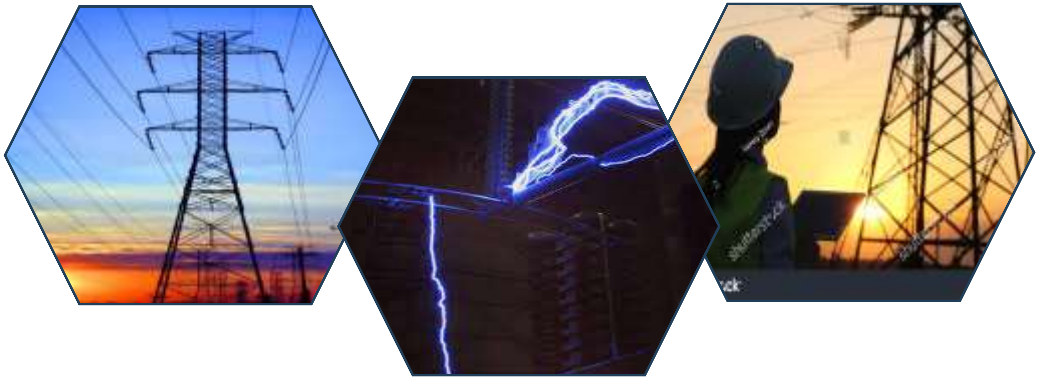

High Voltage Engineering

Prepared by :

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University of Global Village (UGV), Barishal

Basic Course Information

Course Title	**High Voltage Engineering**
Course Code	**EEE 409**
Credit	**03**
Marks	**150**

SYNOPSIS/RATIONALE

- High Voltage Engineering deals with the design, analysis, and application of systems and equipment that operate at high voltages, typically above 1,000 volts (1 kV). It is essential in power generation, transmission, distribution, and insulation systems to ensure safe and efficient operation.

OBJECTIVE

- The objectives of the course are:
  - Understand the principles and applications of high voltages in power systems.
  - Learn methods for generating high AC, DC, and impulse voltages.
  - Study the properties and breakdown mechanisms of insulating materials.
  - Familiarize with high voltage testing techniques and standards.
  - Analyze overvoltage phenomena and design protection systems.
  - Master techniques for measuring high voltages and currents.
  - Explore applications in power transmission, distribution, and industrial systems.

Course Learning Outcome (CLO)

CLO1	Explain the aspects of construction, principles of operations and applications of high voltage equipment.
CLO2	Execute performance analysis of high voltage testing equipment.
CLO3	Design high voltage generation circuits subject to specific requirements.
CLO4	Conduct experiments for analysis of high voltage phenomenon, generation circuit, and testing high voltage equipment performance.

ASSESSMENT PATTERN

CIE- Continuous Internal Evaluation (90 Marks)

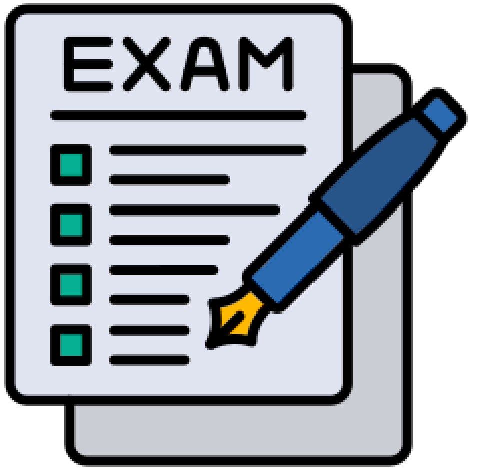
Bloom's Category Marks (out of 90)	**Tests Mid-term (45)**
Remember	08
Understand	08
Apply	08
Analyze	08
Evaluate	08
Create	05

Class Test	**15**
Presentation	**15**
Attendance	**15**

ASSESSMENT PATTERN

SEE- Semester End Examination (60 Marks)

Bloom's Category	**Tests**
Remember	**10**
Understand	**10**
Apply	**10**
Analyze	**10**
Evaluate	**10**
Create	**10**



Course Schedule

Week	Course Content	Teaching-Learning Strategies	Sources	Assessment Strategies	Aligned CLOs
1	**Introduction to High Voltage Engineering**: Overview, significance, and objectives	Lecture, discussion on applications	Course slides, Reference Books	Short quiz on fundamentals	CLO 1
2	**HVDC Transmission Systems**: Basic components and configurations	Lecture, case study of HVDC projects	Course slides, Case Studies	Assignment: Compare HVDC vs HVAC	CLO 4
3	**Principles of AC Transmission**: Voltage, power factor, and stability devices	Interactive lecture, problem-solving	Course slides, Reference Books	Quiz: Power factor calculations	CLO 4:
4	**HVDC Advantages and Limitations**: Economic distances and reliability	Discussion and critical evaluation exercises	Course slides, Reference Books	Group discussion: Future of HVDC	CLO 4:
5	**Insulation Materials**: Types (gas, solid, liquid) and breakdown mechanisms	Lecture, lab demo (if feasible)	Course slides, Reference Books	Quiz: Insulation properties	CLO 2

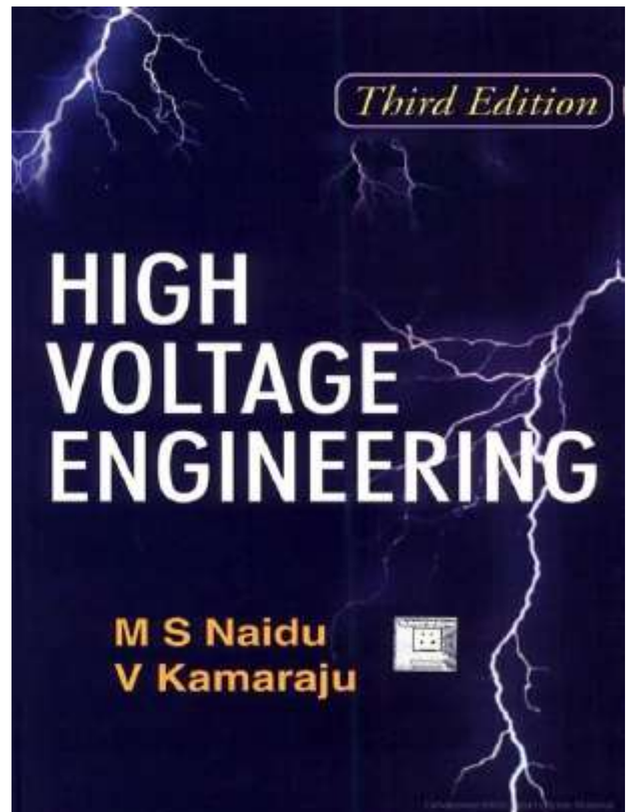
Course Schedule

Week	Course Content	Teaching-Learning Strategies	Sources	Assessment Strategies	Aligned CLOs
6	**HVDC Converters**: Rectifiers, inverters, and basic control strategies	Lecture, MATLAB-based simulation	Course slides, examples	Assignment: Simulate a rectifier	CLO 4: HVDC systems and applications
7	**Testing Techniques and Standards**: Overview of HV testing equipment	Lecture, hands-on demo (if possible)	Course slides,	Assignment: Write a testing report	CLO 3: Testing techniques
8	**Overvoltage Phenomena and Protection Systems**: Causes and mitigation	Case studies, design exercises	Course slides, Case Studies	Project: Design an overvoltage system	CLO 2: Overvoltage and protection systems
9	**Advanced HVDC Systems**: Multiterminal systems and new developments	Seminar discussions, guest lecture	Course slides,	Presentation: Emerging HVDC trends	CLO 4: HVDC systems and applications
10	**Principles of Harmonics in HVDC Systems**: Causes, effects, and mitigation	Lecture, MATLAB demo	Course slides, Case Studies	Assignment: Analyze harmonics	CLO 4: HVDC systems and applications
11	**Reactive Power in HVDC Systems**: Compensation strategies and challenges	Lecture, problem-solving	Course slides	Quiz: Reactive power concepts	CLO 4: HVDC systems and applications
12	**Converter Configurations in HVDC Systems**: Monopolar, bipolar, and homopolar	Lecture, interactive discussion	Course slides	Quiz: Compare converter types	CLO 4: HVDC systems and applications

Course Schedule

Week	Course Content	Teaching-Learning Strategies	Sources	Assessment Strategies	Aligned CLOs
13	**Control of HVDC Systems**: Firing angles, tap changers, and voltage control	Lecture, MATLAB-based examples	Course slides	Assignment: Control simulation	CLO 4: HVDC systems and applications
14	**Applications of HVDC Systems**: Renewable integration, undersea cables	Guest lecture, case studies	Course slides, Case Studies	Presentation: Applications analysis	CLO 4: HVDC systems and applications
15	**Economic Considerations of HVDC Systems**: Cost-benefit analysis	Discussion, evaluation exercises	Course slides	Group activity: Economic case study	CLO 4: HVDC systems and applications
16	**Future Prospects of HVDC Systems**: Emerging technologies and challenges	Seminar, open discussion	Course slides	Presentation: Future prospects	CLO 4: HVDC systems and applications
17	**Course Review and Final Assessment**: Summary of all topics	Review session, Q&A	Course slides, Reference Books	Final exam covering all CLOs	All CLOs

Reference Books




Week-01
Page: 13-21

HVDC TRANSMISSION LINE

INTRODUCTION

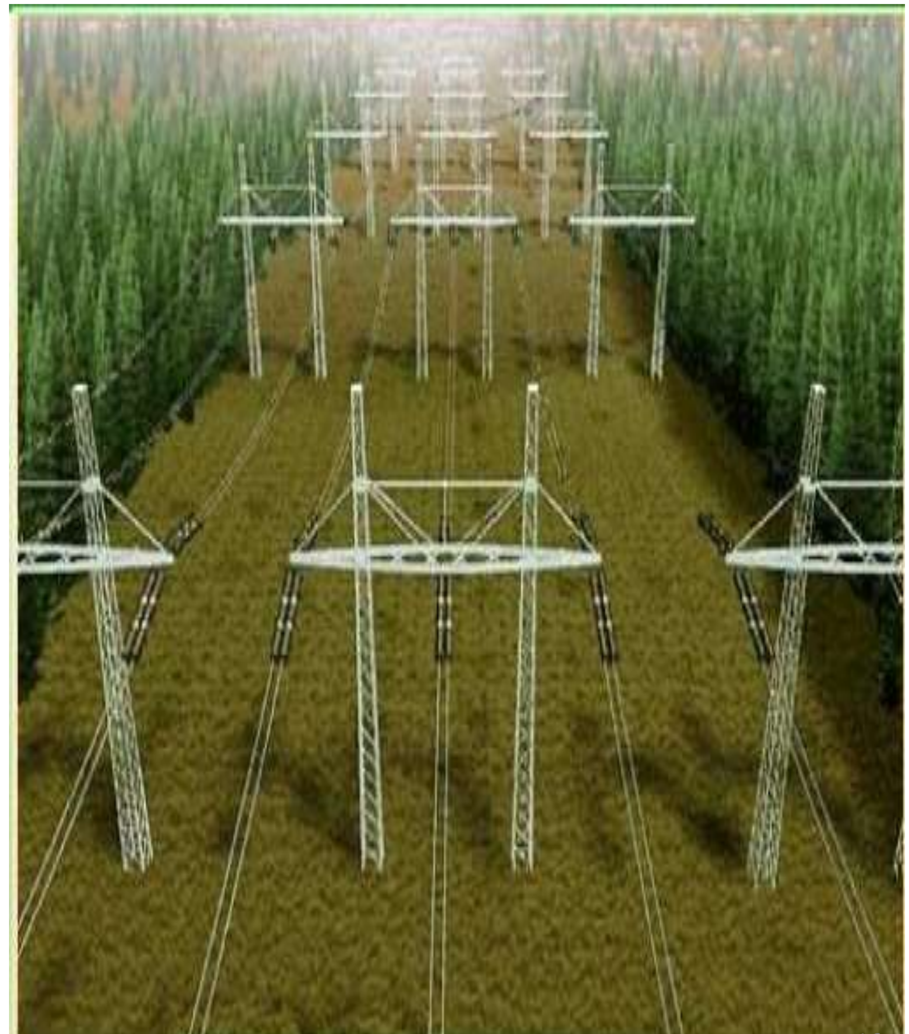
- A high-voltage, direct current (HVDC) electric power transmission system uses direct current for the bulk transmission of electrical power.
- For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses.
- High voltage is used for electric power transmission to reduce the energy lost in the resistance of the wires.

CONTINUE.....

- Recent developments in conversion equipment have reduced their size and cost and improved their reliability.

- The major components of a HVDC transmission system are converter stations where conversion from AC to DC and from DC to AC are performed.

ADVANTAGES OF HVDC



APPLICATIONS OF HVDC

1. For long distance high power transmission.
2. For interconnection (tie lines) between two or more AC systems having their own load frequency control.
3. For back to back asynchronous tie substation where two AC systems are interconnected by a convertor substation without any AC transmission line in between.
4. For underground or submarine cable transmission over long distances at high voltage.

LIMITATION OF HVDC

1. Costly terminal equipments.

- The convertors required at both the ends are more expensive.
- The convertors produce a lot of harmonics both on DC and AC sides and may cause Radio Interference.
- To remove ripples from the DC output, filtering & smoothening equipments are to be provided.

2. More maintenance of insulators is required in HVDC system.
3. Complexity of control.
4. Voltage transformation is not easier in case of DC system.

APPLICATIONS OF HVDC

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THE FUTURE PROSPECTS

There are the following future aspects of the project as:

1. The complete system from generation to distribution is in the from of DC i.e. possible by using power electronics circuits.

2. By using DC Choppers in place of transformers, we have resolved complete system into DC system.

CONCLUSION

- Availability of non- renewable resources is limited.
- HVDC is used for increasing the efficiency of transmission lines.
- Dependency of source from foreign countries are to be reduced.
- HVDC transmission line gives the Reliable, Economical and Stable supply as compares to AC.


Week-02-03
Page:22-37

Principle of AC Transmission

The principle of AC transmission is the use of alternating current (AC) to transfer power from a source to a load. AC transmission works because the direction of the electric charge periodically reverses.

Here are some key principles of AC transmission:

Voltage
AC voltage can be increased or decreased using a transformer. This allows power to be transmitted at high voltage, which reduces energy loss and can be transformed to a lower voltage for use.

Power factor
The power in an AC circuit is the product of the voltage and current, multiplied by the power factor. The power factor is the cosine of the phase angle between the voltage and current.

Principle of AC Transmission

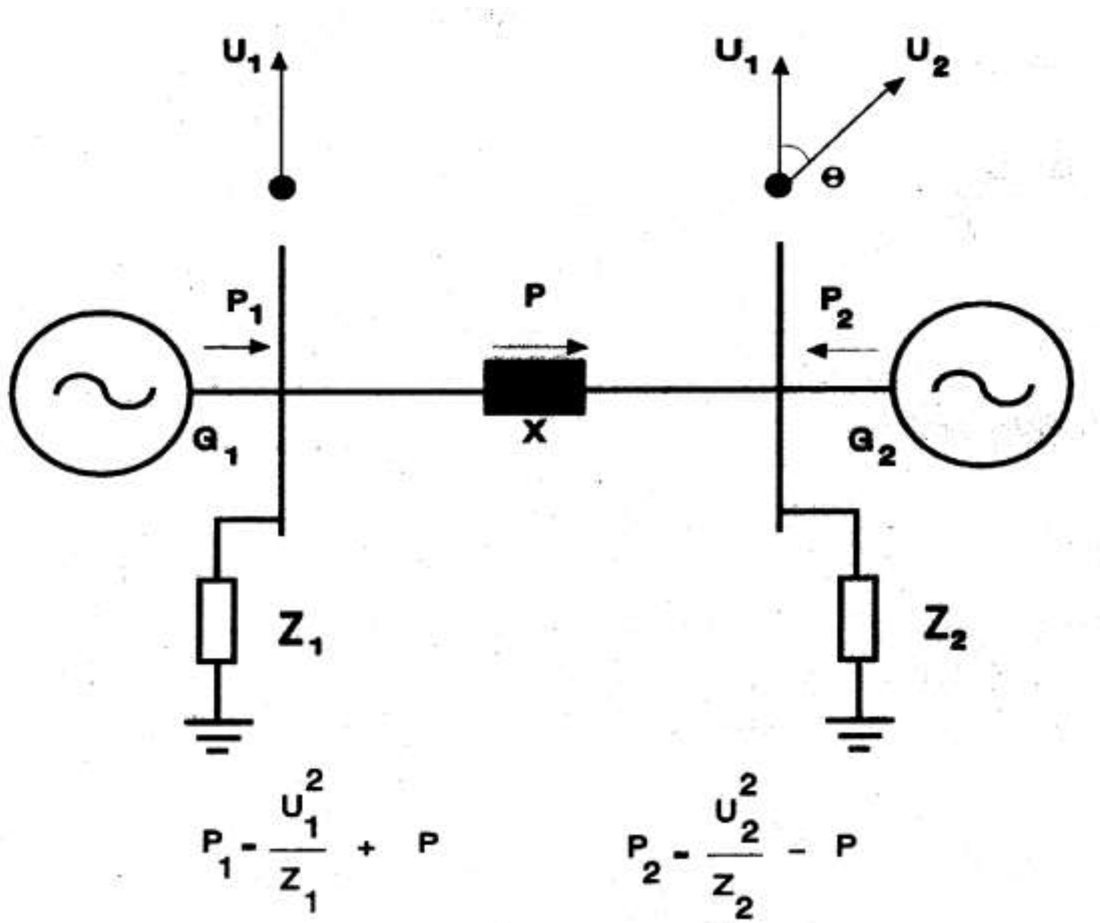
Phase-shifting transformers

Phase-shifting transformers (PSTs) are used to manage power flow between distant buses in large grids.

Series compensation devices

Series compensation devices can be used to transfer more power. The lower the angle between voltage and current, the better the system stability.

Principle of AC Transmission



$$P = \frac{U_1 U_2}{X} \sin\theta$$

Schematic of AC system

REASONS FOR AC GENERATION AND TRANSMISSION

- Due to ease of transformation of voltage levels (simple transformer action)
- Alternating Current is universally utilized.—Both for GENERATION and LOADS and hence for Transmission.
- Generators are at remote places, away from the populated areas i.e. the load centers
- They are either PIT HEAD THERMAL or HYDEL
- Turbines drive synchronous generators giving an output at 15-25 kV.
- Voltage is boosted up to 220 or 400 KV by step-up transformers for transmission to LOADS.
- To reach the loads at homes/industry at required safe levels, transformers step down voltage

COMPARISION OF HVAC & HVDC SYSTEMS

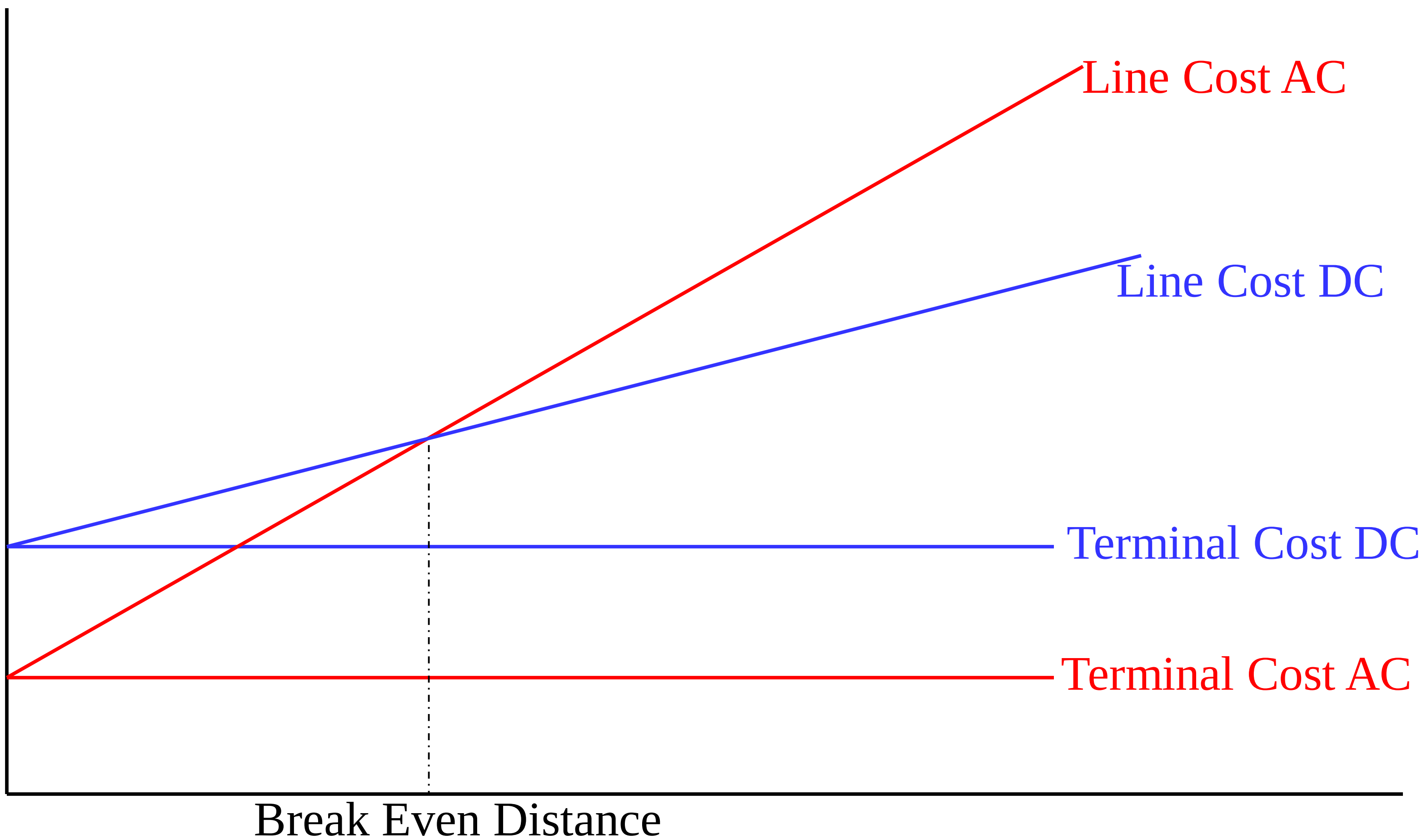
- HVAC transmission is having several limitations like line length , uncontrolled power flow, over/low voltages during lightly / over loaded conditions, stability problems, fault isolation etc
- The advantage of HVDC is the ability to transmit large amounts of power over long distances with lower capital costs and with lower losses than AC.
- HVDC transmission allows efficient use of energy sources remote from load centers. Depending on voltage level and construction details, losses are quoted as about 3% per 1,000 km.
- In a number of applications HVDC is more effective than AC transmission. Examples include:
  - Undersea cables, where high capacitance causes additional AC losses. (e.g. 250 km Baltic Cable between Sweden and Germany) .
  - 600 km NorNed cable between Norway and the Netherlands

COMPARISION OF HVAC & HVDC SYSTEMS

- In HVDC Long power transmission without intermediate taps, for example, in remote areas .
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install
- Power transmission and stabilization between unsynchronized AC distribution systems
- Connecting a remote generating plant to the distribution grid
- Asynchronous operation possible between regions having different electrical parameters .
- Facilitate power transmission between different countries that use AC at differing voltages and/or frequencies
- Reducing line cost:
  - fewer conductors
  - thinner conductors since HVDC does not suffer from the skin effect

COMPARISION OF HVAC & HVDC SYSTEMS

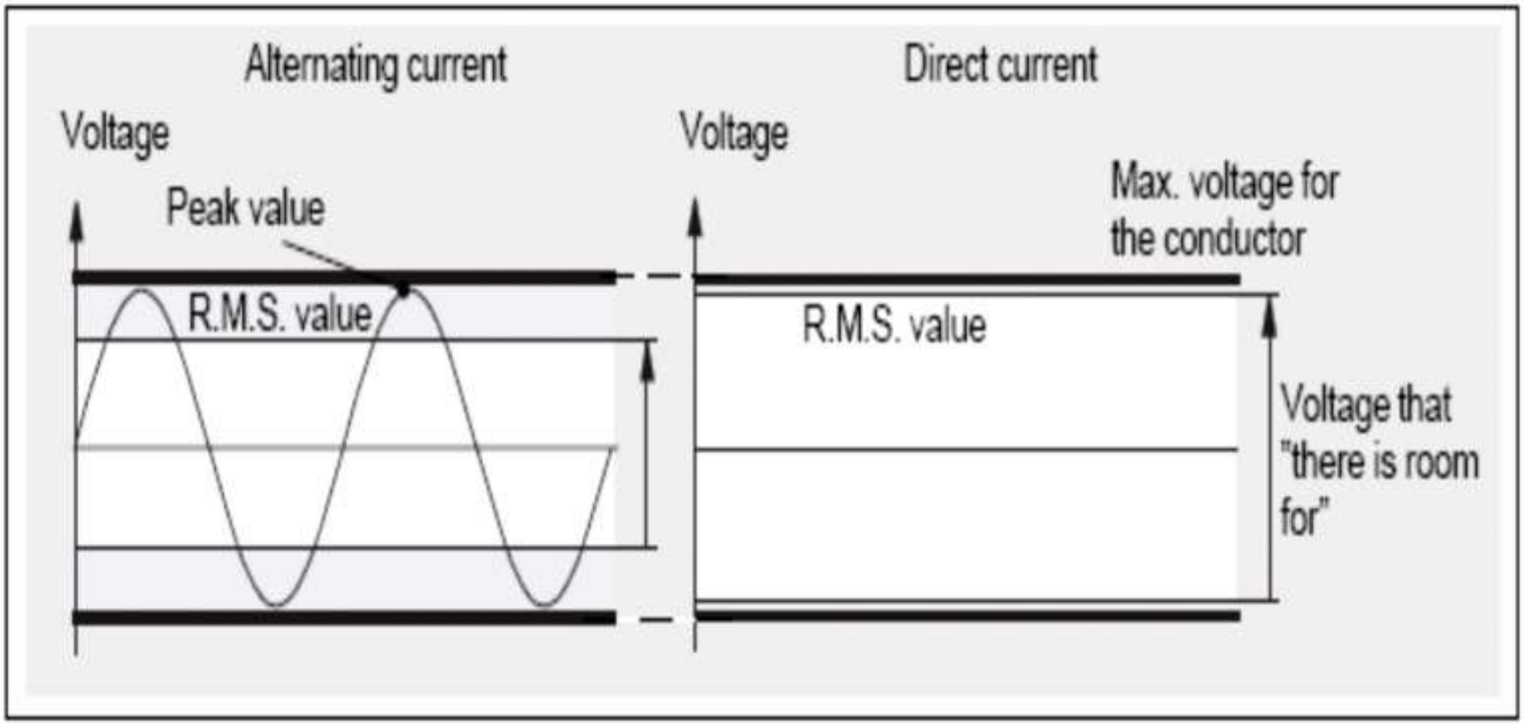
- HVDC Cheaper than HVAC for long distance.



