect the individual thyristors from overvoltage, excessive rate-of-rise of voltage (dv/dt) and rate-of-rise of inrush current (di/dt).
- The thyristor, together with its local voltage-grading and thyristor-triggering circuits, known as a **thyristor level**

Thyristor Level

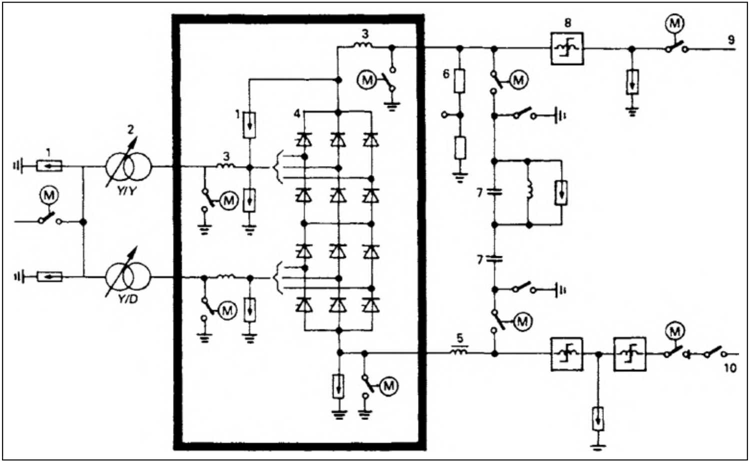


Thyristor Valves

- Thyristor level contains
    - Saturating reactor
    - DC grading resistor(R_G)
    - RC grading circuits (R_D & C_D)
    - Fast-grading capacitor (C_{FG})

(b) Mechanical Considerations
(c) Valve Cooling System
(d) Valve Control Circuitry
(e) Valve Tests
(f) Valve Hall Arrangement

Station Layout



1.Surge Arrester 2.Converter Transformer 3.Air-core Reactor 4.Thyristor Valve 5.Smoothing Reactor 6.Direct Voltage Measuring Divider 7.DC Filter 8.Current Measuring Transducer 9.DC Line 10.Electrode Line

Converter Transformer

- 12 Pulse Converter can be obtained from any of the following arrangements
  - Six single-phase two winding
  - Two three-phase two winding
- **Star or Delta** connection
- In conventional transformers the insulation gap between winding and yoke is relatively small
- In converter transformer the entire winding must be fully insulated → radial leakage flux at the ends of the windings increases → **greater eddy-current loss and hot spots** in the transformer tank.
- Converter transformer is subjected to a **direct voltage** depending on its position with respect to the ground.
- **Noise** due to **magnetostriction**
- **Harmonics** → noise and special measures are often taken such as suspending the core, special tank design or providing sound-absorbing walls.

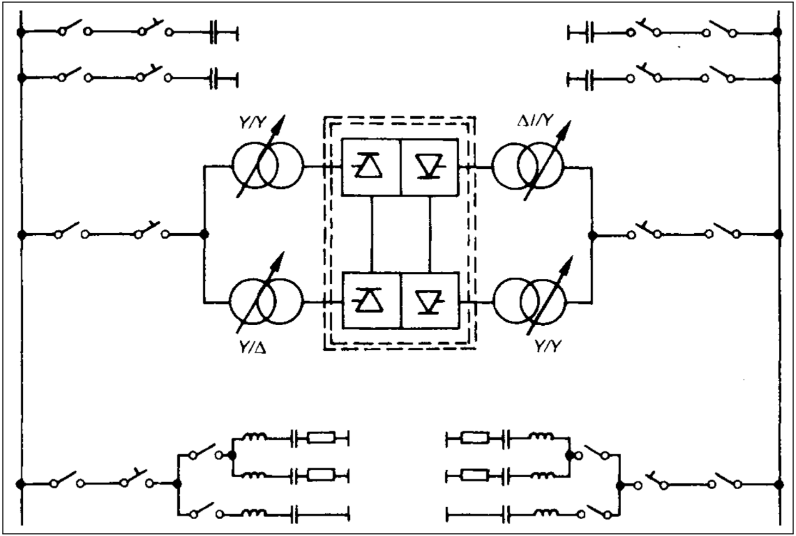
Converter Transformer

- **On-load tap changer**
- **Shipping weight & dimensional limitations**
- Converter transformers are subjected to power-transformer tests. Addition tests are
  - DC voltage polarity reversal
  - Switching impulse-to-ground
  - Lightning impulse along winding

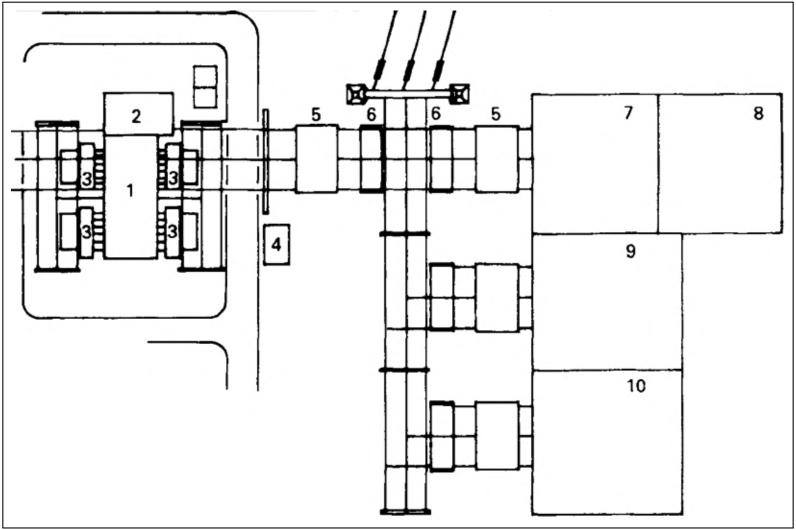
Design Considerations

- Overhead Lines
- Cable Transmission
- Earth Electrodes

Design of Back-to-Back Thyristor Converter System



Design of Back-to-Back Thyristor Converter System



Design of Back-to-Back Thyristor Converter System

- Power-handling capacity of a thyristor increases with increasing current
- Water cooling permits higher current ratings
- In two-terminal transmission schemes, the rated voltage and current values are mainly determined by the transmission line, which means that it may often not be possible to fully utilise the capacity of modern large thyristors.
- In back-to-back link, it is possible to utilise the thyristors optimally, which means a high current and a low voltage. This will minimise the number of thyristors, and thereby also the valve cost. Other voltage-dependent costs will also be reduced
- In back-to-back system, transmission line is eliminated → some DC equipment can be avoided or shared by the rectifier and the inverter
- With the back-to-back circuitry the two valve halls can be combined into one, with the DC loop maintained inside the hall and with transformer on both sides of the building
- As is normal, the AC switchyard with buses and filters dominates the picture, whereas the converters themselves occupy only a minor area.

References

1. E. W. Kimbark, *'Direct Current Transmission-Vol.1'*, Whley Interscience, New York 1971
2. J. Arrilage, *'High Voltage Direct Current Transmission'*, Peter Pereginver Ltd., London U.K. 1983
3. K. R. Padiyar, *'HVDC Transmission Systems'*, Wiley Eastern Ltd., New Delhi 1992

Thank You

*for private circulation only