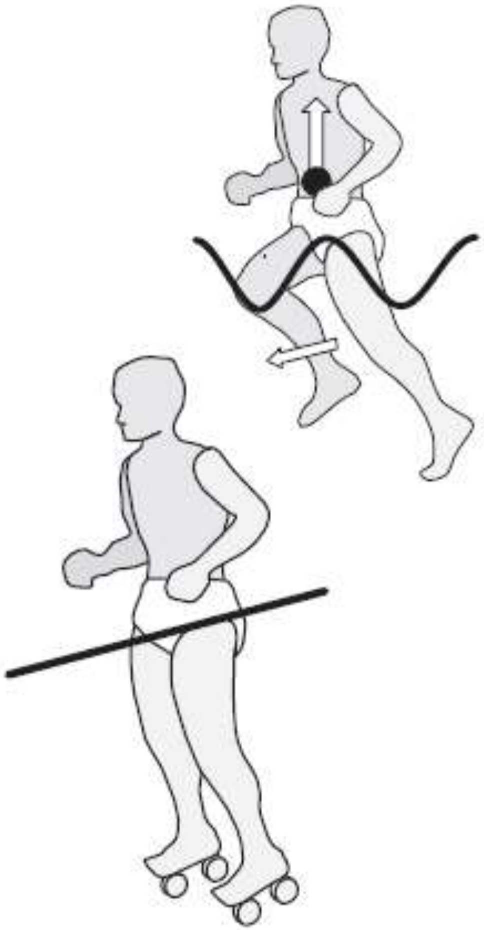
COST: HVAC vs. HVDC Transmission

COMPARISION OF HVAC & HVDC SYSTEMS

- No restriction on line length as no reactance in dc lines
- HVDC can carry more power per conductor because, for a given power rating, the constant voltage in a DC line is lower than the peak voltage in an AC line.



COMPARISION OF HVAC & HVDC SYSTEMS



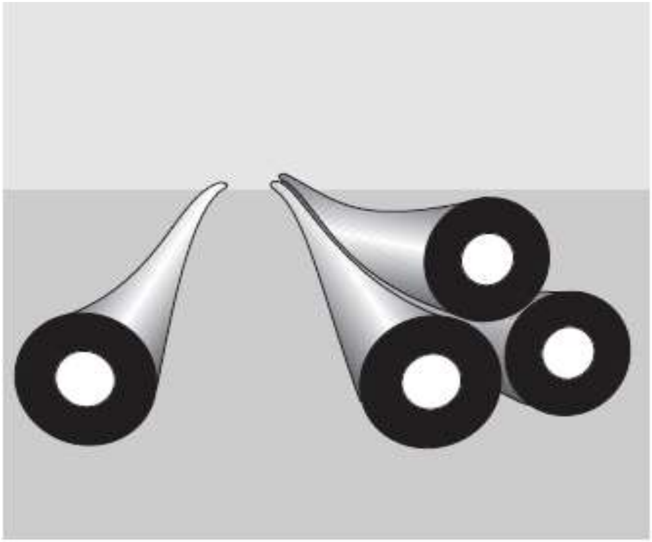
- HVDC uses less current i.e. low losses.

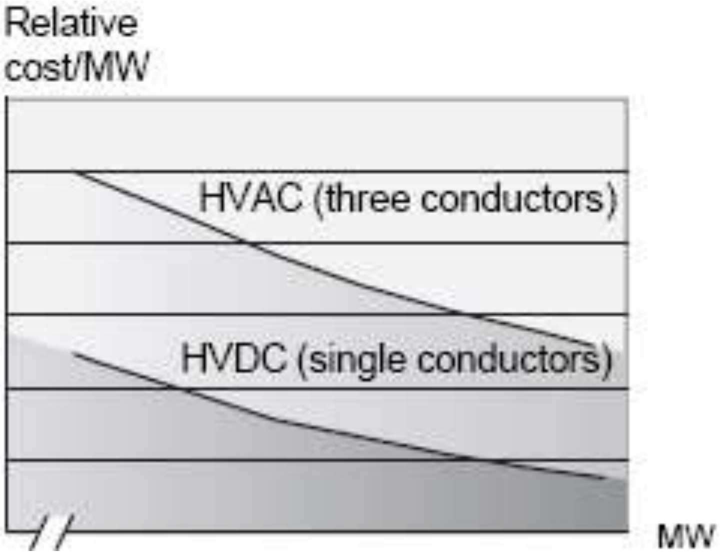
- AC current will struggle against inertia in the line (100times/sec)-electrical resistance –inductance-reactive power

- Direct current : Roll along the line ; opposing force friction (electrical resistance)

COMPARISION OF HVAC & HVDC SYSTEMS

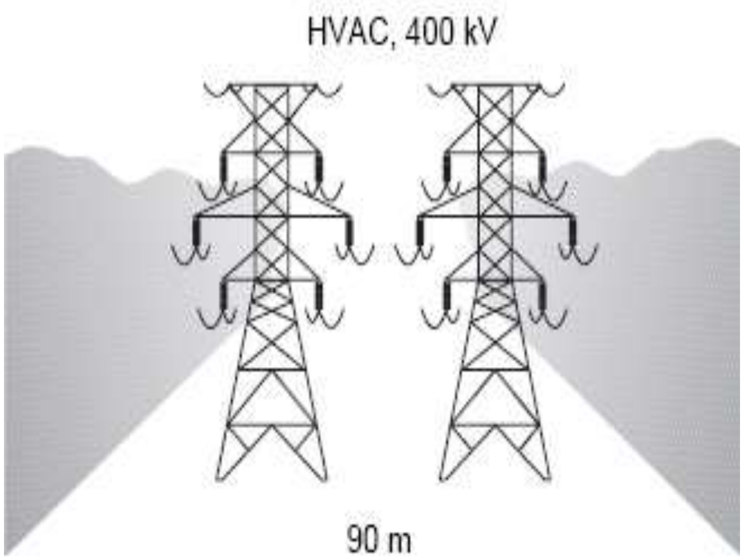
- **Distance as well as amount of POWER determine the choice of DC over AC**

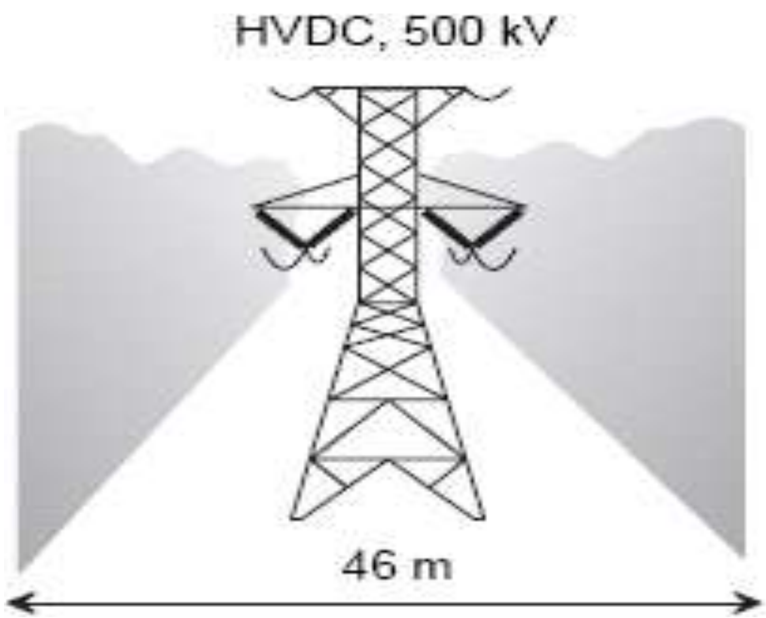




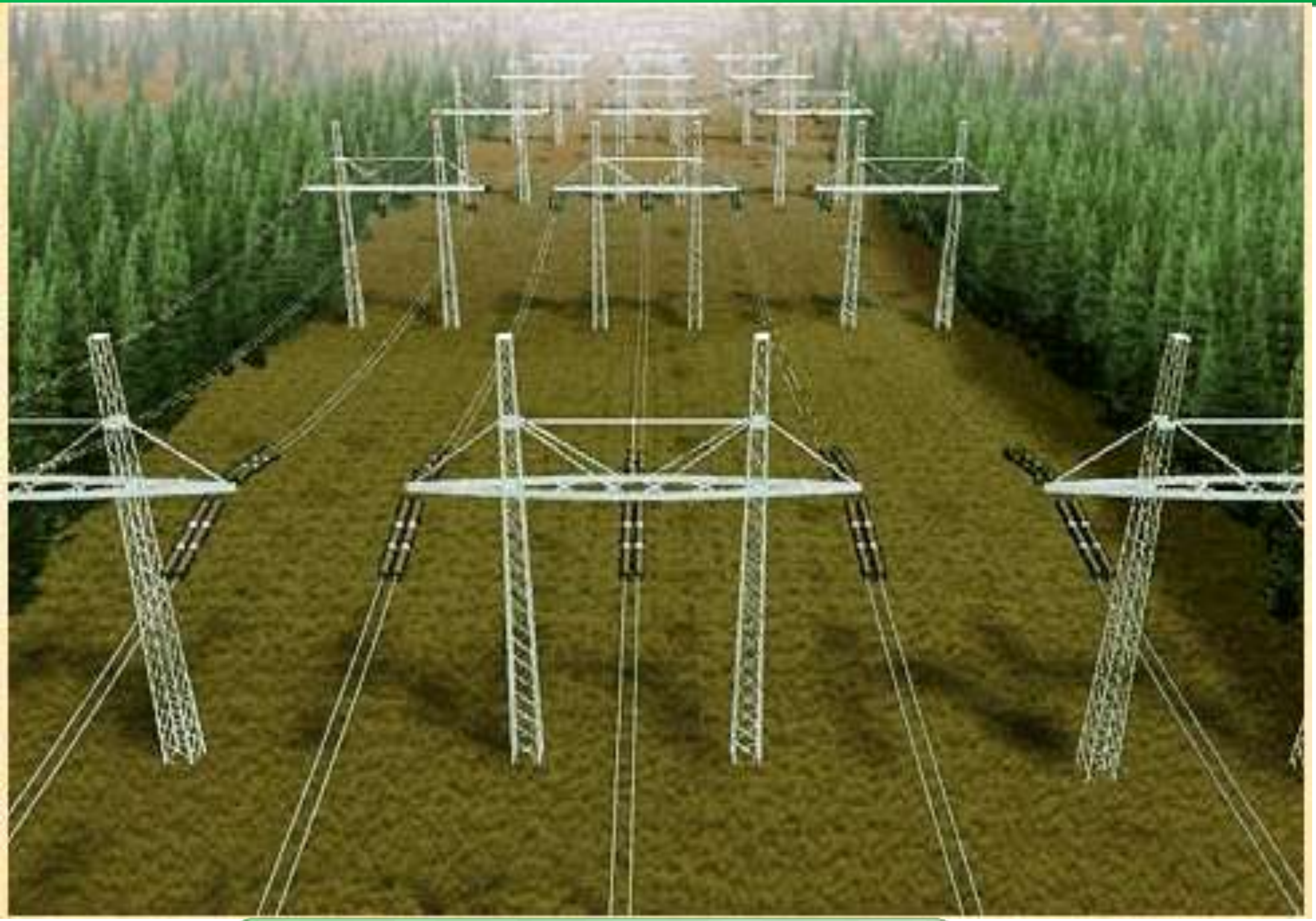
COMPARISION OF HVAC & HVDC SYSTEMS

- Direct current conserves forest and saves land
- The towers of the dc lines are narrower, simpler and cheaper compared to the towers of the ac lines.



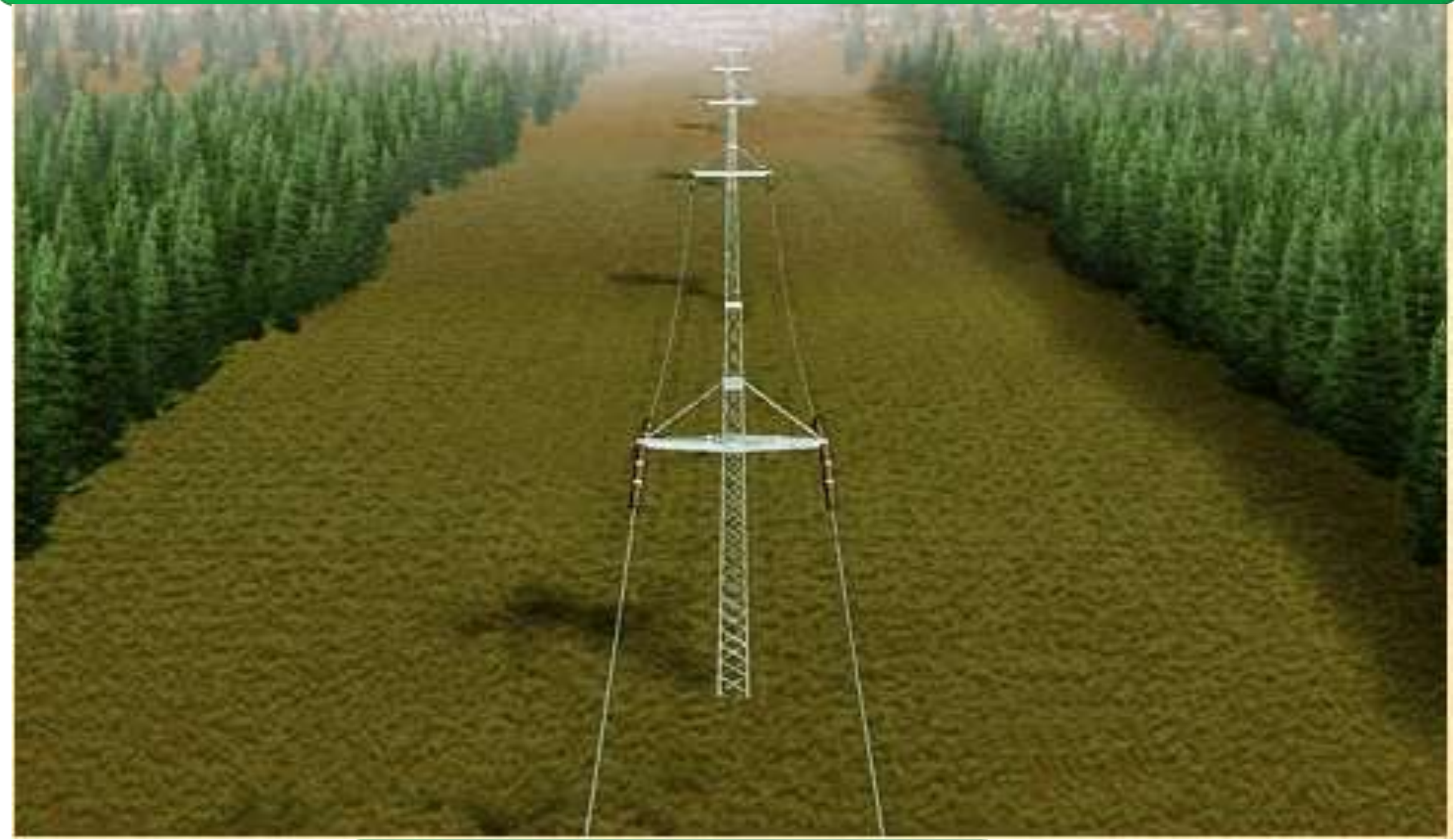


COMPARISION OF HVAC & HVDC SYSTEMS



AC Transmission Line Corridor

COMPARISION OF HVAC & HVDC SYSTEMS



DC Transmission Line Corridor

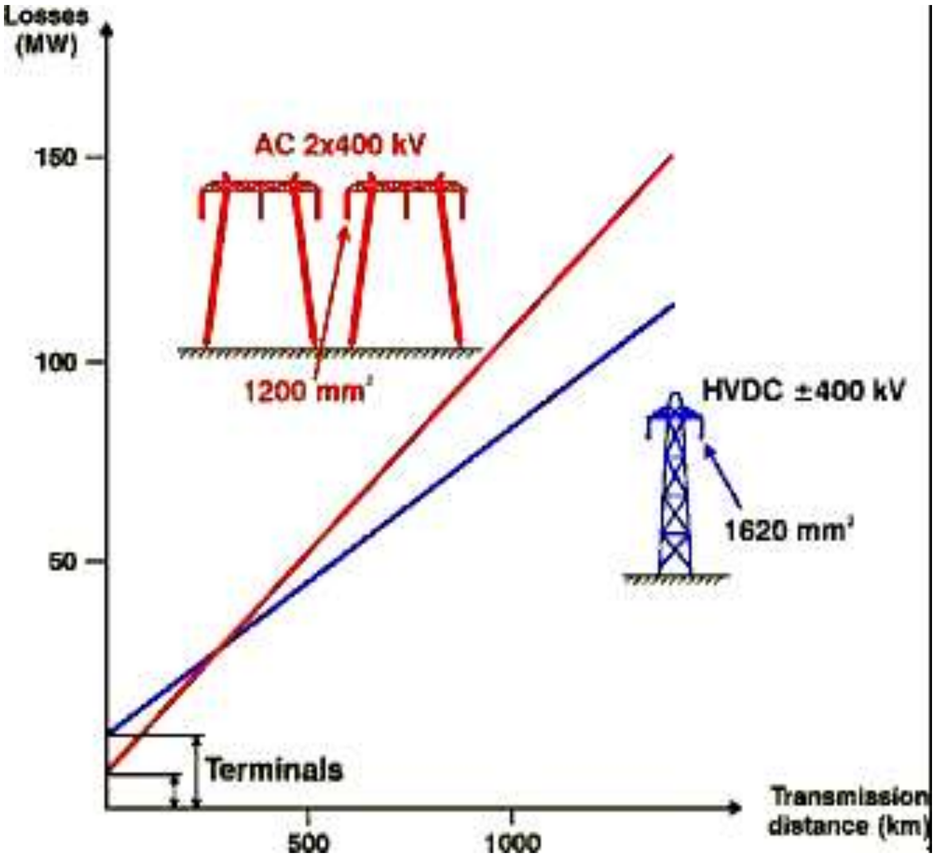
COMPARISION OF HVAC & HVDC SYSTEMS

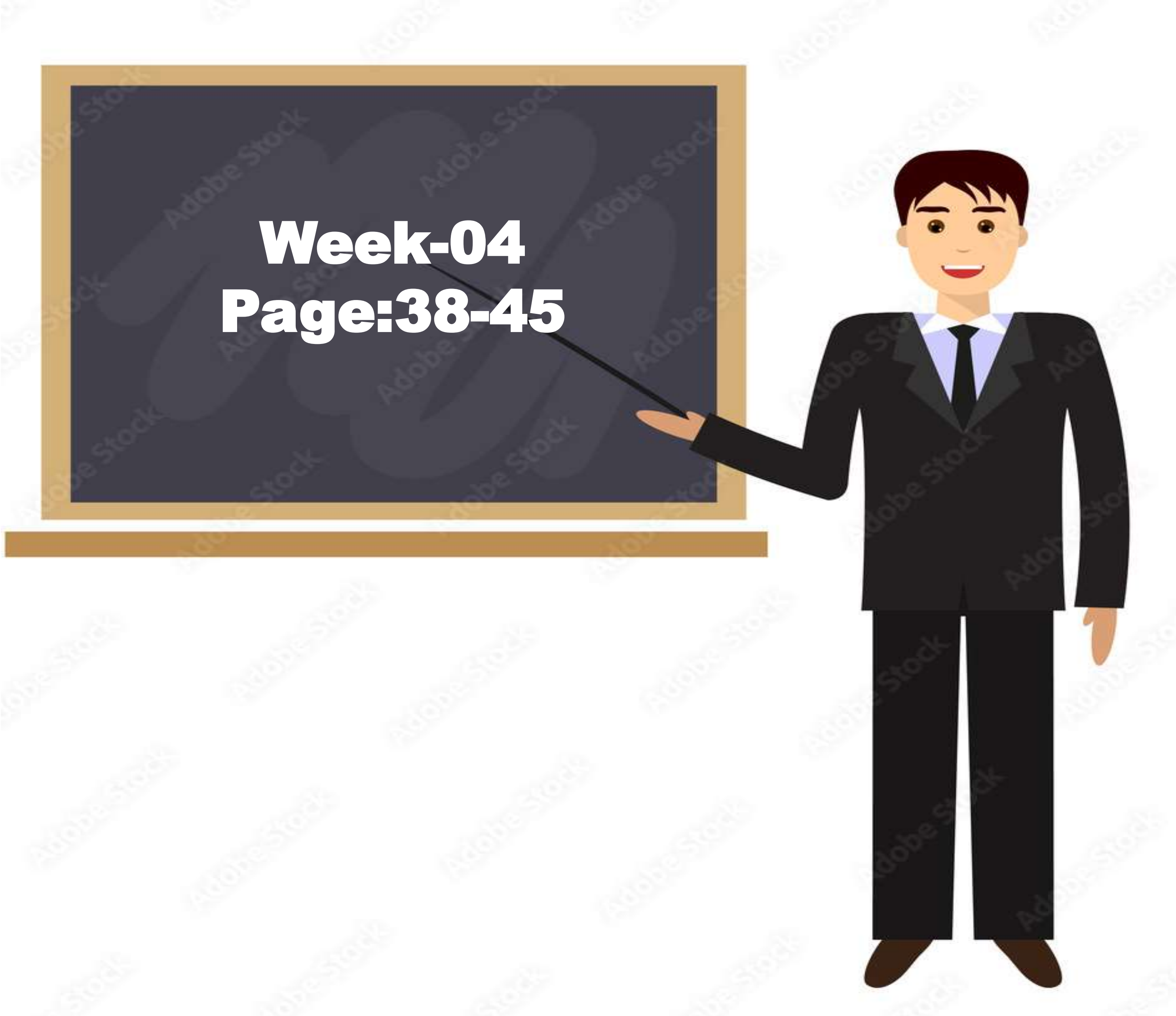
DC Transmission Line Corridor

COMPARISION OF HVAC & HVDC SYSTEMS

- Lesser Corona Loss than HVAC at same voltage and conductor diameter and less Radio interference.
- Direction of power flow can be changed very quickly
- HVDC has greater reliability. i.e. bipolar dc is more reliable than 3 phase HVAC
- DC requires less insulation.
- An optimized DC link has smaller towers than an optimized AC link of equal capacity.
- DC line in Parallel with AC link.

Corona ⟶ (f+25)




Week-04
Page:38-45

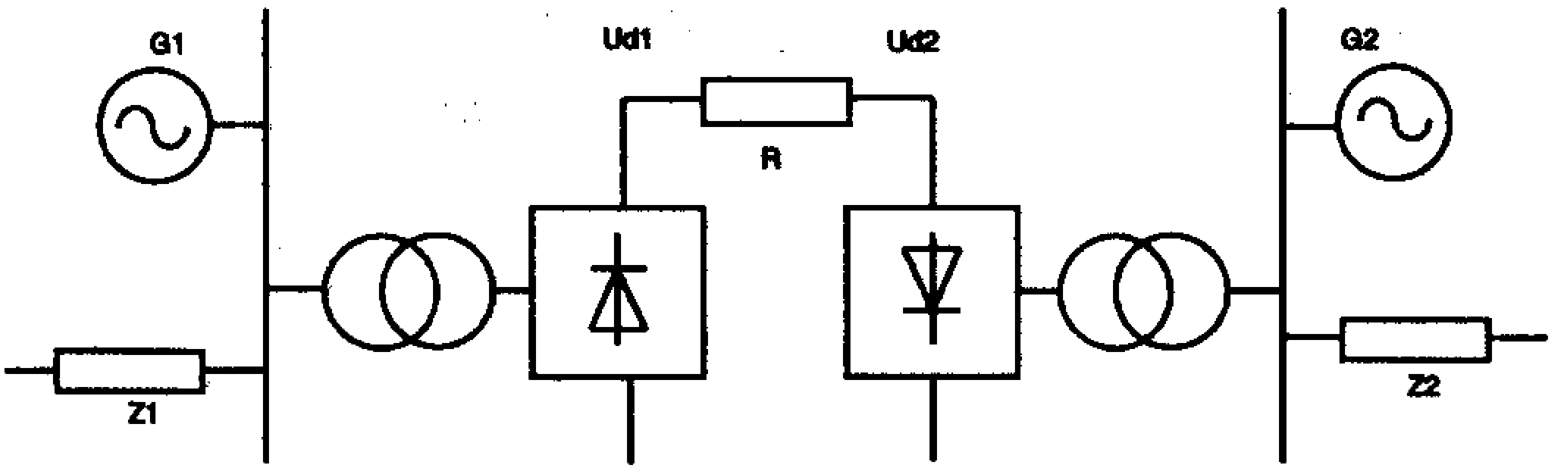
BASIC PRINCIPLES

OF

HVDC TRANSMISSION

HVDC Introduction

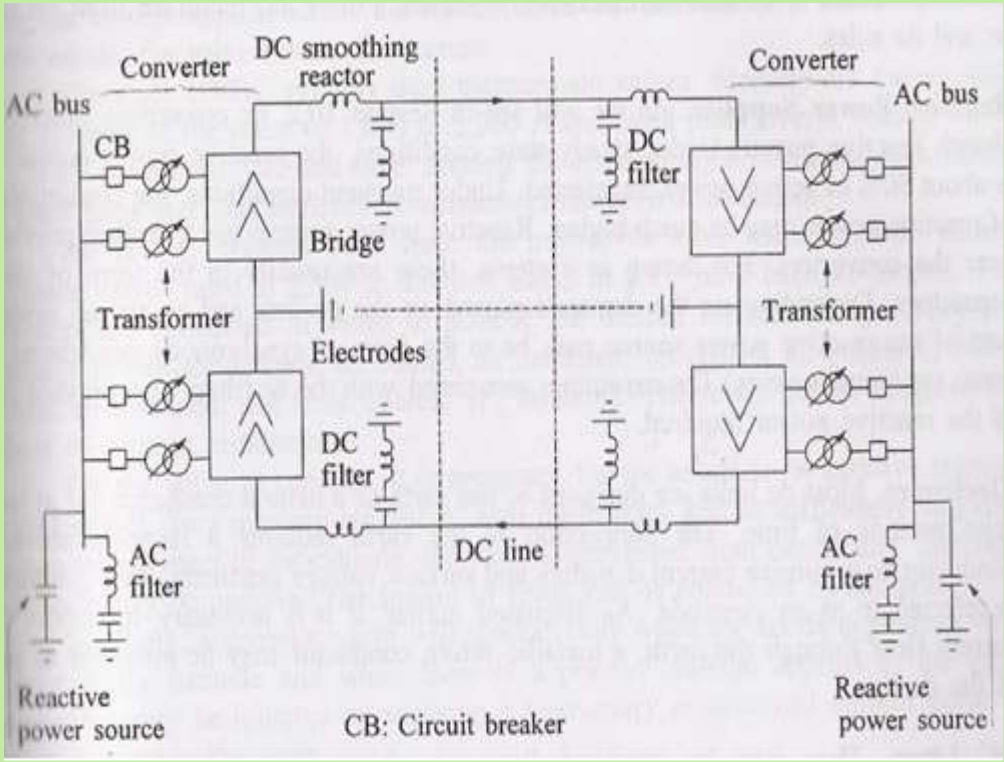
HVDC technology is used to transmit electricity over long distances by overhead transmission lines or submarine cables.



HVDC Principle

Components of HVDC Transmission Systems

1. **Converters**
2. **Smoothing reactors**
3. **Harmonic filters**
4. **Reactive power supplies**
5. **Electrodes**
6. **DC lines**
7. **AC circuit breakers**

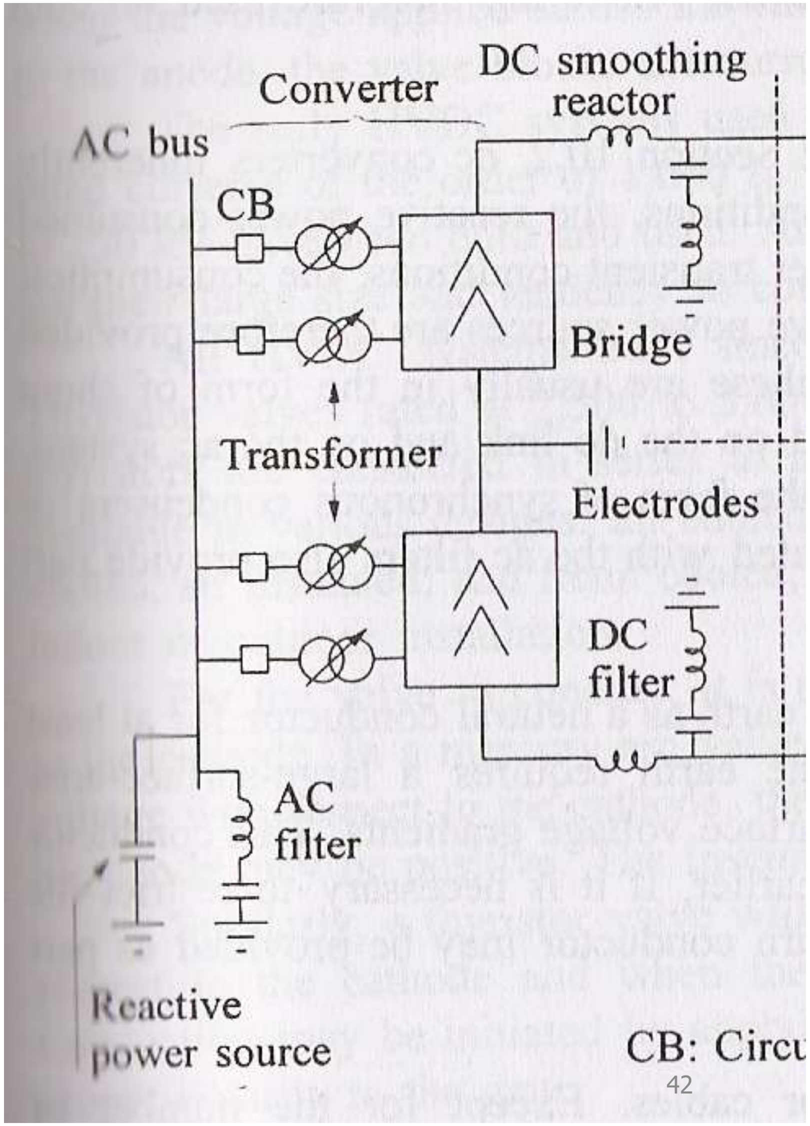


Components of HVDC

Components of HVDC Transmission Systems….

Converters

- They perform AC/DC and DC/AC conversion
- They consist of valve bridges and transformers
- Valve bridge consists of high voltage valves connected in a 6-pulse or 12-pulse arrangement
- The transformers are ungrounded such that the DC system will be able to establish its own reference to ground



Components of HVDC Transmission Systems….

Smoothing reactors

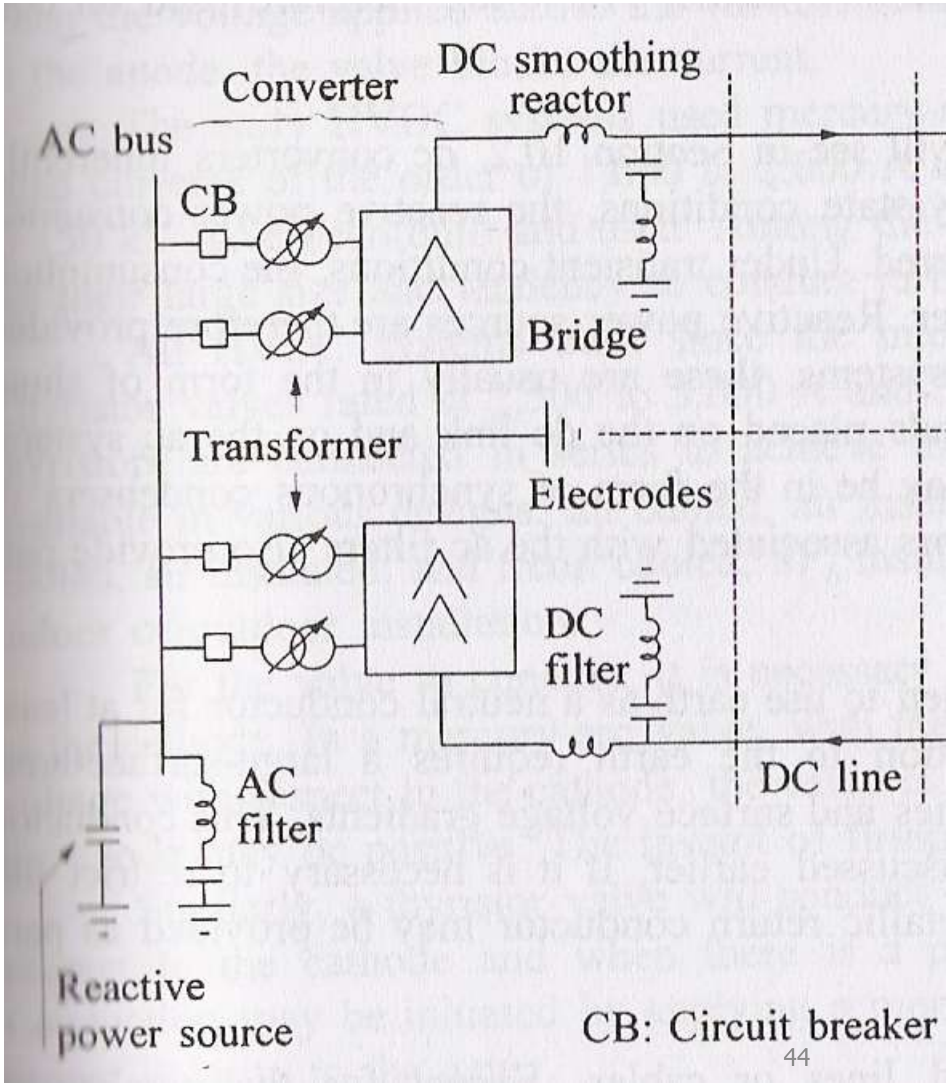
- They are high reactors with inductance as high as 1 H in series with each pole
- They serve the following:
  - They decrease harmonics in voltages and currents in DC lines
  - They prevent commutation failures in inverters
  - Prevent current from being discontinuous for light loads

Harmonic filters

- Converters generate harmonics in voltages and currents. These harmonics may cause overheating of capacitors and nearby generators and interference with telecommunication systems
- Harmonic filters are used to mitigate these harmonics

Reactive power supplies

- Under steady state condition, the reactive power consumed by the converter is about 50% of the active power transferred
- Under transient conditions it could be much higher
- Reactive power is, therefore, provided near the converters
- For a strong AC power system, this reactive power is provided by a shunt capacitor



Components of HVDC Transmission Systems....

Electrodes

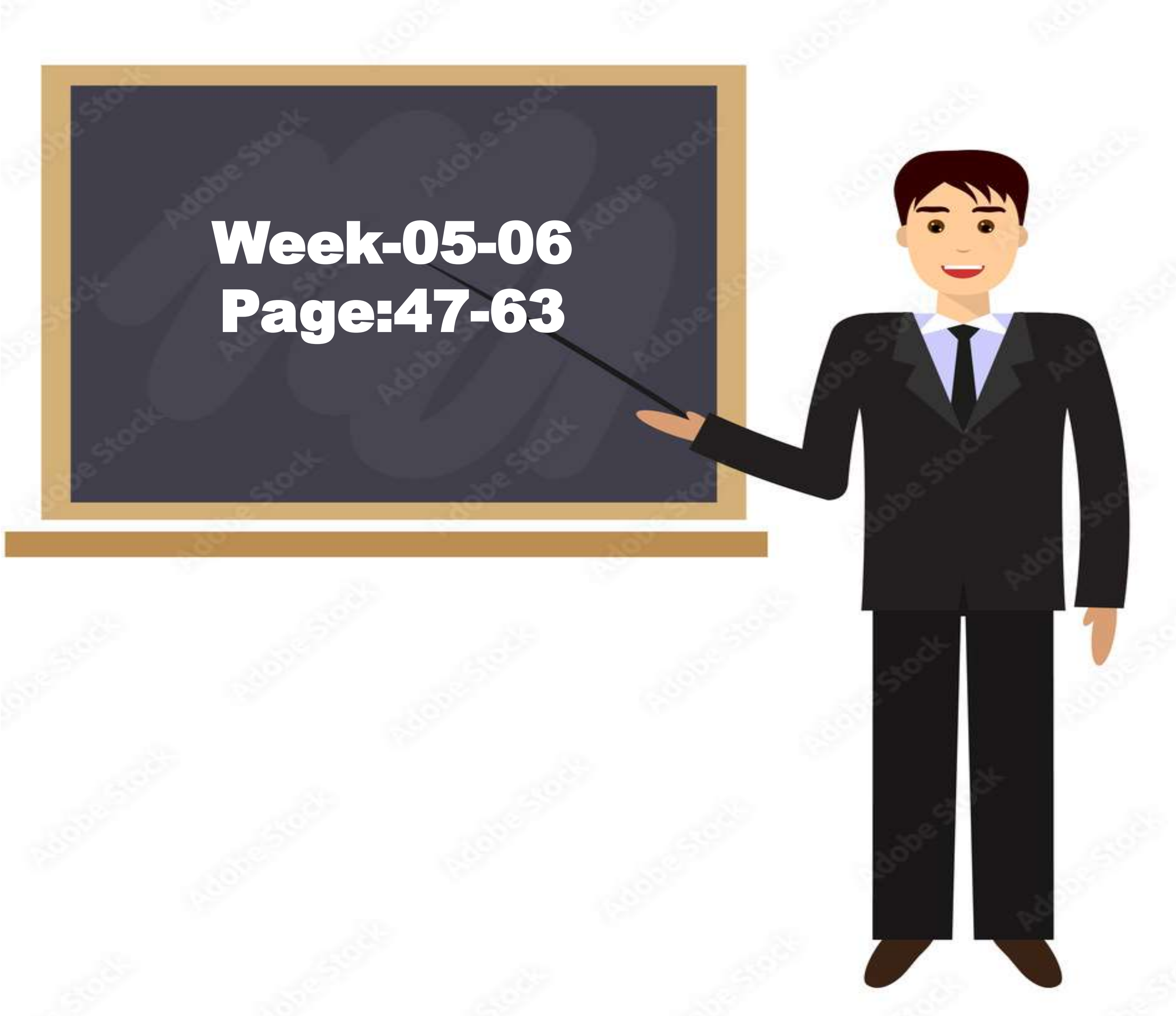
- Electrodes are conductors that provide connection to the earth for neutral. They have large surface to minimize current densities and surface voltage gradients

DC lines

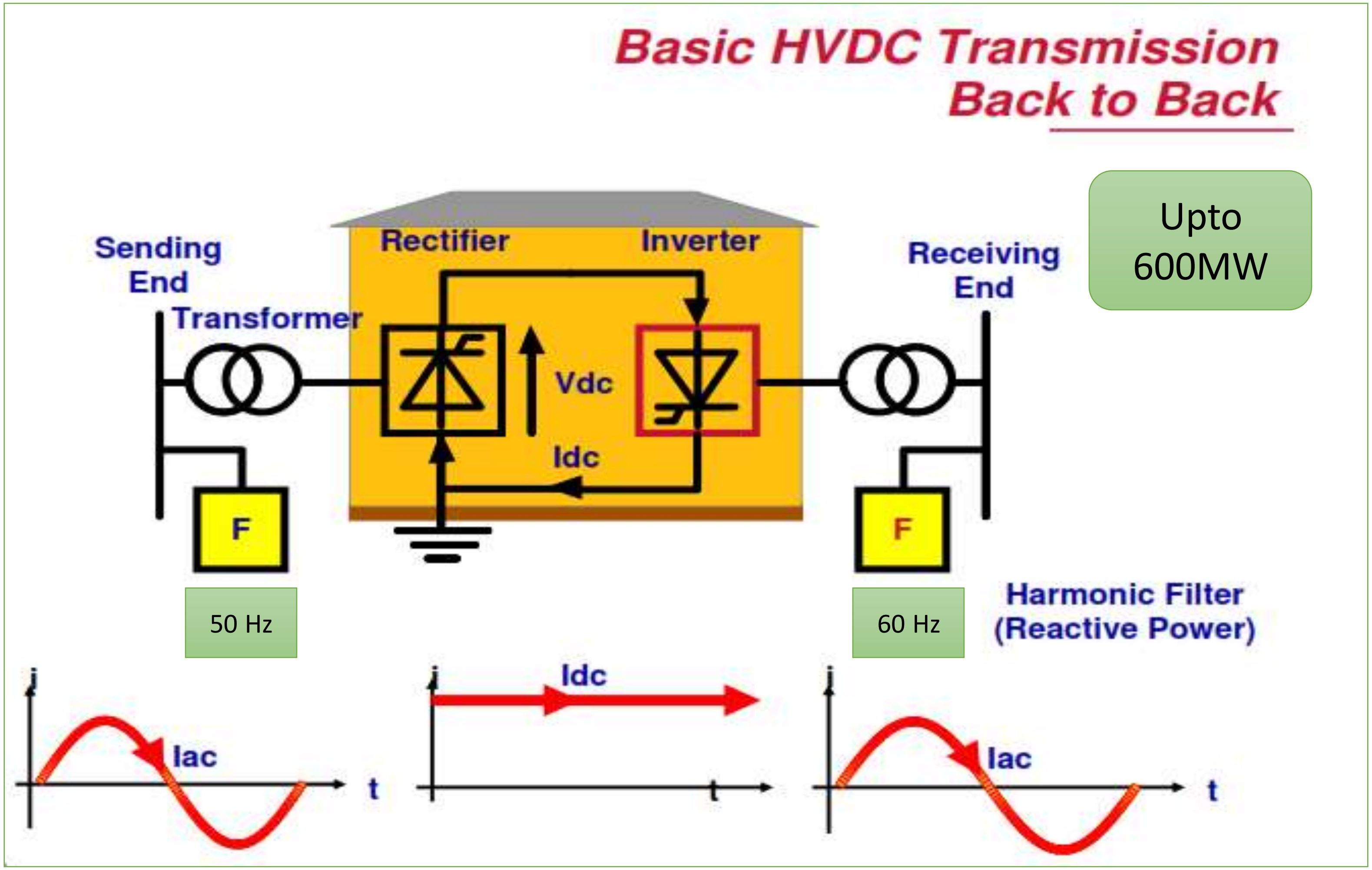
- They may be overhead lines or cables
- DC lines are very similar to AC lines

AC circuit breakers

- They used to clear faults in the transformer and for taking the DC link out of service
- They are not used for clearing DC faults
- DC faults are cleared by converter control more rapidly


Week-05-06
Page:47-63

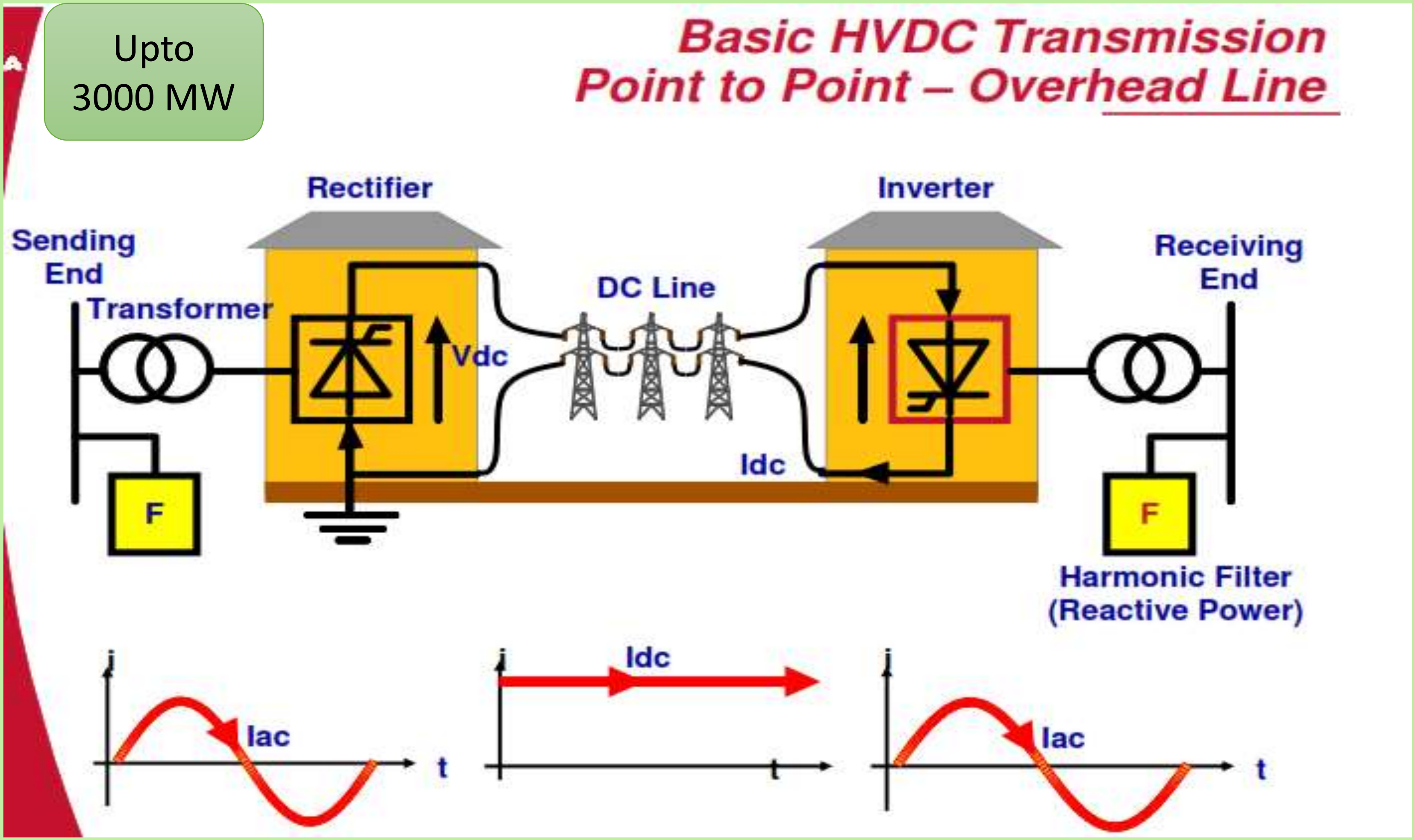
Application based HVDC Transmission Types



HVDC is the unique solution to interconnect Asynchronous systems or grids with different frequencies.

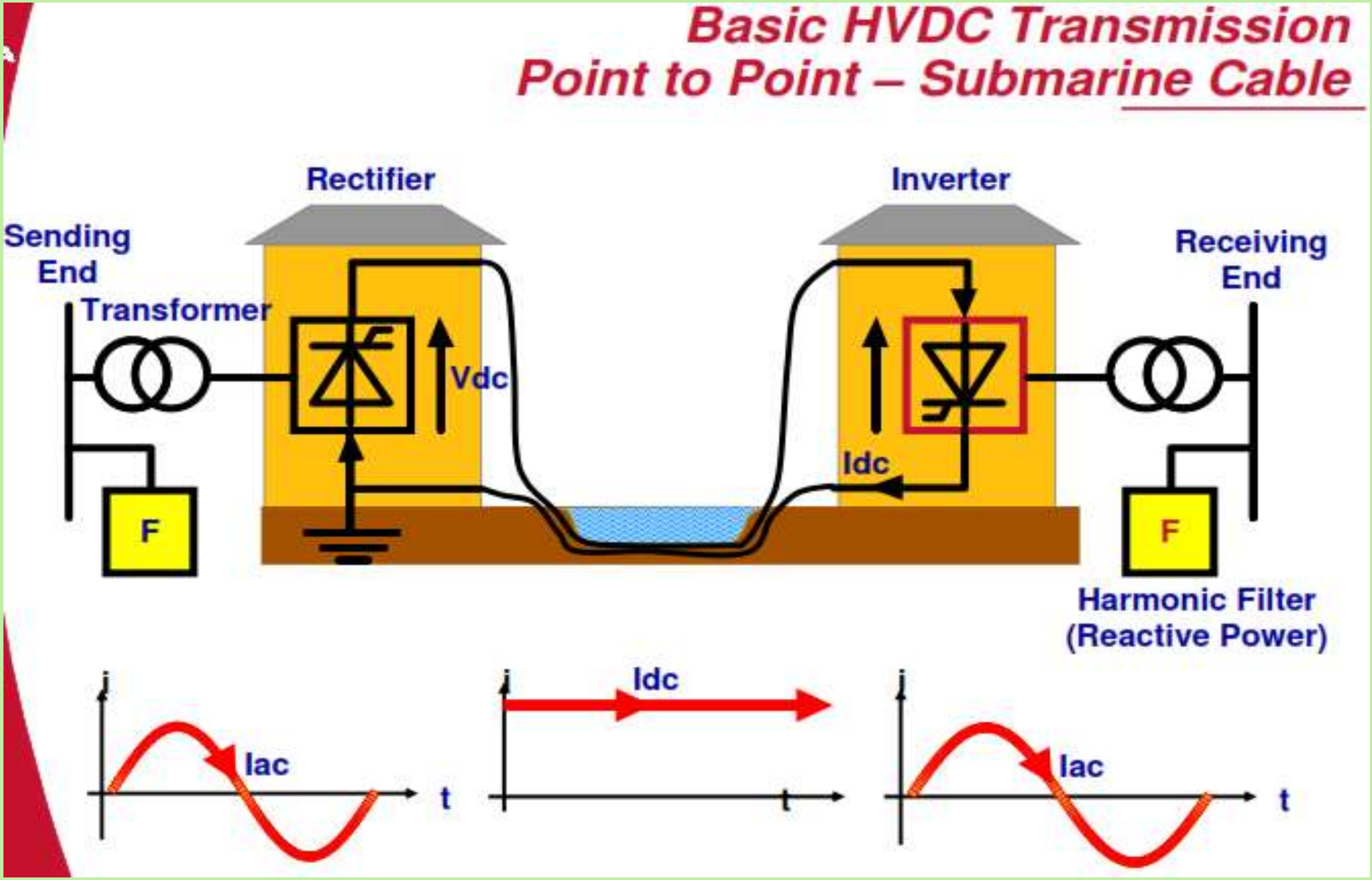
Application based HVDC Transmission Types

Upto 3000 MW



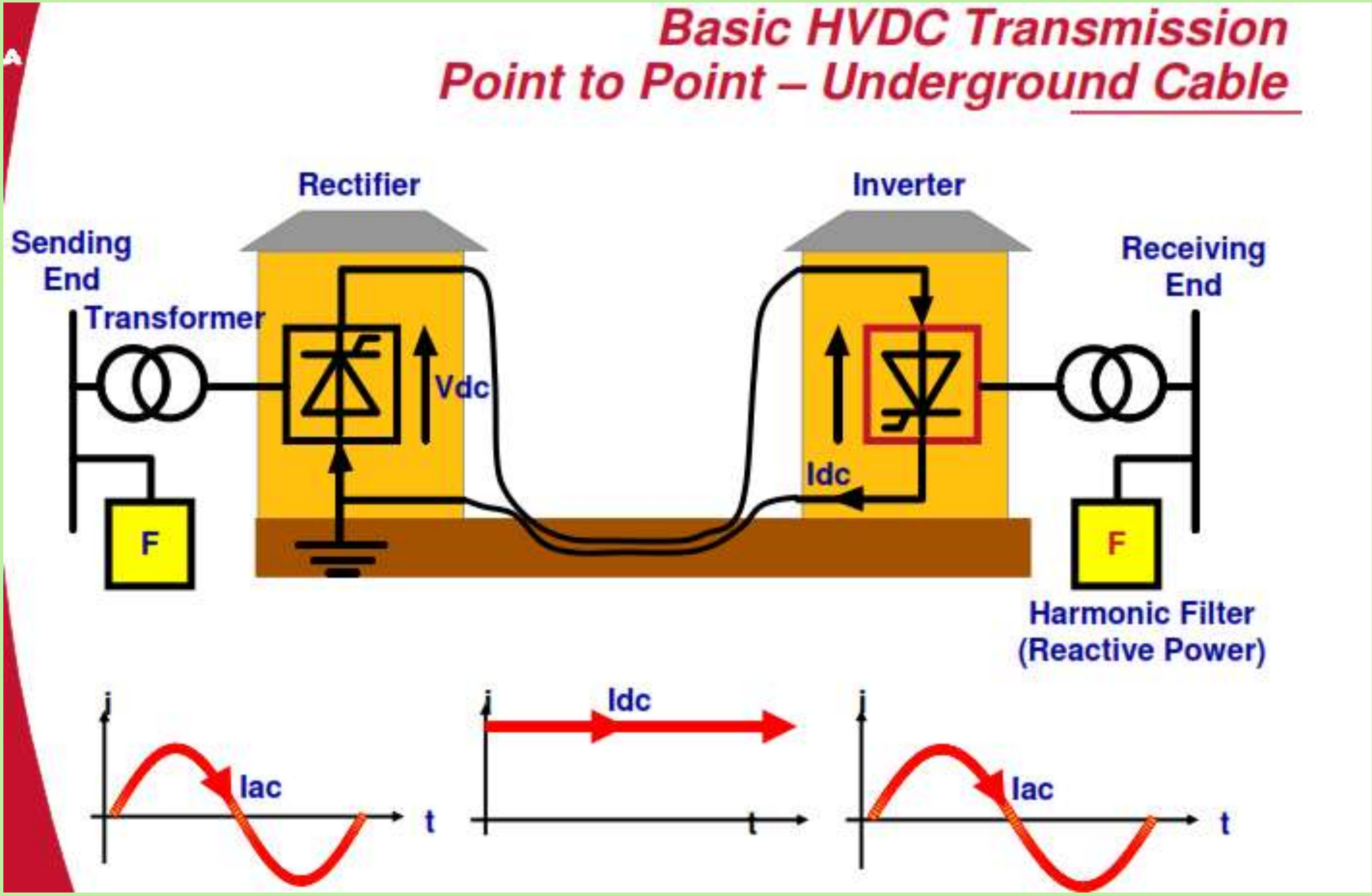
HVDC represents the most economical solution to transmit electrical energy over distances greater than approx. 600 km

Application based HVDC Transmission Types



HVDC is an alternative for submarine transmission. Economical even for shorter distances such as a few 10km/miles

Application based HVDC Transmission Types



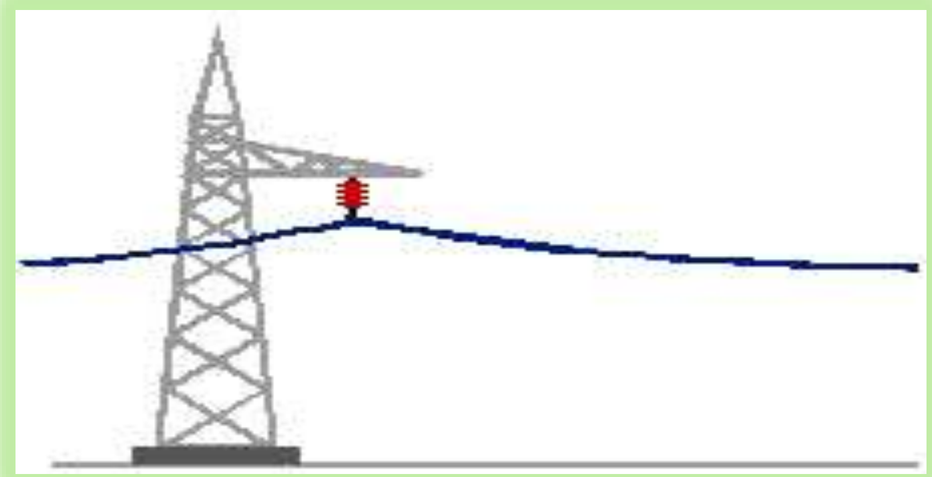
HVDC System Configurations

HVDC links can be broadly classified into:

- Monopolar links
- Bipolar links
- Homopolar links
- Multiterminal links

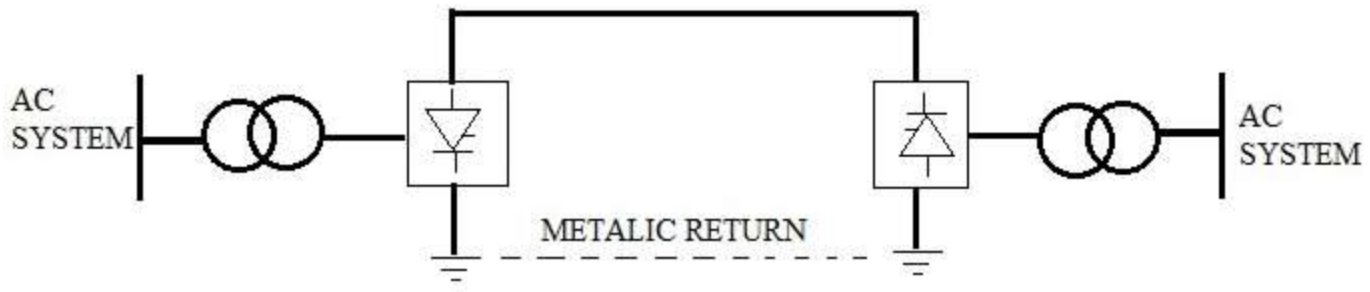
Monopolar Links

Monopolar link has only one conductor and return path is provided by permanent earth or sea. The line usually operates with negative polarity with respect to ground so as to reduce corona loss and radio interference.



Monopolar Links

- It uses one conductor .
- The return path is provided by ground or water.
- Use of this system is mainly due to cost considerations.
- A metallic return may be used where earth resistivity is too high.
- This configuration type is the first step towards a bipolar link.

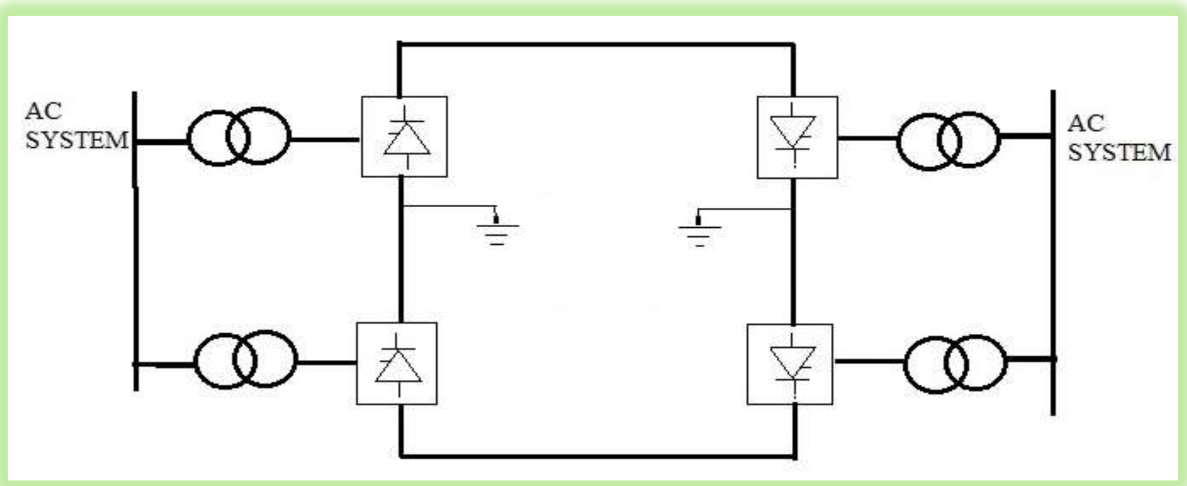


Bipolar Links

A bipolar link is a transmission system in high voltage direct current (HVDC) that has two conductors, one positive and one negative, connected to the earth. It also has a converter station at each end, with the midpoints of the stations earthed through electrodes.

Bipolar Links

- Each terminal has two converters of equal rated voltage, connected in series on the DC side.
- The junctions between the converters is grounded.
- If one pole is isolated due to fault, the other pole can operate with ground and carry half the rated load (or more using overload capabilities of its converter line).



Advantages

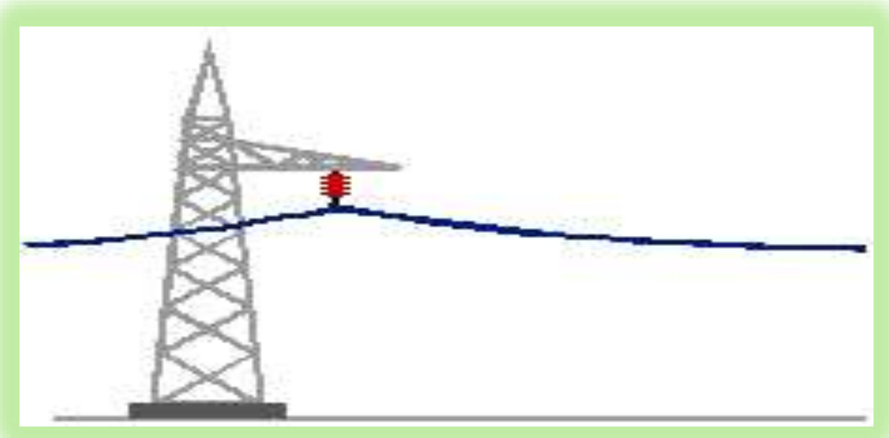
A bipolar link has a number of advantages, including:

- **Monopolar mode:** If one of the conductors stops working, the bipolar link can operate in monopolar mode, allowing the other half of the system to continue supplying power.

- **Common use:** Bipolar links are commonly used in HVDC systems.

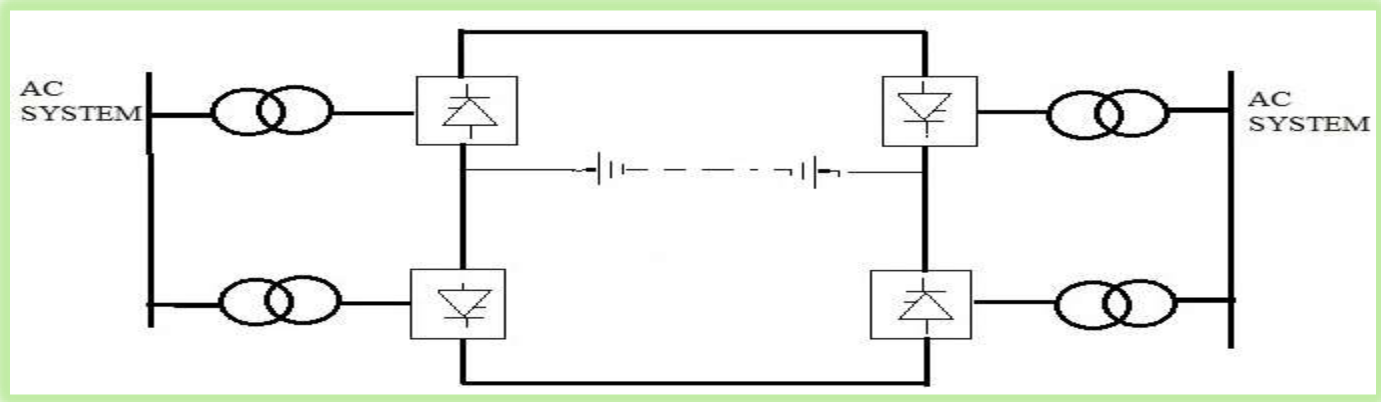
Homopolar Links

A homopolar link is a type of High Voltage Direct Current (HVDC) transmission system that uses two or more conductors with the same polarity, usually negative, and a ground return conductor:



Homopolar Links

- It has two or more conductors all having the same polarity, usually negative.
- Since the corona effect in DC transmission lines is less for negative polarity, homopolar link is usually operated with negative polarity.
- The return path for such a system is through ground.



Advantages and Disadvantages

Advantages

Reduced insulation costs, reduced corona loss, and reduced radio interference. If one conductor fails, the other can supply power.

Disadvantages

Larger return current in the ground, which causes losses. Control and protection are more difficult than bipolar links. Rarely used due to high environmental impact.

Dc as a Means of Transmission

DC Transmission has been possible with beginning of

- High power/ high current capability thyristor.
- Fast acting computerized controls

Since our primary source of power is A.C, The three basic steps are

1. Convert AC into DC (**rectifier)**
2. Transmit DC
3. Convert DC into AC (**inverter**)

Rectifier

A rectifier is an electrical device that converts alternating current (AC) into direct current (DC):

Rectifiers are used in many devices because most modern electronics require DC to operate properly. The process of converting AC to DC is called rectification.

Rectifiers work by using diodes, which act like one-way valves to allow current to flow in one direction. Rectifiers can come in many forms, including:

- Vacuum tube diodes
- Crystal radio receivers
- Silicon-based designs
- Solid-state diodes
- Mercury-arc valves
- Silicon-controlled rectifiers

Rectifier

There are several types of rectifiers, including:

•**Full wave rectifiers**: Have a rectification efficiency that's double that of half wave rectifiers, and a lower ripple factor.

•**Bridge rectifiers**: Don't require a center-tapped transformer, and are used with transformers for efficient use.

•**Single-phase and three-phase rectifiers**: Classified by the type of supply.

•**Uncontrolled, half controlled, and full controlled rectifiers**: Classified by the control nature.

Rectifier

To convert alternating current (AC) to direct current (DC) using a rectifier, you can follow these steps:

1.**Step down the voltage**: Use a step-down transformer to reduce the AC voltage to the desired level.

2.**Use a rectifier**: A rectifier uses diodes to convert the AC to DC. There are two main types of rectifiers:

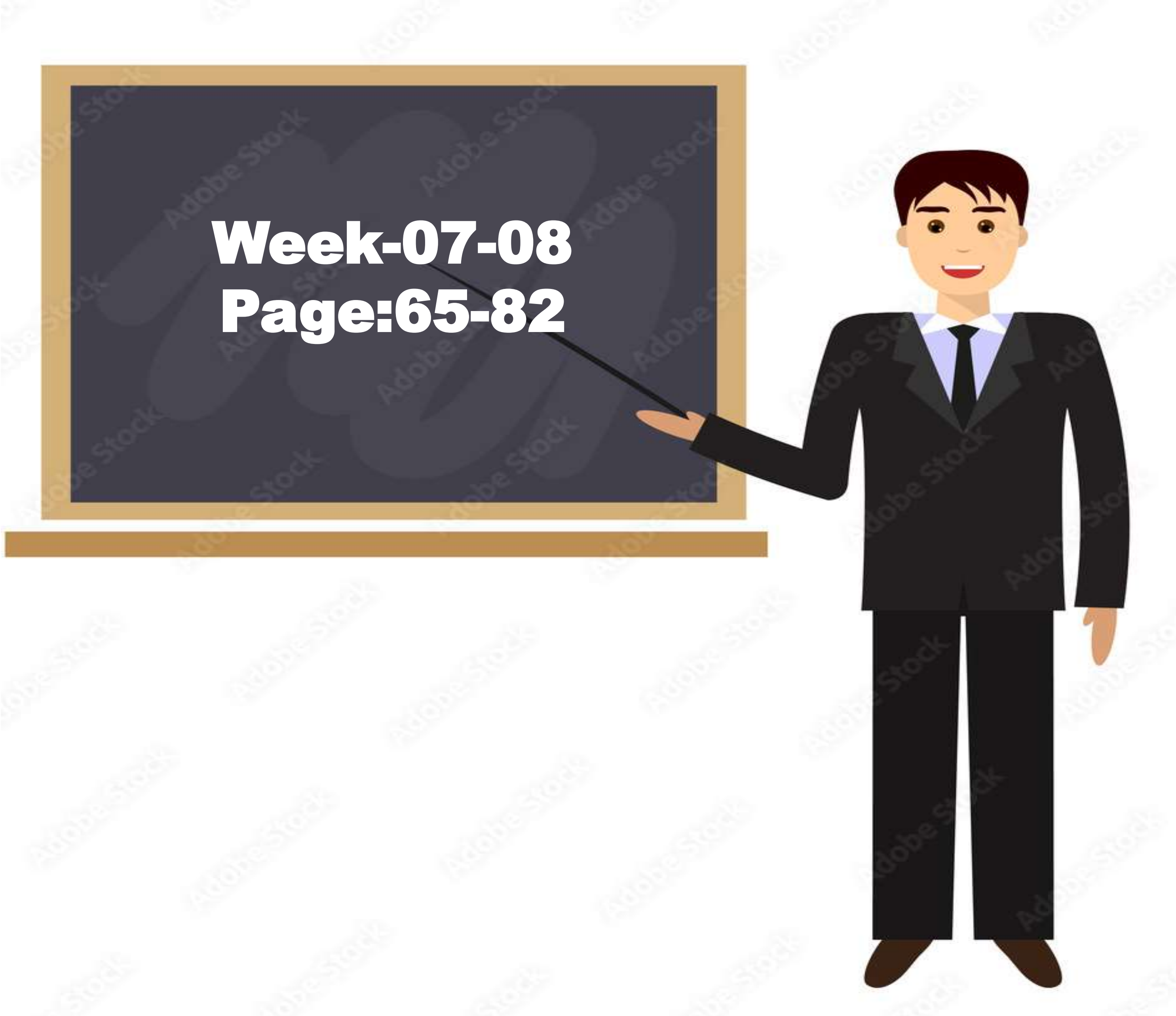
2. **Half-wave rectifier**: Cuts off half of the AC signal's electrical output, leaving DC pulses.

3. **Full-wave rectifier**: Turns the entire AC waveform into a series of DC pulses with a single polarity. A full-bridge rectifier is a common type of full-wave rectifier that uses four diodes to convert both halves of the AC waveform.

3.**Smooth the DC**: Attach capacitors to smooth the rectified DC. Larger capacitors can keep the voltage higher for longer, resulting in less rippling.

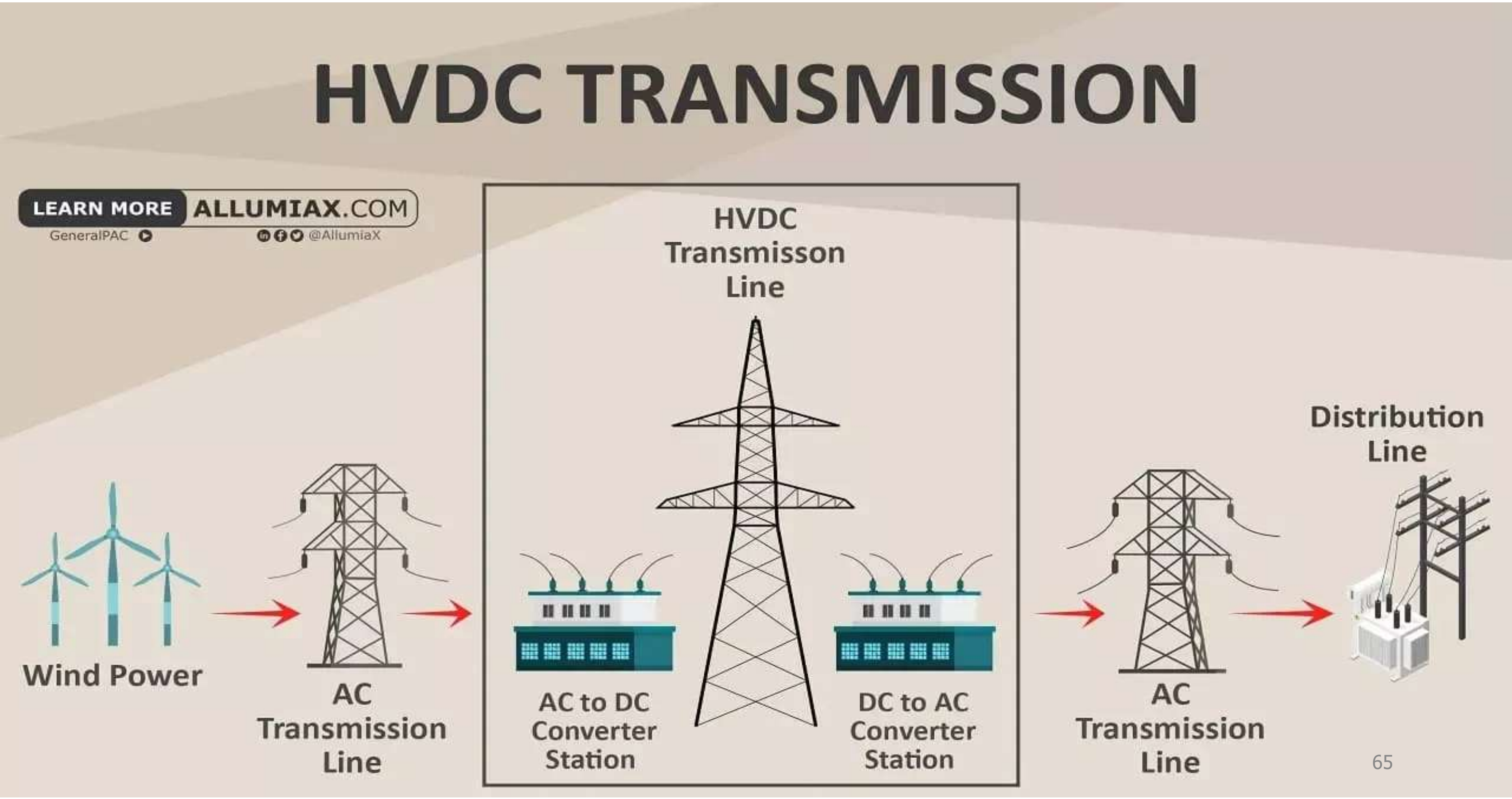
4.**Regulate the voltage**: Use a voltage regulator for a consistent output.

5.**Check the output**: Use a multimeter to ensure the DC conversion is correct.


Week-07-08
Page:65-82

DC transmission

DC transmission, or direct current transmission, is a technique for transmitting electrical energy using direct current. DC electricity flows in one direction, while alternating current (AC) electricity periodically reverses direction.



DC transmission

DC transmission is often used for long-distance power transmission because it's more efficient than AC transmission:

- **Power loss**
- DC transmission systems experience less power loss than AC systems over long distances.
- **Conductor use**
- DC transmission systems require fewer conductors than AC systems.
- **Stability**
- DC transmission systems can stabilize networks against disturbances caused by rapid power changes.
- **Frequency transfer**
- DC transmission systems can transfer power between grid systems that run at different frequencies.

DC transmission

Some examples of DC transmission systems include:

Point-to-point HVDC: A straight line that connects two places

Multi-terminal HVDC: A more complex system with multiple connections and converters that allows for more flexible power routing

Back-to-back HVDC: A system that links two asynchronous AC systems together

DC transmission is also used in renewable energy integration and maritime electrical systems.

DC transmission

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Multi-terminal HVDC: A more complex system with multiple connections and converters that allows for more flexible power routing

Back-to-back HVDC: A system that links two asynchronous AC systems together

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Inverter

A power inverter, inverter, or invertor is a power electronic device or circuitry that changes direct current (DC) to alternating current (AC). The resulting AC frequency obtained depends on the particular device employed.

Inverter

To convert DC (direct current) to AC (alternating current), you can use a device called an inverter:

1. **Choose an inverter**: Select an inverter that can handle the load you want to connect to it.

2. **Connect the DC power source**: Connect a DC power source, like a battery or solar panel, to the inverter's input terminals. Make sure the polarity is correct.

3. **Connect the AC load**: Connect the AC load to the inverter's output terminals. Make sure the polarity is correct.

4. **Turn on the inverter**: Turn on the inverter and wait for it to initialize.

5. **Turn on the AC load**: Turn on the AC load.

6. **Monitor the inverter**: Check the inverter's display to make sure it's operating safely.

7. **Turn off the inverter**: When you're done, turn off the AC load, then the inverter.

Inverter

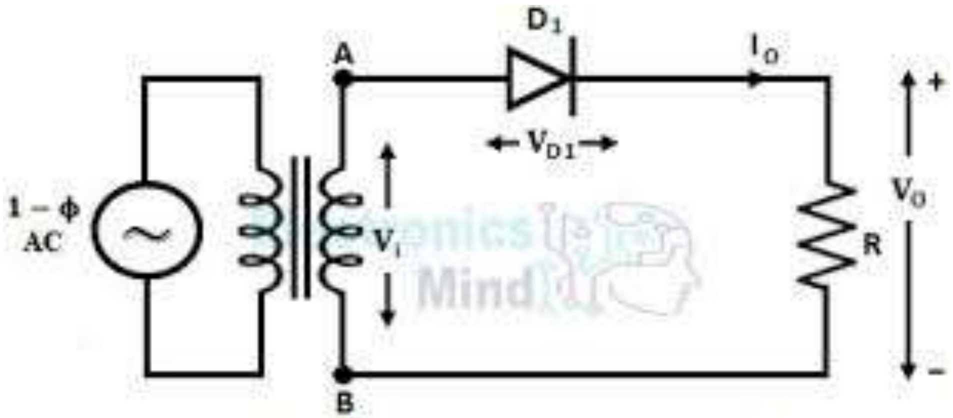
Inverters work by using an electronic circuit called an H-bridge to rapidly switch the DC input on and off. This creates pulses of current that alternate between positive and negative. Capacitors and inductors then filter and smooth the pulses to create a sinusoidal waveform, which is the most common type of AC.

Inverters are used to power AC devices, like lights, refrigerators, and power tools, with DC sources, like batteries or solar

Conversion

Single Phase Half wave Rectifier

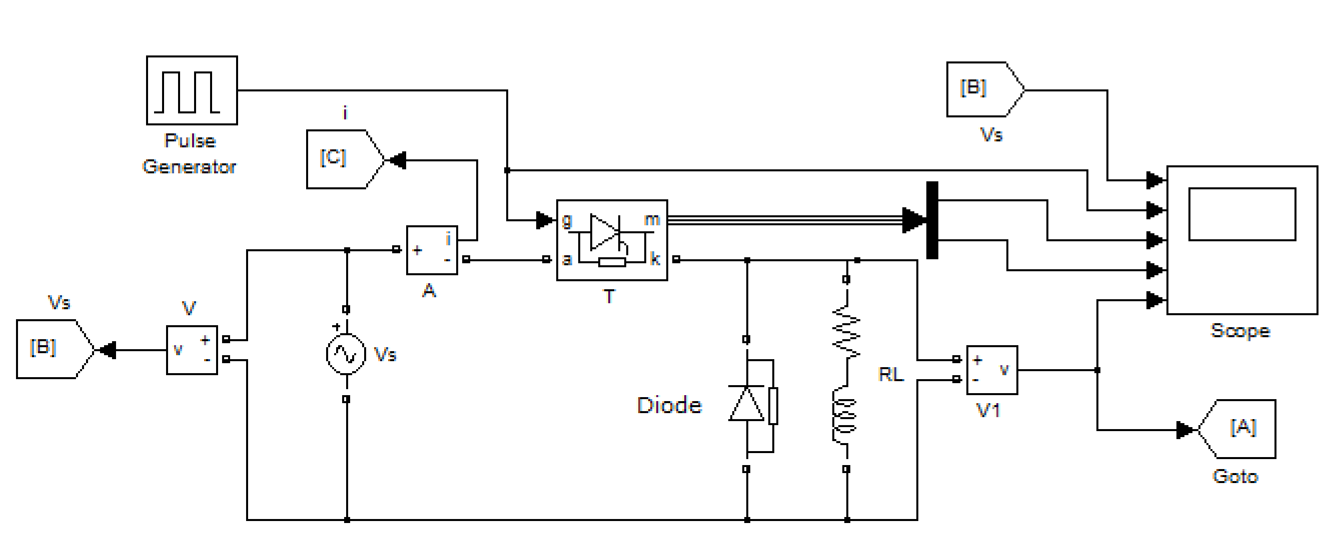
Single-phase half-wave rectifiers pass voltage across a single diode. In this circuit, only the positive half of the AC input voltage transmits to the output across the load resistor. If the diode is reversed, only the negative half of the AC input voltage would appear across the resistor.

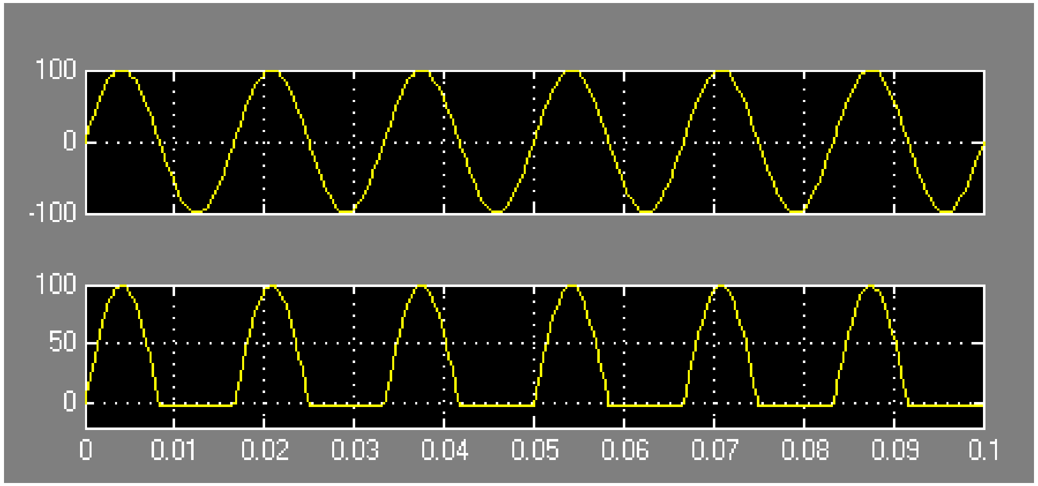


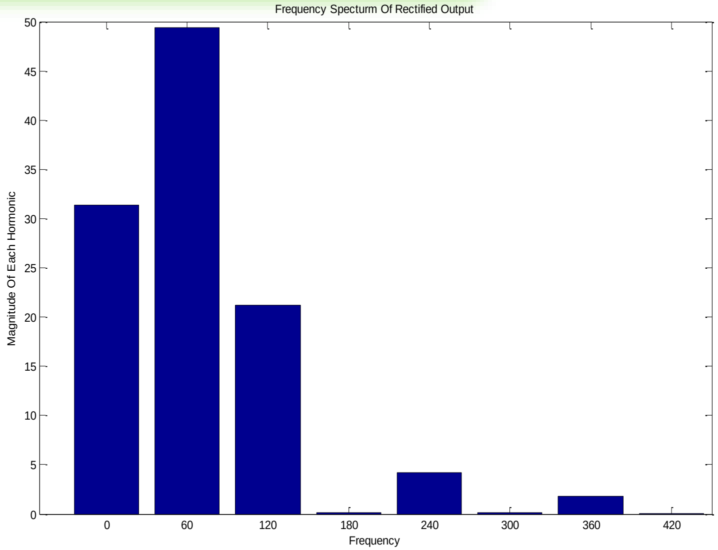
Single-Phase Half-wave Uncontrolled Rectifier with R-Load

Conversion

Single Phase Half wave Rectifier



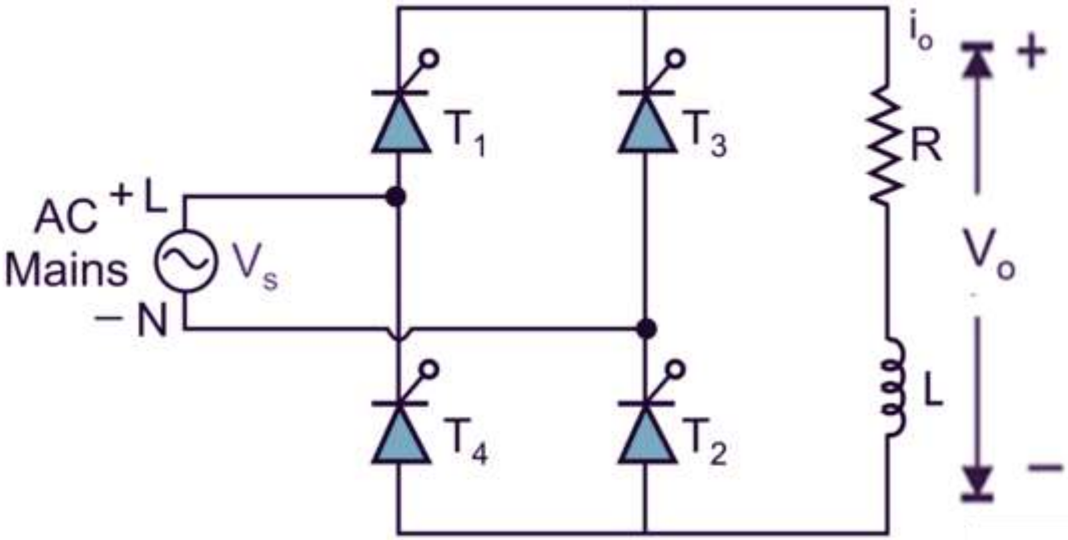




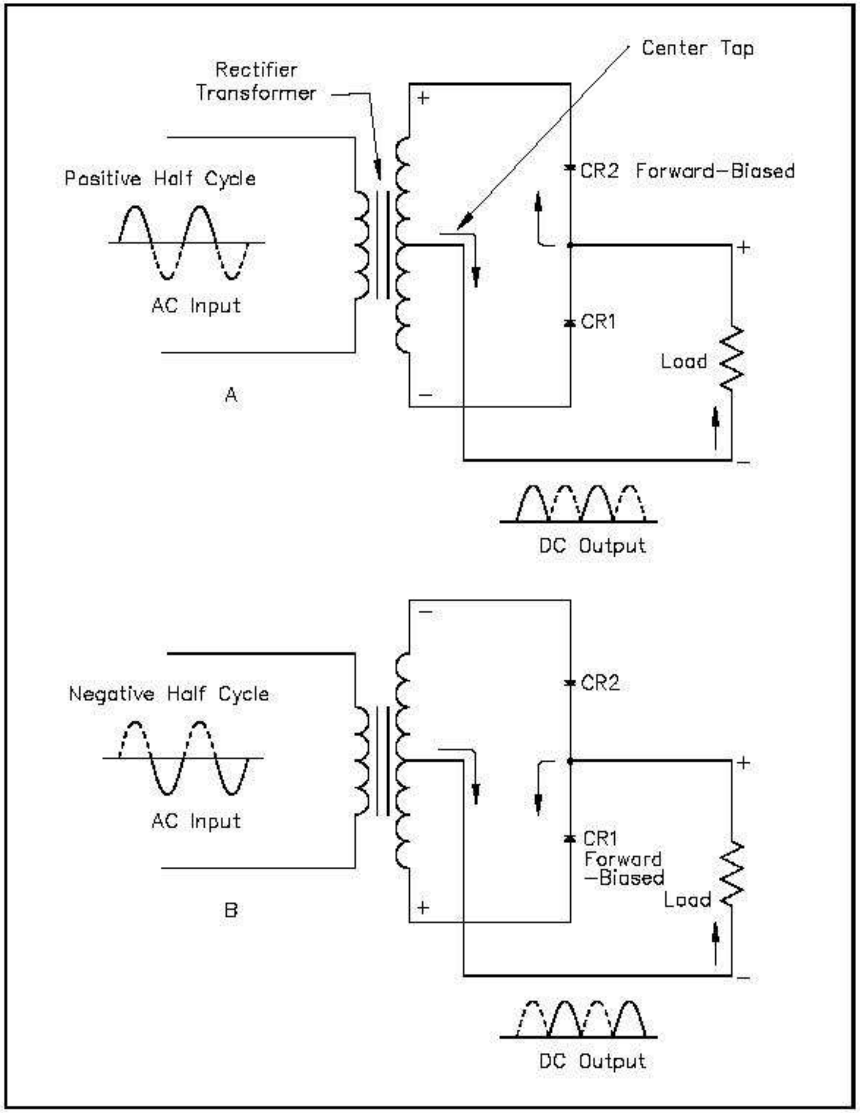
Conversion

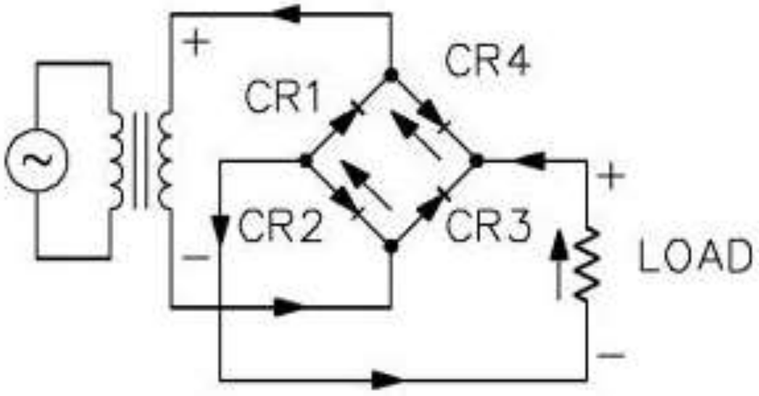
Single Phase Full wave Rectifier

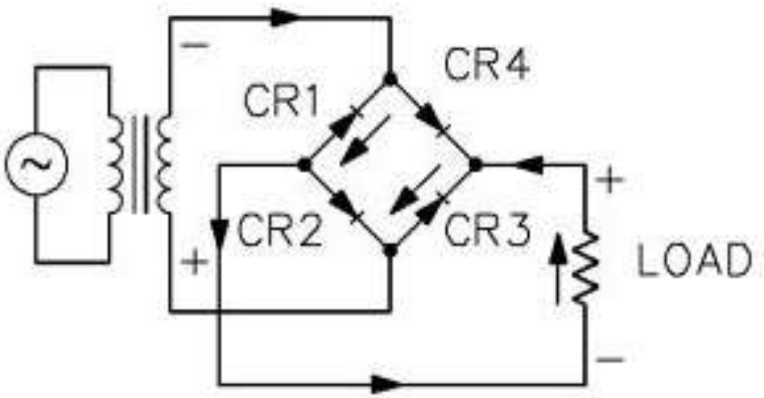
Single Phase Full Wave Controlled Rectifier (or Converter) both positive and negative halves of AC supply are used and, therefore, the effective value of DC voltage is increased and ripple content is reduced compared to half-wave rectifiers.



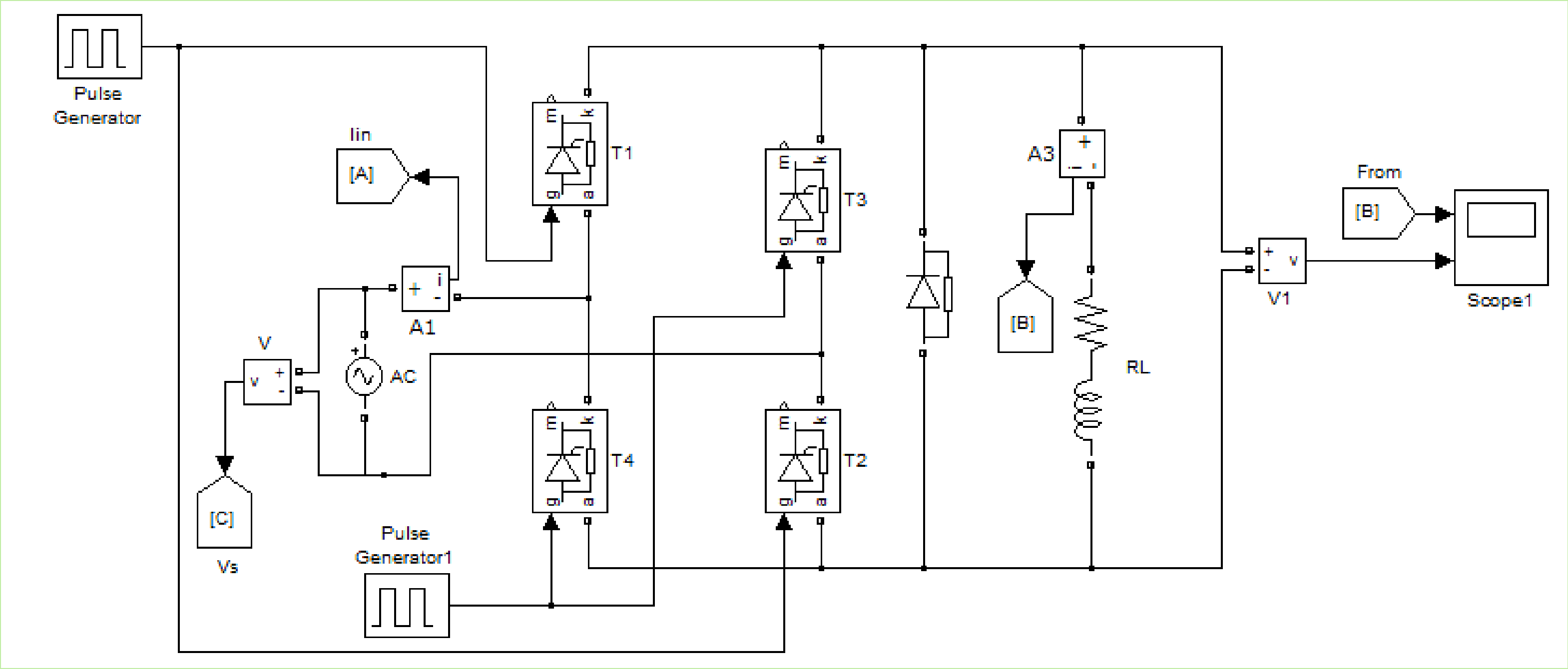
Single Phase Full wave Rectifier

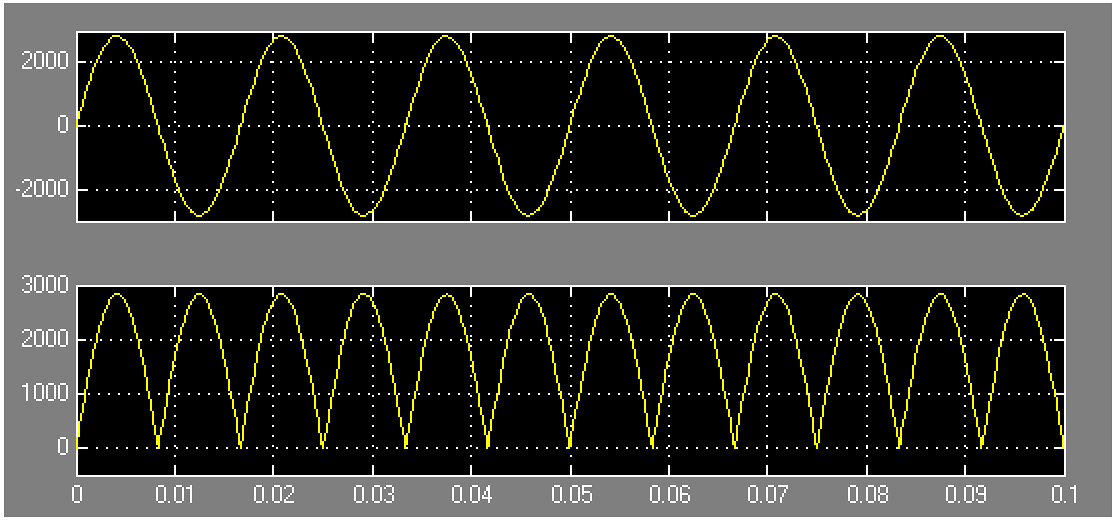


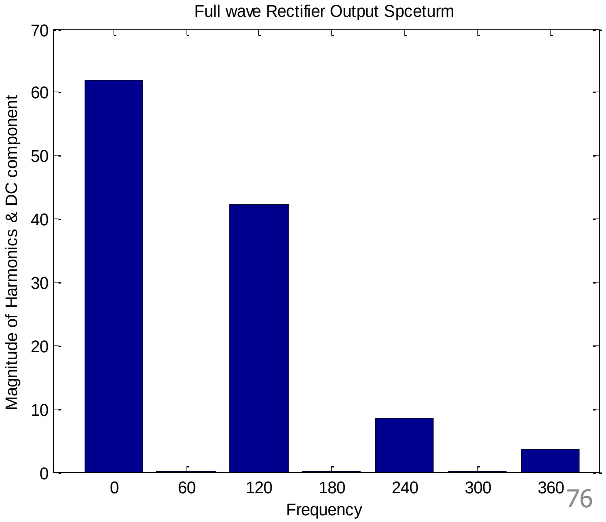




Single Phase Full wave Rectifier







Six Pulse Rectifier

The term "6-pulse" refers to the number of diodes used in the rectifier circuit of the VFD. In a 6-pulse VFD, the rectifier circuit is made up of six diodes that convert the incoming AC power into DC power, which is then used to drive the motor.

Six Pulse Rectifier

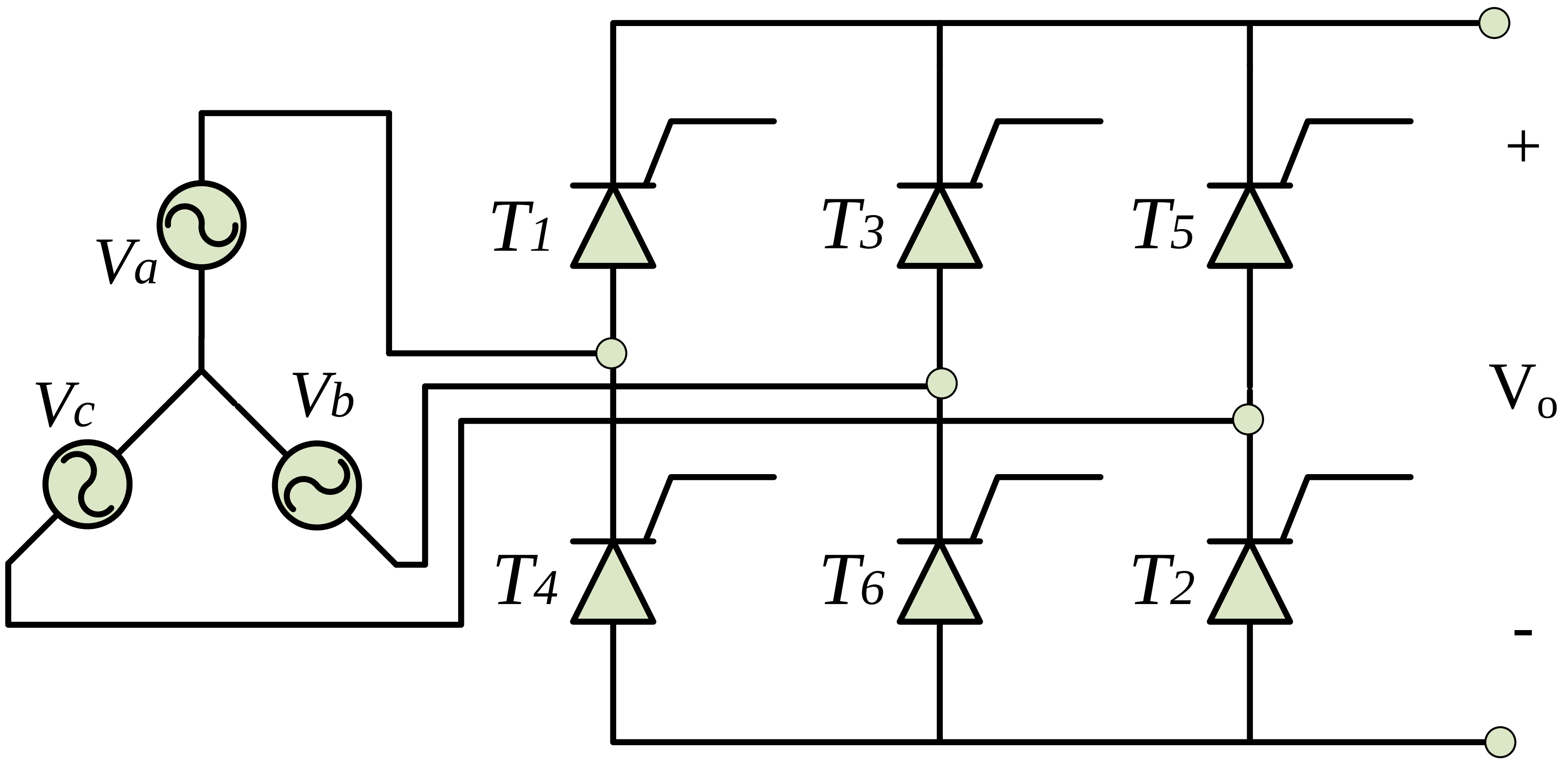


Fig : Six Pulse Rectifier

Six Pulse Rectifier

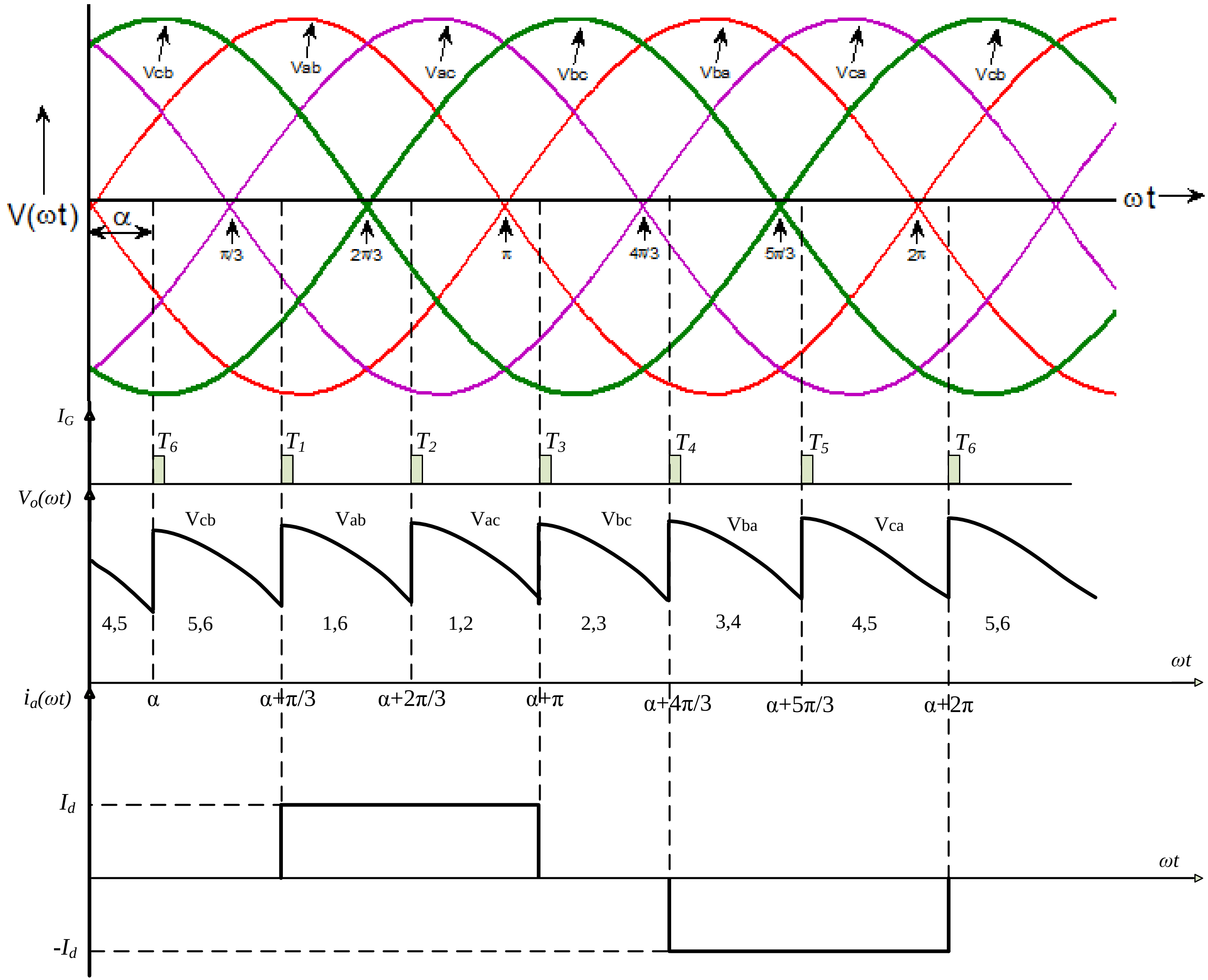
The operating principle of the circuit is that, the pair of SCR connected between the lines having highest amount of line-to-line voltage will conduct provided that the gate signal is applied to SCRs at that instant.

Between $0 \leq \omega t \leq \pi/3$ the highest line-to-line voltage is V_{cb}, with T_4 & T_5 intially conducting. By firing T_6 at delay angle of α, results V_{cb} at load

The converters are called Line Commutated converters or current source converter.

Every 60º one Thyristor from +ve limb and one Thyristor from –ve limb is triggered

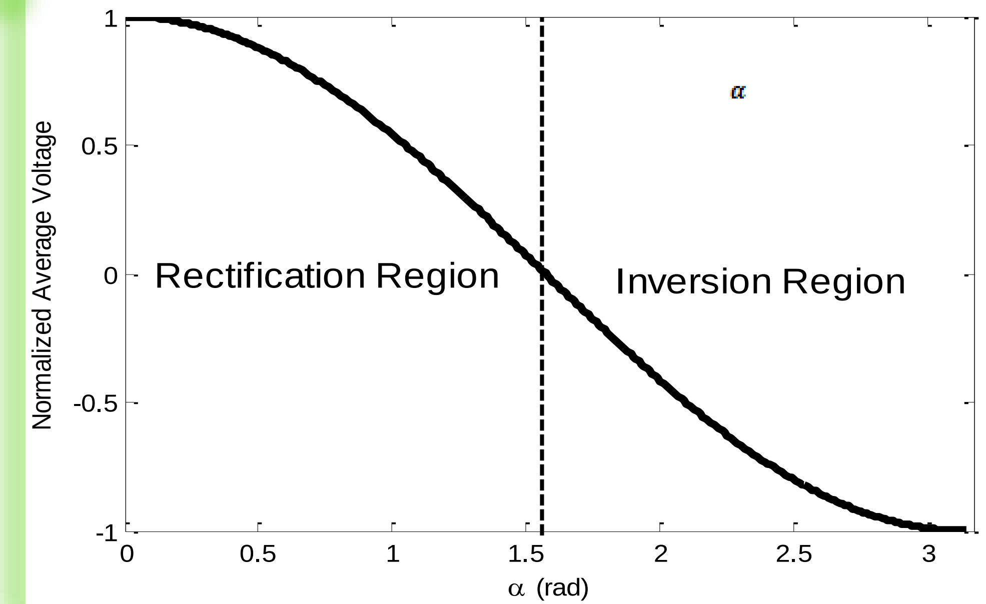
Six Pulse Rectifier Waveforms



Operation of Six Pulse Rectifier

It can be seen from Fig that for $\alpha = \pi/3$ the rectified output voltage reaches zero crossing. If α is increased beyond $\pi/3$ i.e. $\alpha > \pi/3$, the load voltage becomses discontinous for resistive load where as for inductive load the negative voltage appears across load.

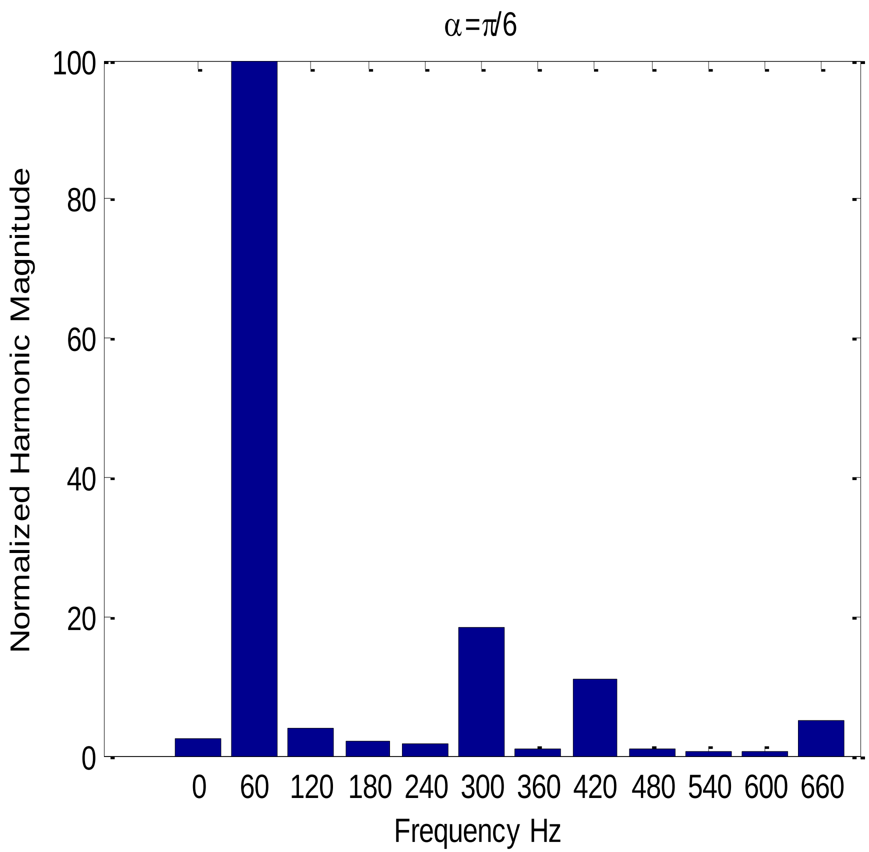
$$V_n = \frac{V_{dc}}{V_{dm}} \cos(\alpha)$$



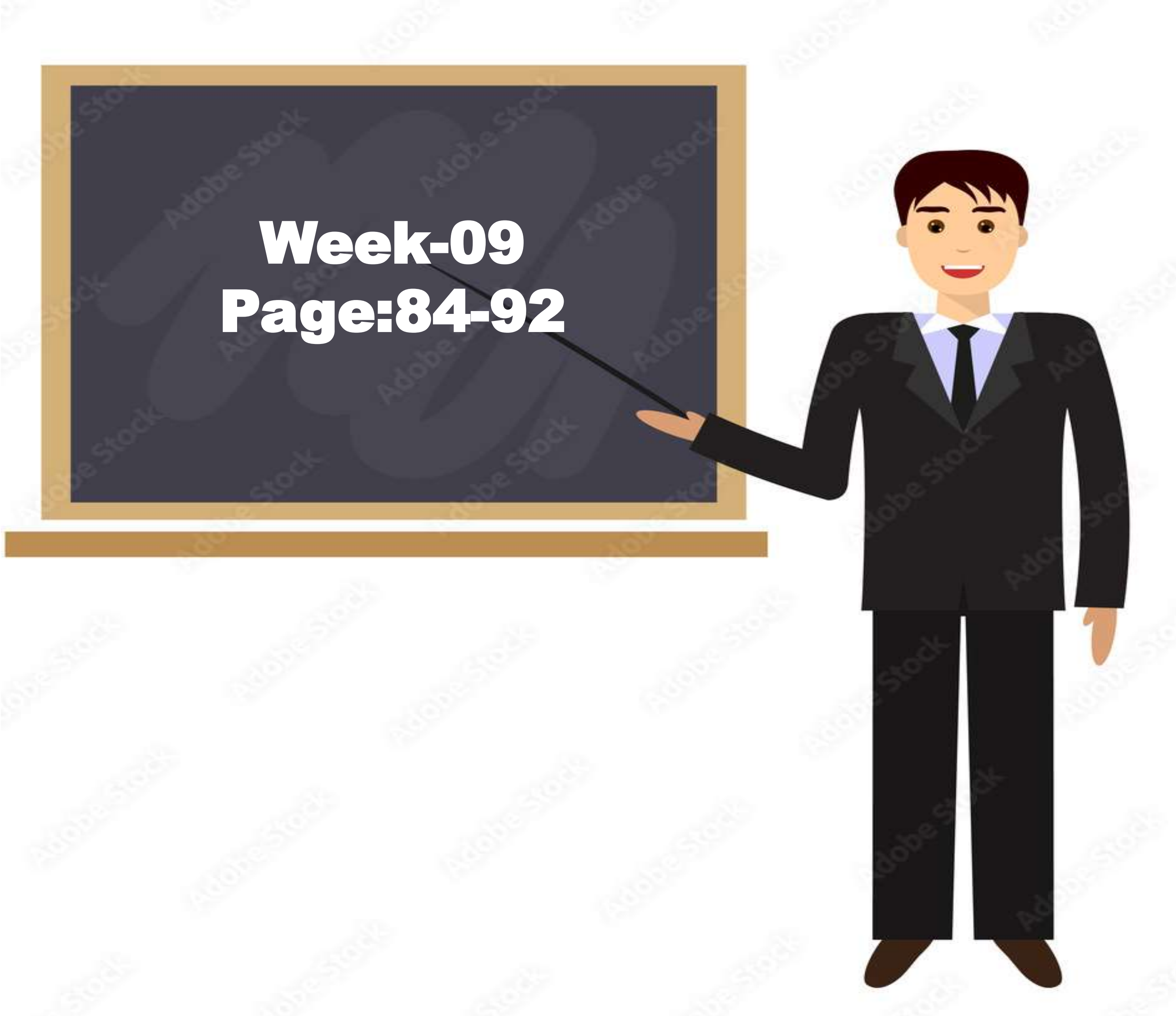
Normalized Average (DC) Voltage as function

Fig shows that by varying α between $0 \; to \; {}^{\pi}/_{2}$ output varies between 1 & 0 i.e. rectification region and by varying α between ${}^{\pi}/_{2} \; to \; \pi$ output varies between $0 \; \& -1$ i.e. inversion region. Rectification region is represented by 1st Quardant and inversion region by 4th Quardant resulting in 2 Quardant operation.

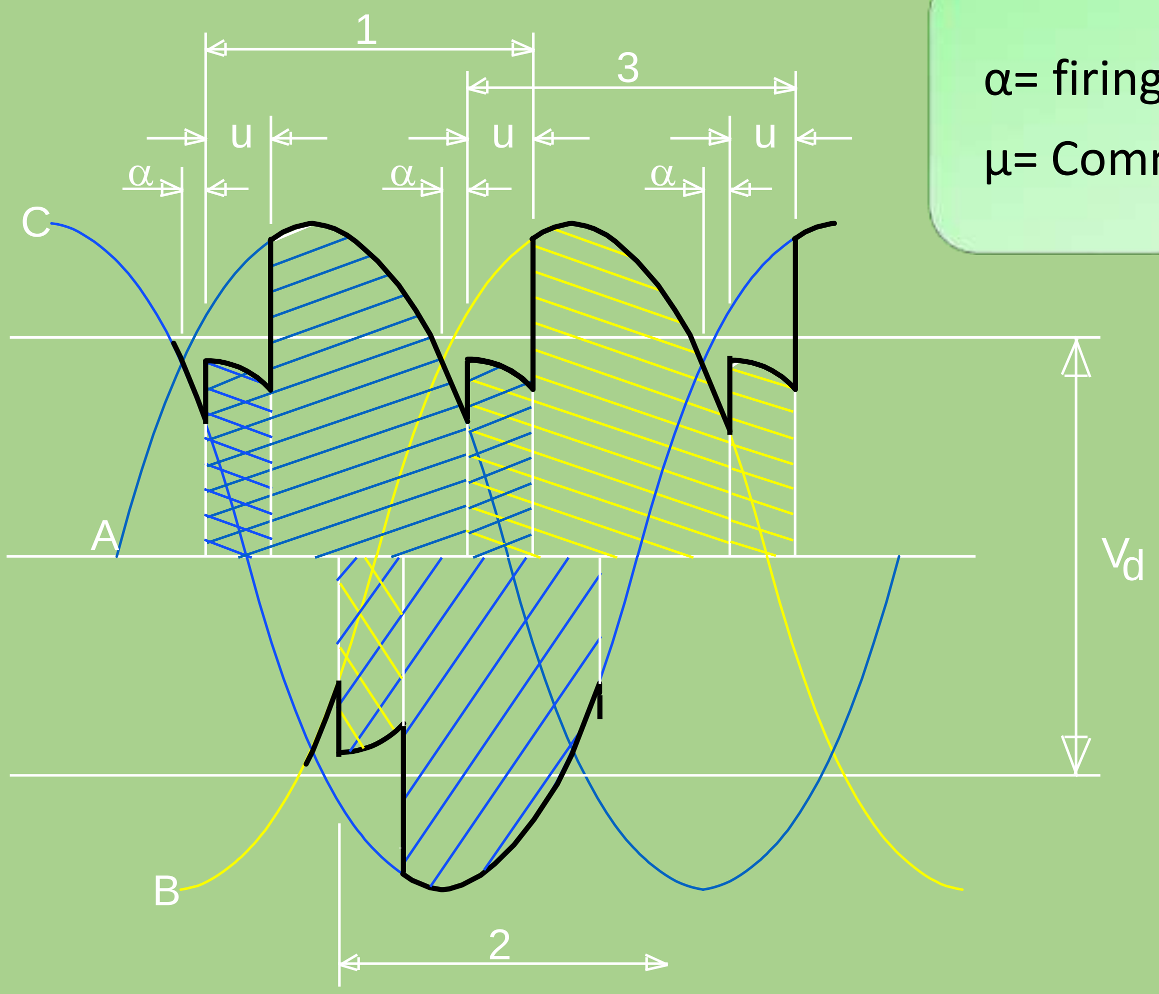
$$P.F = 0.9 \; \cos(\alpha)$$



Specturm at alpha=pi/6


Week-09
Page:84-92

Effect of Control Angel

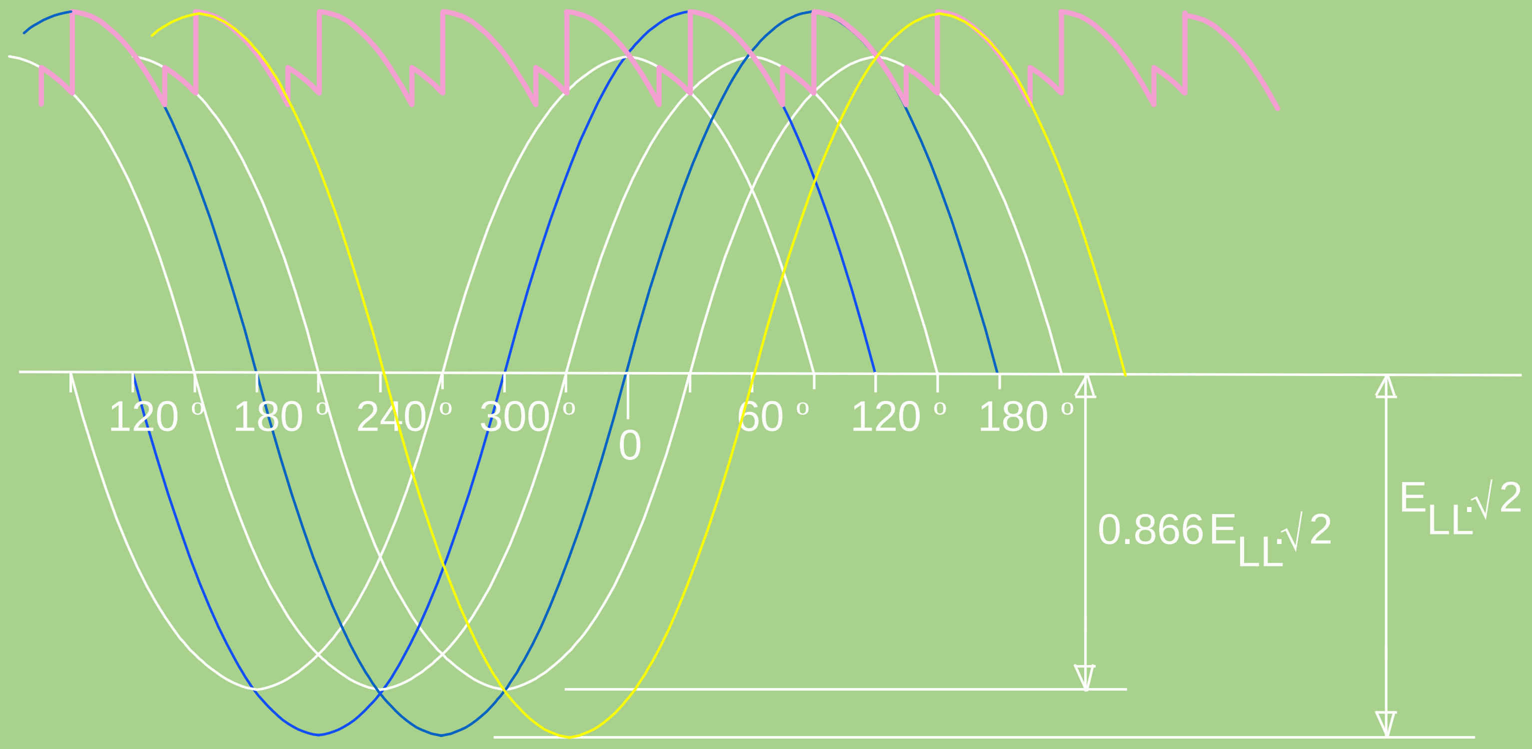


α= firing Angle

μ= Commutation Interval

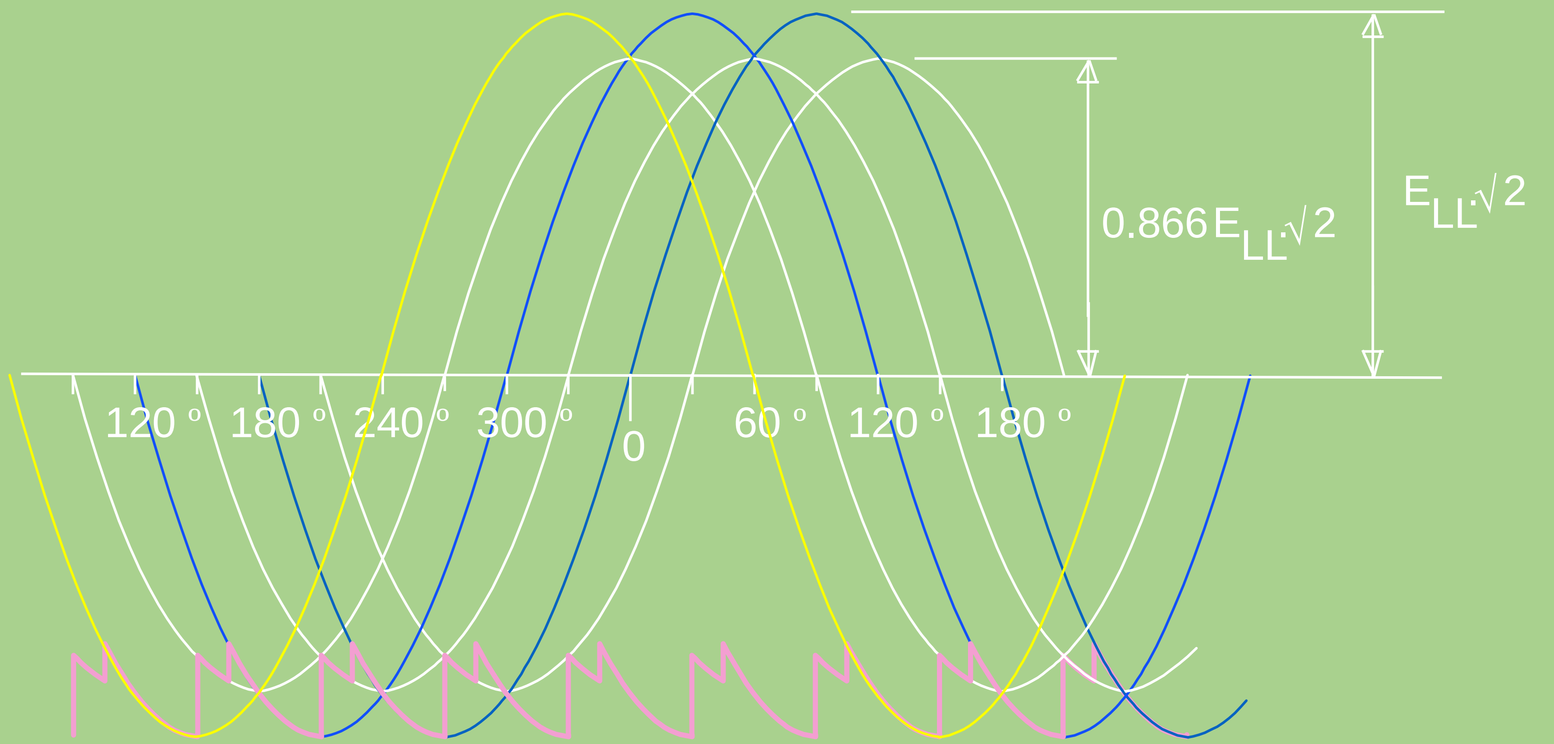
DC Terminal Voltage

RECTIFICATION



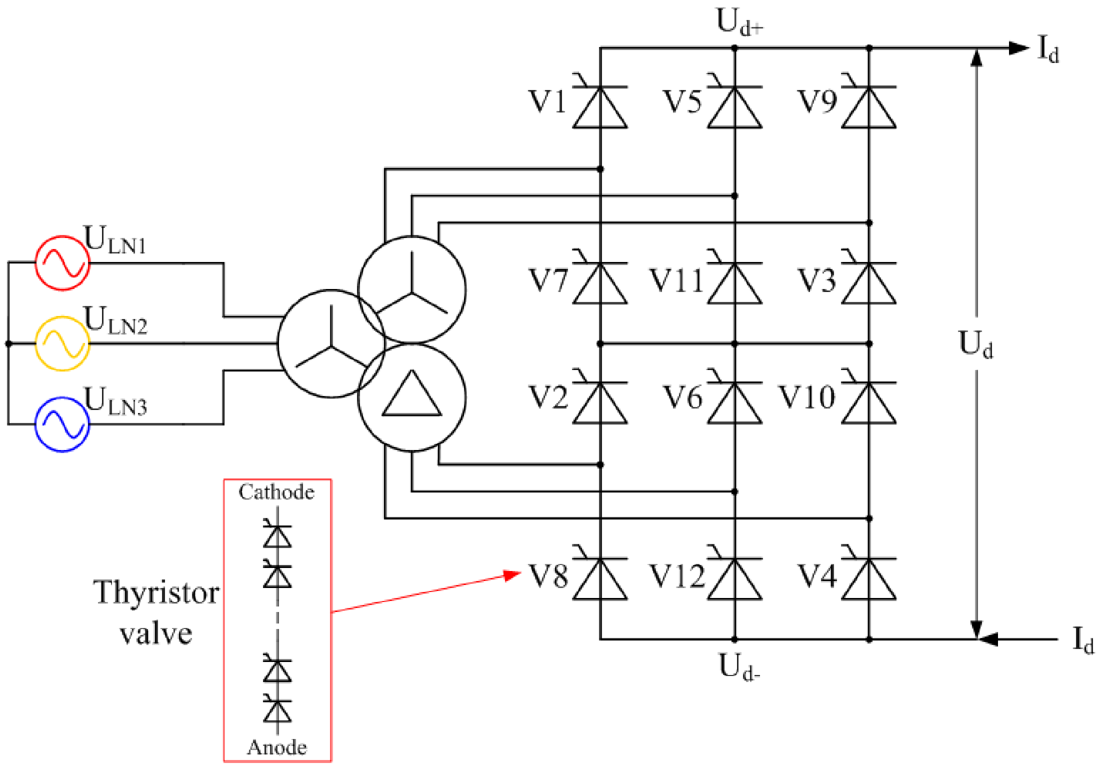
DC Terminal Voltage

INVERSION



12-Pulse Convertr Bridge

A 12-pulse bridge converter is made up of two six-pulse bridge circuits that are connected in parallel or series. The AC connections of the two bridges are fed from a supply transformer that produces a 30° phase shift between them. This phase shift cancels out many of the harmonics that the six-pulse bridges produce



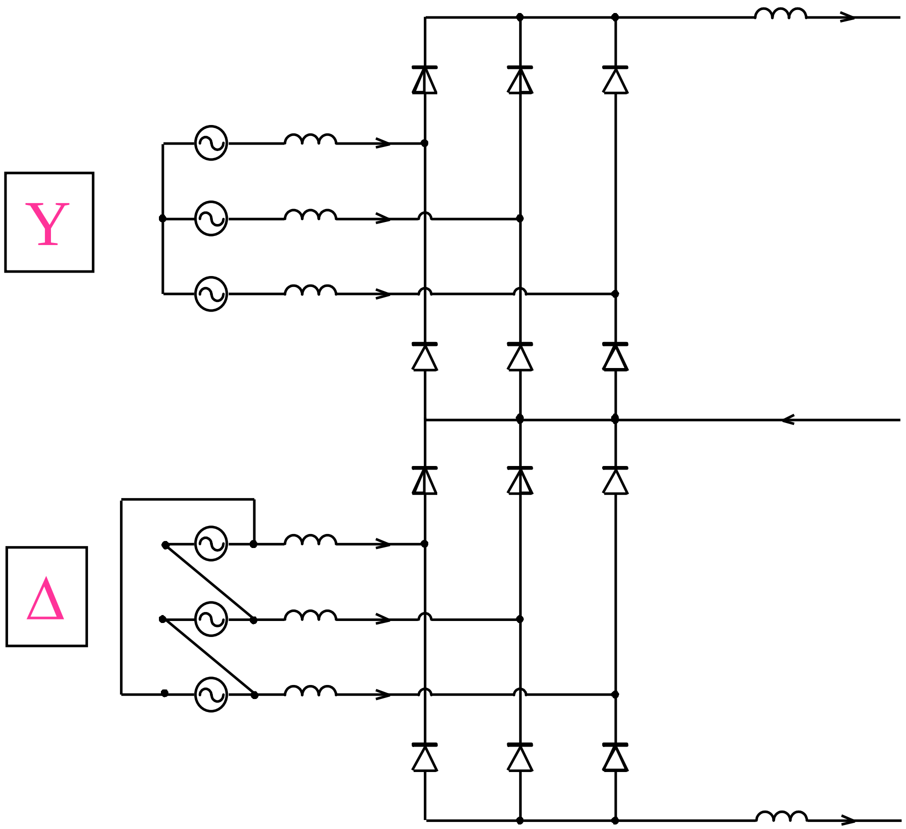
12-Pulse Converter Bridge

Here are some advantages of a 12-pulse converter:

- **Reduced ripple content**: The ripple content of the AC voltage is reduced significantly.
- **Improved power factor**: The value of g increases, which effectively improves the power factor.

However, increasing the number of pulses can be offset by the complexity of the transformer connection and the difficulty of maintaining balance in the system. For this reason, it's not recommended to increase the pulse number beyond 12 or 24.

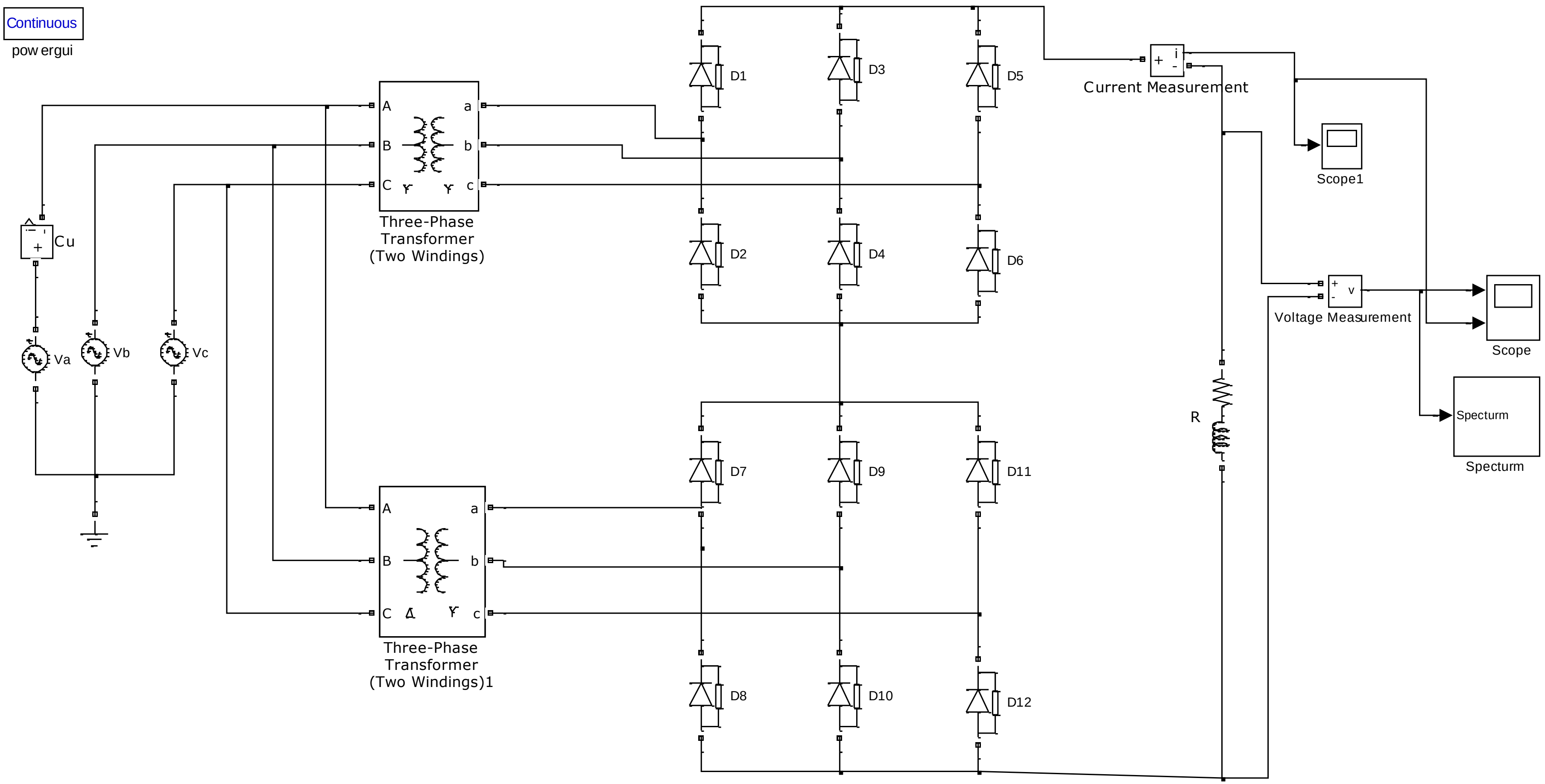
12-Pulse Converter Bridge



Δ Give π/6 phase shift with respect to Y

Commonly Used in HVDC systems

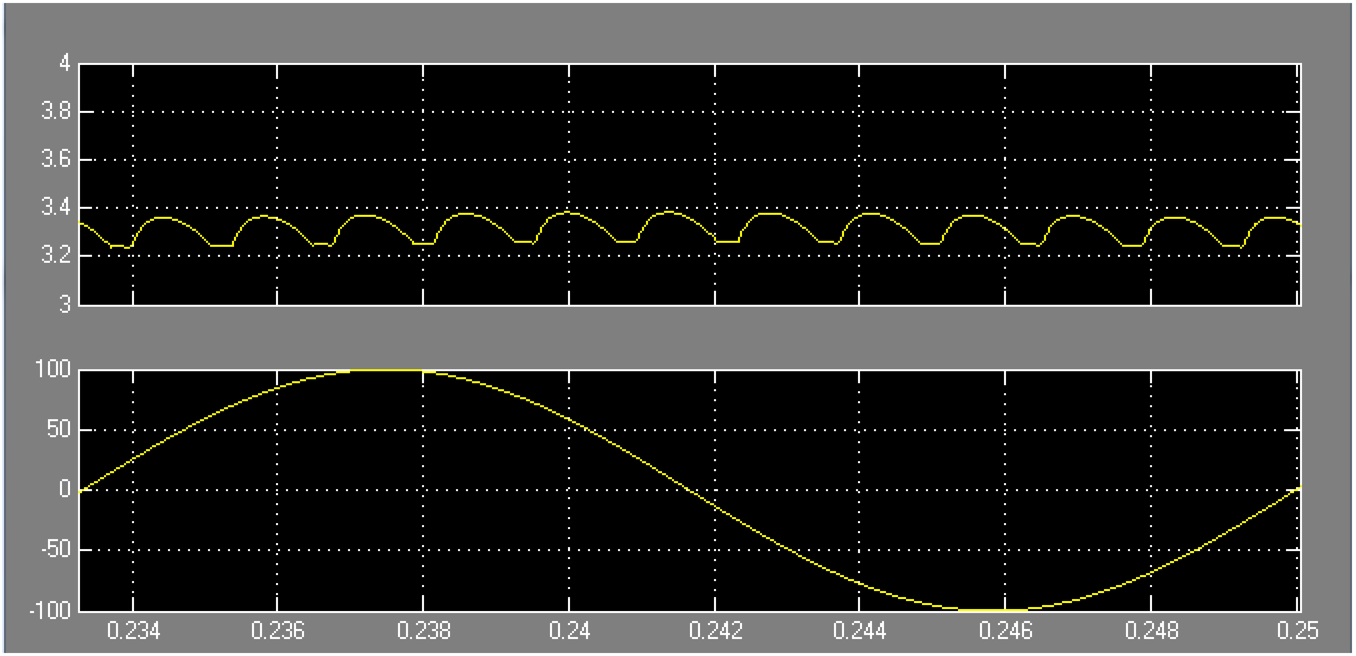
12-Pulse Convertor Bridge



Matlab Model of 12 Pulse Rectifier

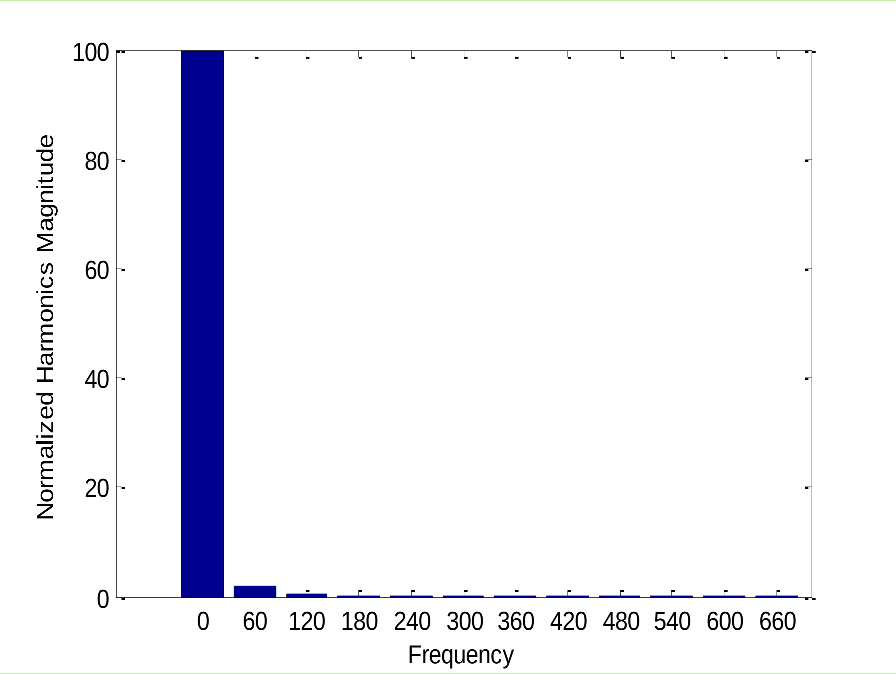
12-Pulse Convertor Bridge

- Commonly adopted in all HVDC applications
- Two 6 pulse bridges connected in series
- 30º phase shift between Star and Delta windings of the converter transformer
- Due to this phase shift, 5^{th} and 7^{th} harmonics are reduced and filtering higher order harmonics is easier
- Higher pulse number than 12 is not economical



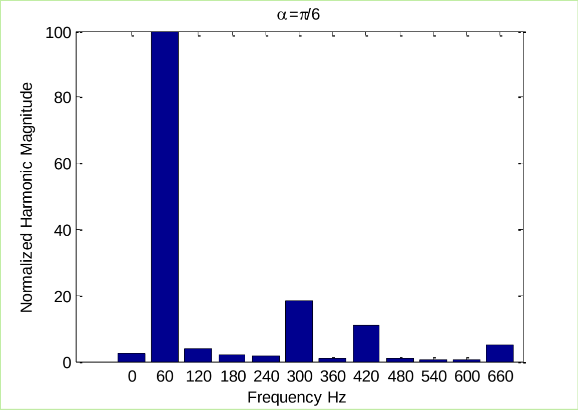
12-Pulse Convertor Bridge

- From Voltage spectrum it can be seen that by using 12 pulse, nearly harmonic free DC output is obtained.

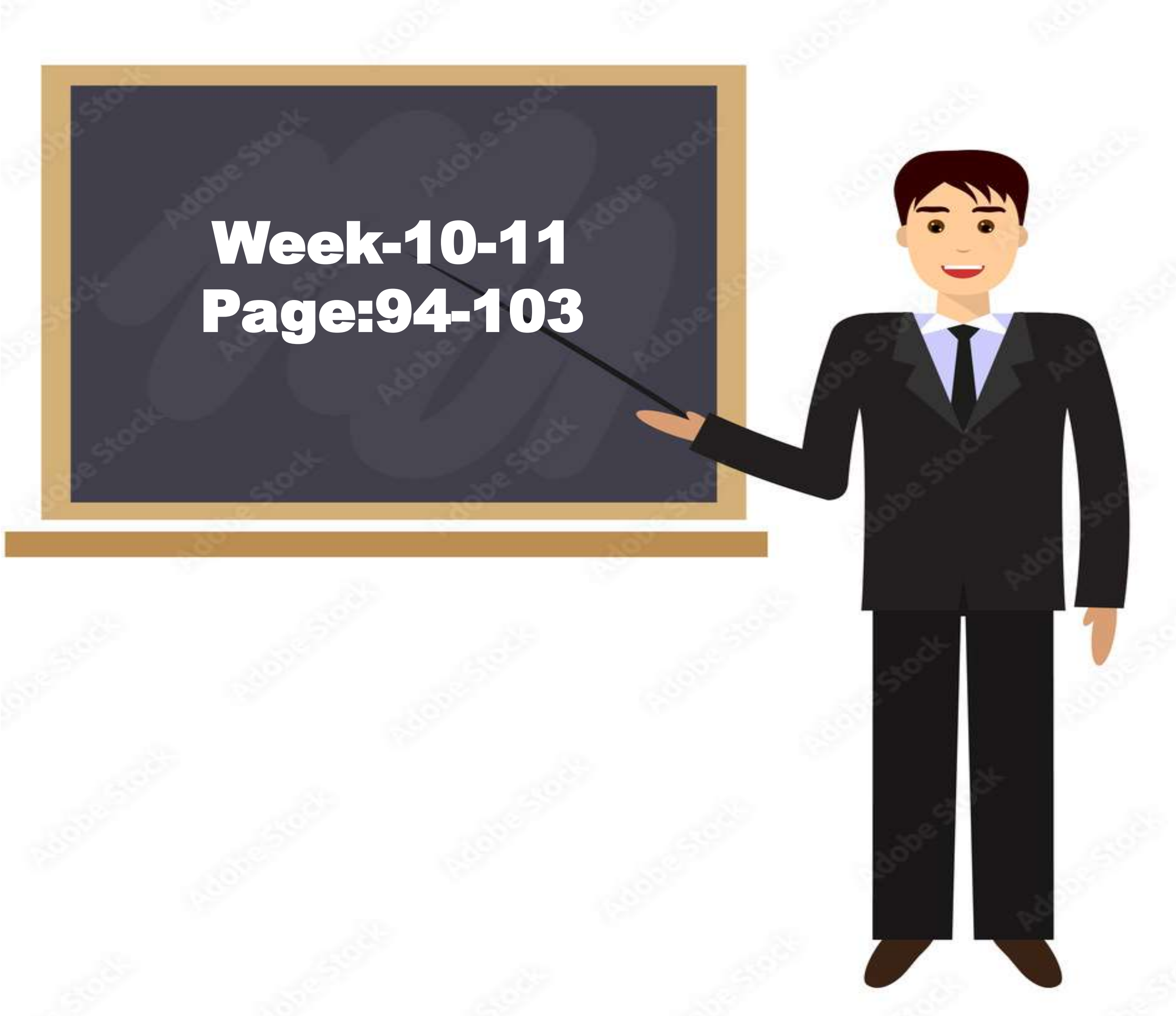


12 Pulse Rectifier Normalized output Voltage Spectrum

α	Displacement Factor	Distortion Factor	Power Factor
$\pi/6$	0.7583	0.9755	0.7397
$\pi/4$	0.6391	0.9677	0.6185
$\pi/3$	0.4873	0.9556	0.4656

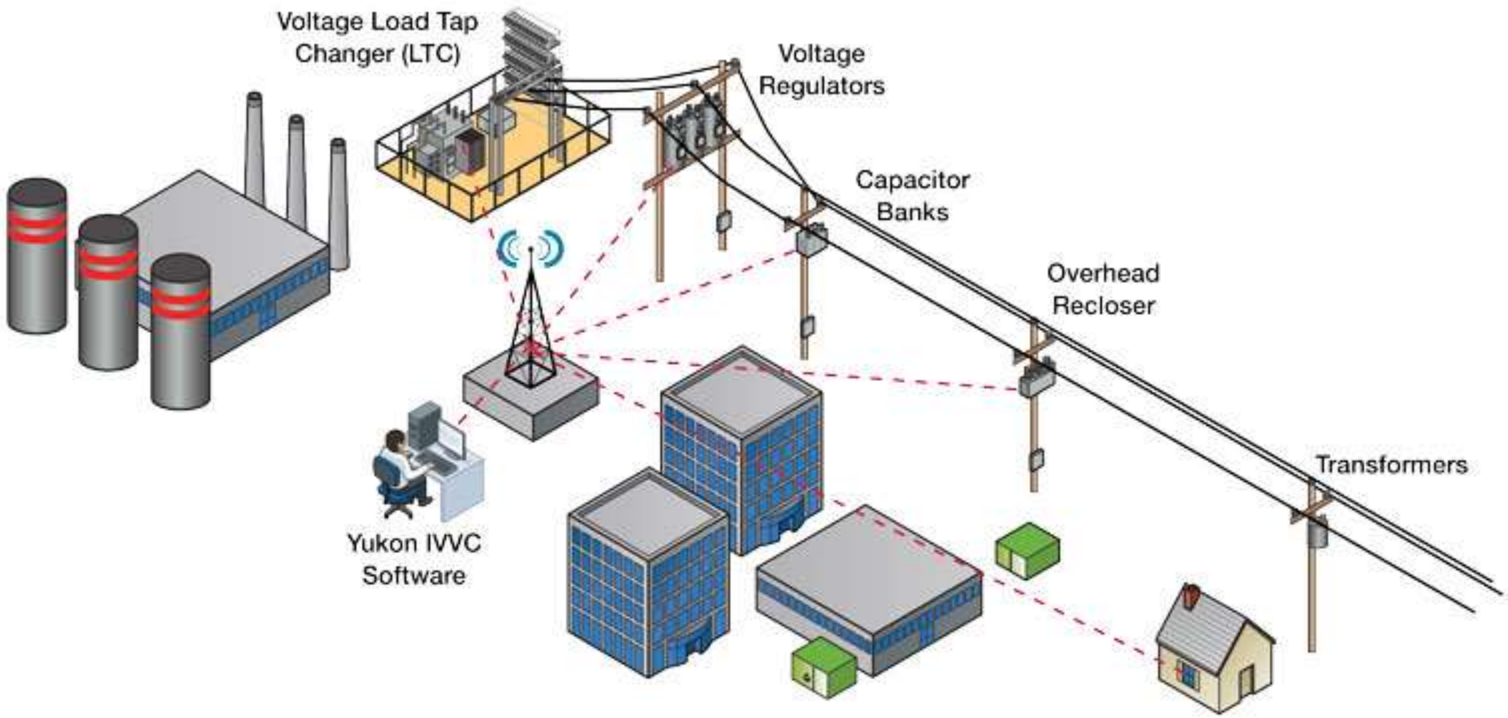


12 Pulse Rectifier Normalized input current Spectrum for $\alpha = \pi/6$


Week-10-11
Page:94-103

Control of DC Voltage

DC voltage is often preferred for control circuits because it has several advantages over AC voltage, including: No inrush current, No need for a large UPS or costly inverter circuit, No harmonics, High reliability, and Lower maintenance costs.



Control of DC Voltage

DC voltage in a power system is controlled in several ways, including:

Pulse Width Modulation (PWM): A conventional controller that adjusts the output voltage by manipulating the duty cycle of the PWM signal.

Digital compensators: Used in most power converters and inverters, these are a result of the widespread development of digital microprocessors.

Proportional–Integral–Derivative (PID) compensators: A well-known PWM-based controller in DC–DC converters.

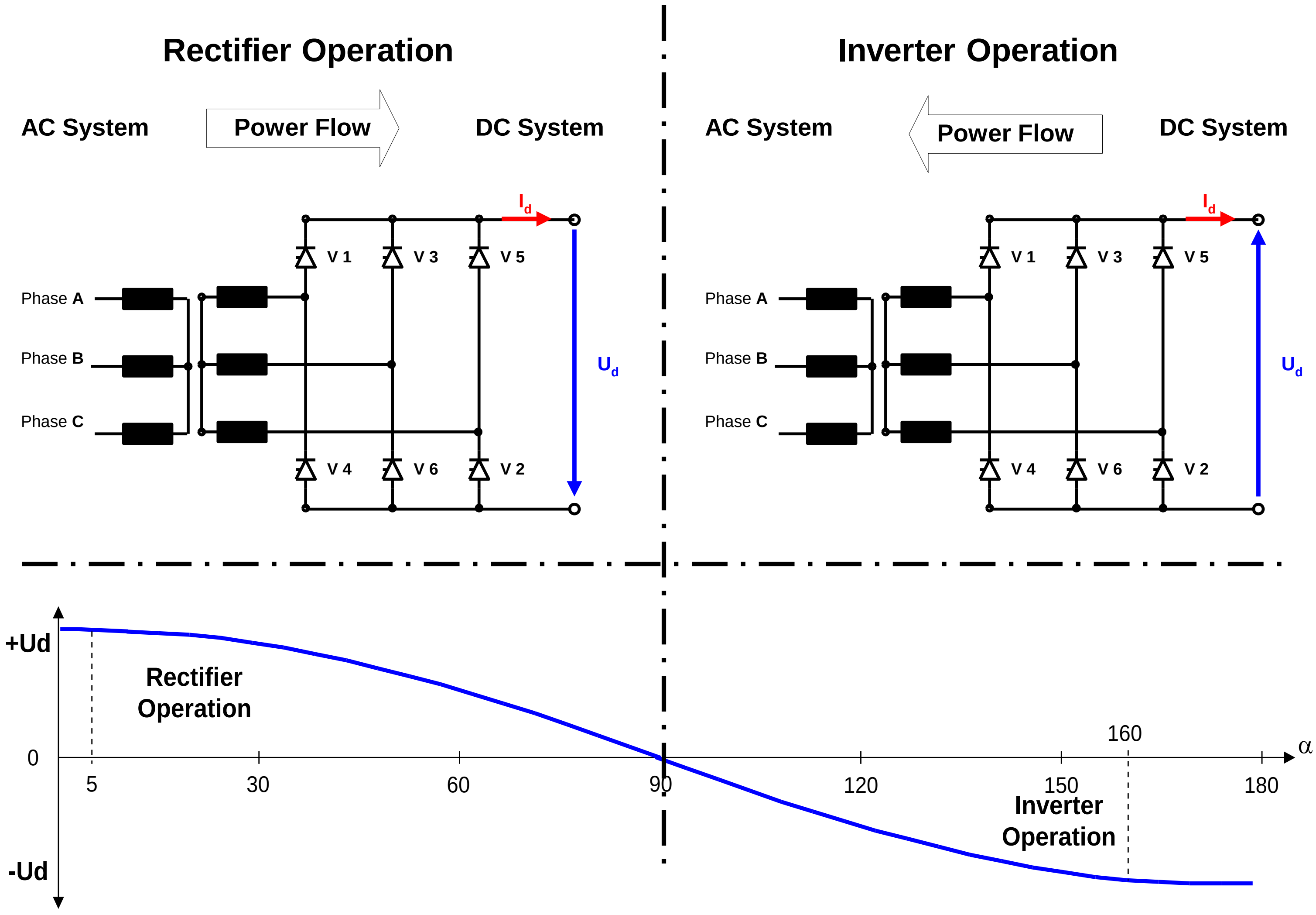
Series or shunt regulators: Simple DC power supplies use these to regulate voltage.

Control of DC Voltage

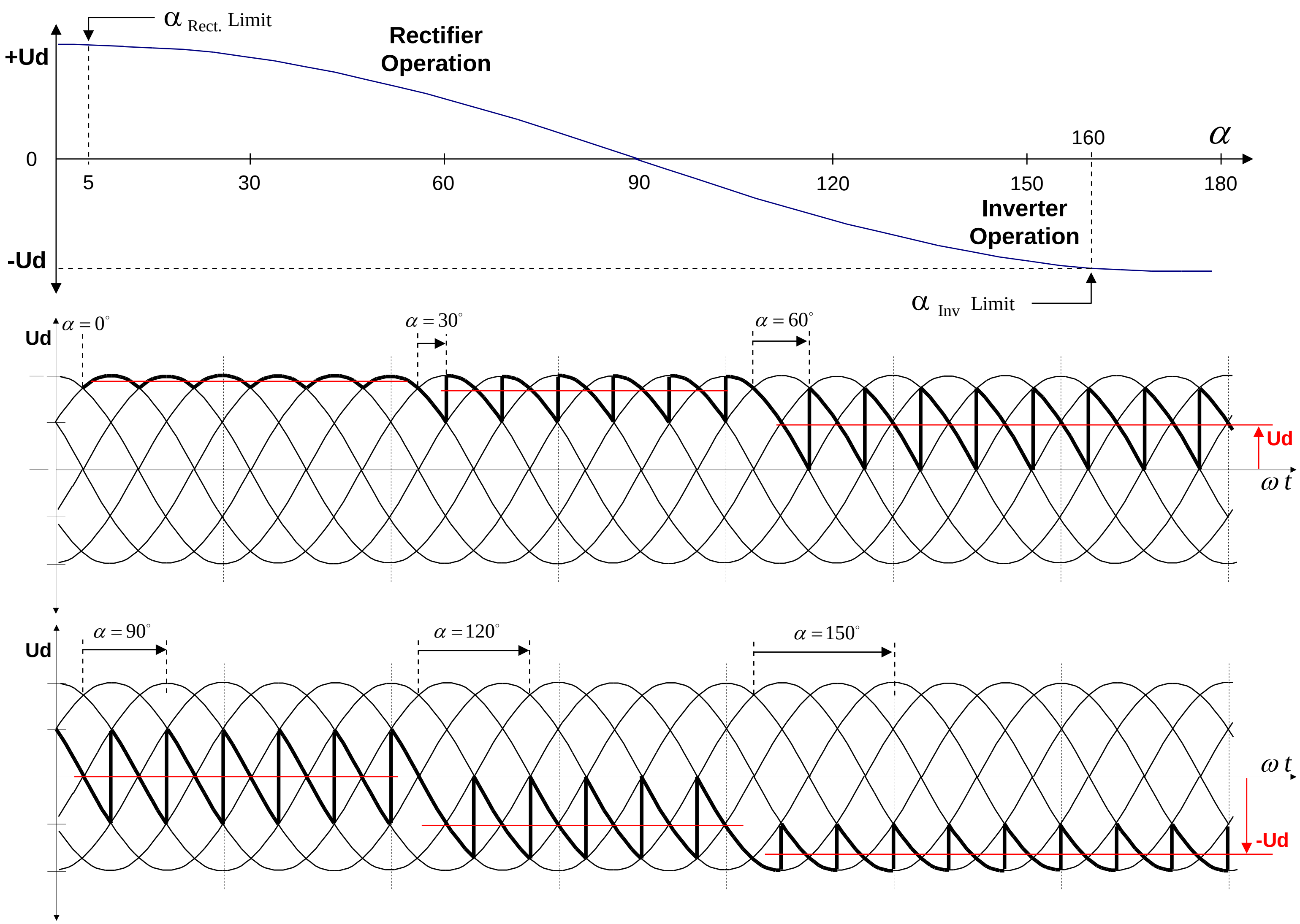
Voltage reference: Most DC power supplies use a shunt regulator, such as a Zener diode, avalanche breakdown diode, or voltage regulator tube, to apply a voltage reference.

Controllers and actuators: Controllers remotely operate actuators, such as tap-changer transformers and switched capacitor banks, to maintain voltage levels.

Control of DC Voltage



Relationship of DC Voltage Ud and Firing Angle α



How does HVDC Works?

Definition: High voltage direct current (HVDC) power systems use D.C. for transmission of bulk power over long distances. For long-distance power transmission, HVDC lines are less expensive, and losses are less as compared to AC transmission. It interconnects the networks that have different frequencies and characteristics.

In AC transmission, alternating waves of voltage and current travels in the line which change its direction every millisecond; due to which losses occur in the form of heat. Unlike AC lines, the voltage and current waves don't change their direction in DC. HVDC lines increase the efficiency of transmission lines due to which power is rapidly transferred.

How does HVDC Works?

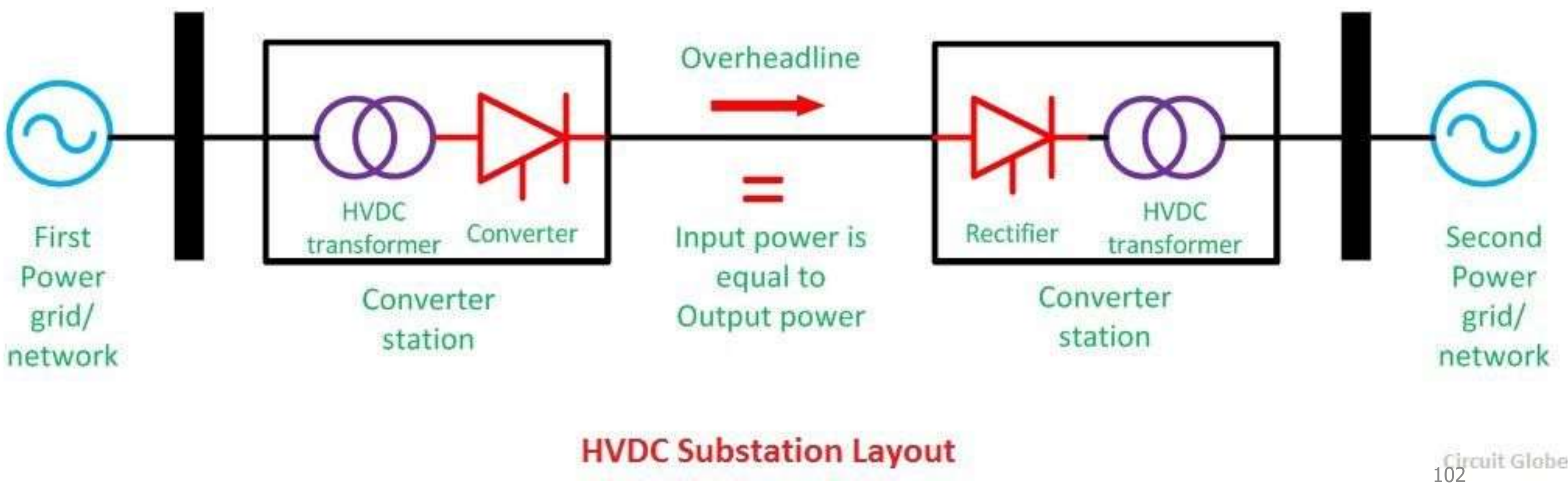
In a combined AC and DC system, generated AC voltage is converted into DC at the sending end. Then, the DC voltage is inverted to AC at the receiving end, for distribution purposes. Thus, the conversion and inversion equipment are also needed at the two ends of the line. HVDC transmission is economical only for long distance transmission lines having a length more than 600kms and for underground cables of length more than 50kms.

How does HVDC Works?

In generating substation, AC power is generated which can be converted into DC by using a rectifier. In HVDC substation or converter substation rectifiers and inverters are placed at both the ends of a line. The rectifier terminal changes the AC to DC, while the inverter terminal converts DC to AC.

How does HVDC Works?

The DC is flowing with the overhead lines and at the user end again DC is converted into AC by using inverters, which are placed in converter substation. The power remains the same at the sending and receiving ends of the line. DC is transmitted over long distances because it decreases the losses and improves the efficiency.



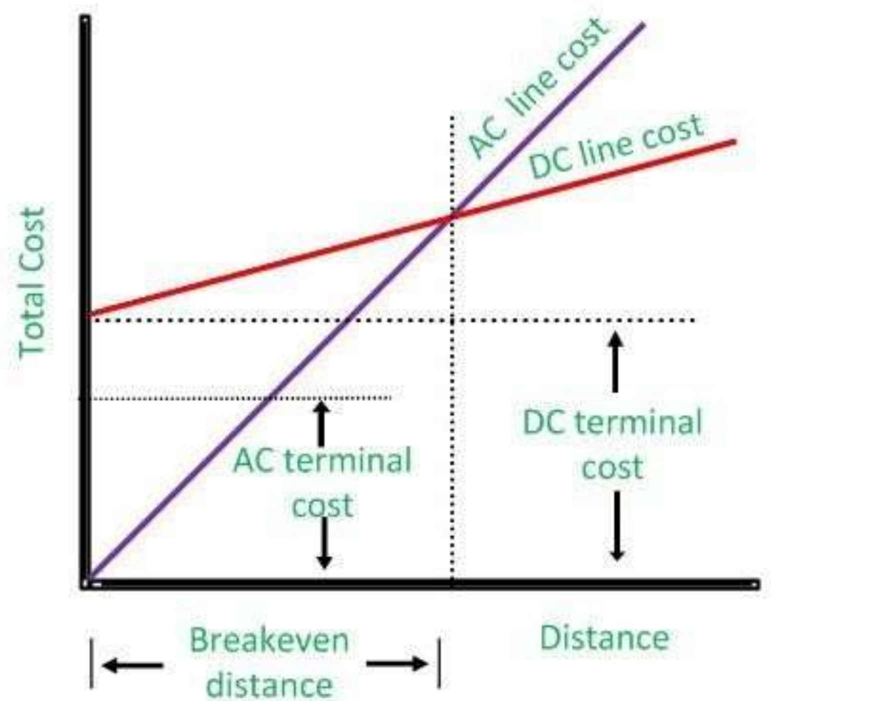
How does HVDC Works?

A system having more than two converter stations and one transmission line is called a ‘two terminal DC system’ or a ‘point-to-point system’. Similarly, if substation has more than two converter stations and interconnecting DC terminal lines, it is called multiterminal DC substation.


Week-12
Page:104-111

Economic Distance For HVDC transmission lines

DC lines are cheaper than the AC lines, but the cost of DC terminal equipment is very high as compared to AC terminal cables (shown in the graph below). Thus, the initial cost is high in HVDC transmission system, and it is low in the AC system.



Comparision of the costs of AC and DC transmission

Economic Distance For HVDC transmission lines

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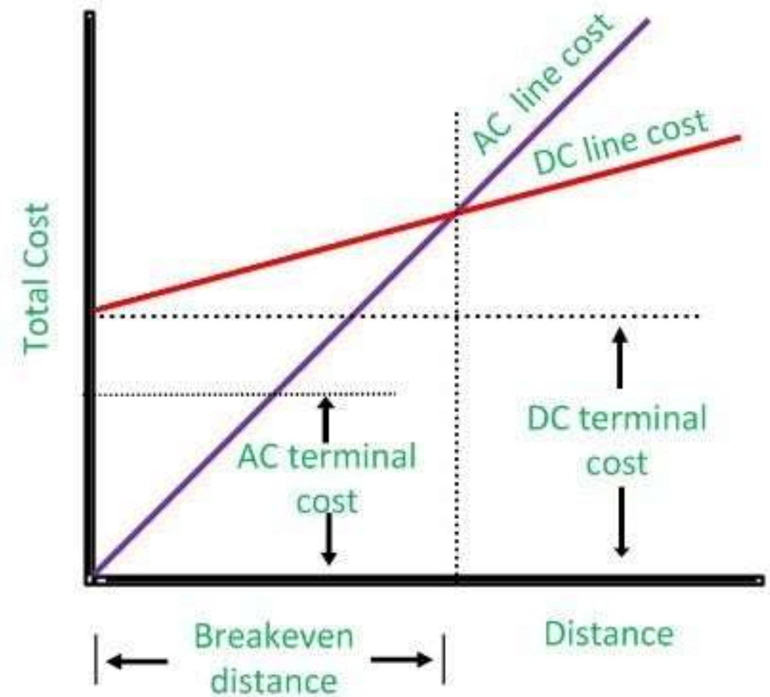


Comparision of the costs of AC and DC transmission

Economic Distance For HVDC transmission lines

The point where two curves meet is called the breakeven distance. Above the breakeven distance, the HVDC system becomes cheaper. Breakeven distance changes from 500 to 900 km in overhead transmission lines.

Advantages of HVDC transmissions

1. A lesser number of conductors and insulators are required thereby reducing the cost of the overall system.

2.It requires less phase to phase and ground to ground clearance.

3.Their towers are less costly and cheaper.

4.Lesser corona loss is less as compared to HVAC transmission lines of similar power.

5.Power loss is reduced with DC because fewer numbers of lines are required for power transmission.

Advantages of HVDC transmissions

6. The HVDC system uses earth return. If any fault occurs in one pole, the other pole with 'earth returns' behaves like an independent circuit. This results in a more flexible system.

7. The HVDC has the asynchronous connection between two AC stations connected through an HVDC link; i.e., the transmission of power is independent of sending frequencies to receiving end frequencies. Hence, it interconnects two substations with different frequencies.

8. Due to the absence of frequency in the HVDC line, losses like skin effect and proximity effect does not occur in the system.

9. It does not generate or absorb any reactive power. So, there is no need for reactive power compensation.

10. The very accurate and lossless power flows through DC link.

Disadvantages of HVDC transmissions

1.Converter substations are placed at both the sending and the receiving end of the transmission lines, which result in increasing the cost.

2.Inverter and rectifier terminals generate harmonics which can be reduced by using active filters which are also very expensive

3. If a fault occurs in the AC substation, it may result in a power failure for the HVDC substation placed near to it

4. Inverter used in Converter substations have limited overload capacity.

Disadvantages of HVDC transmissions

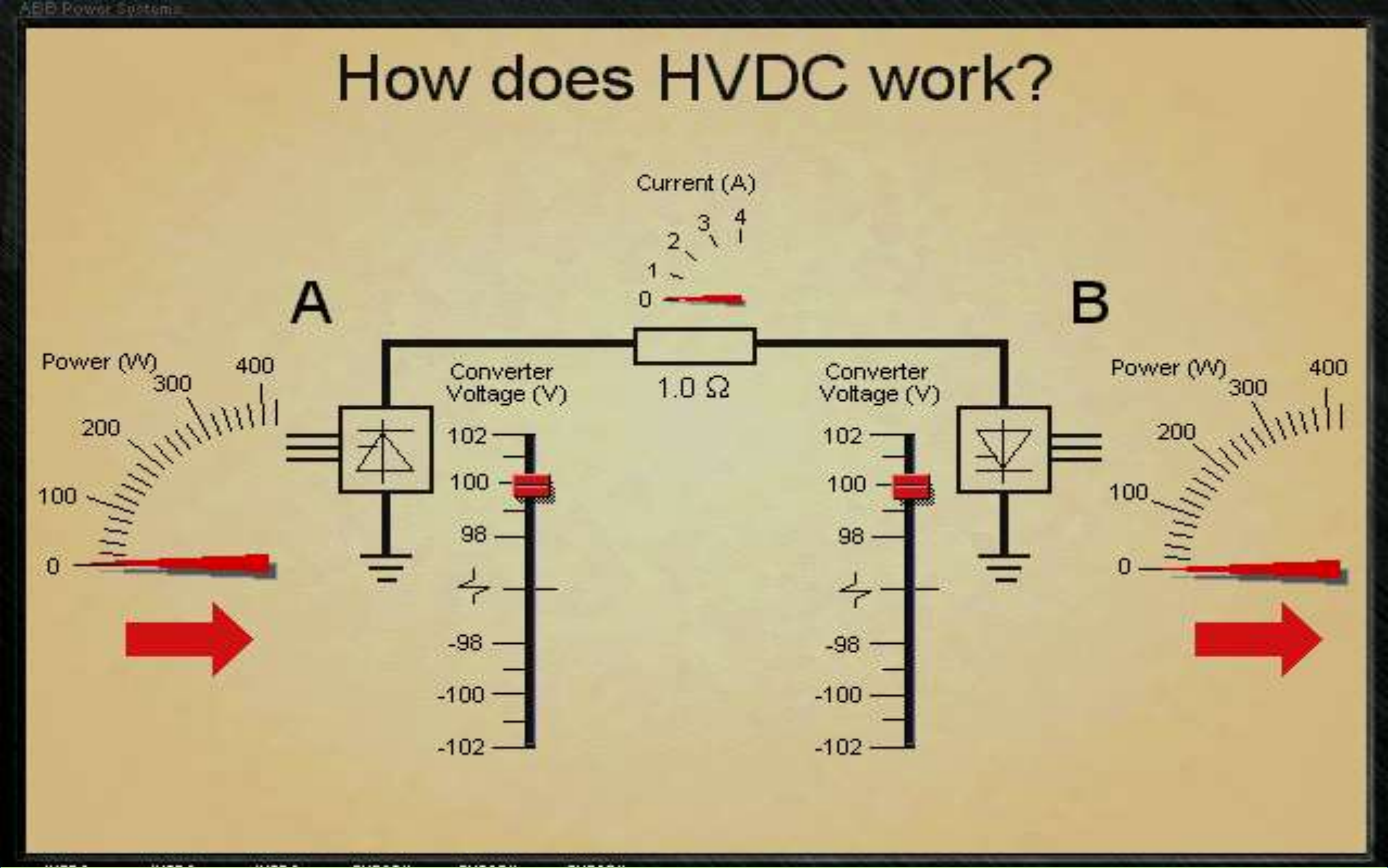
4. Circuit breakers are used in HVDC for circuit breaking, which is also very expensive.

5. It does not have transformers for changing the voltage levels.

6. Heat loss occurs in converter substation, which has to be reduced by using the active cooling system.

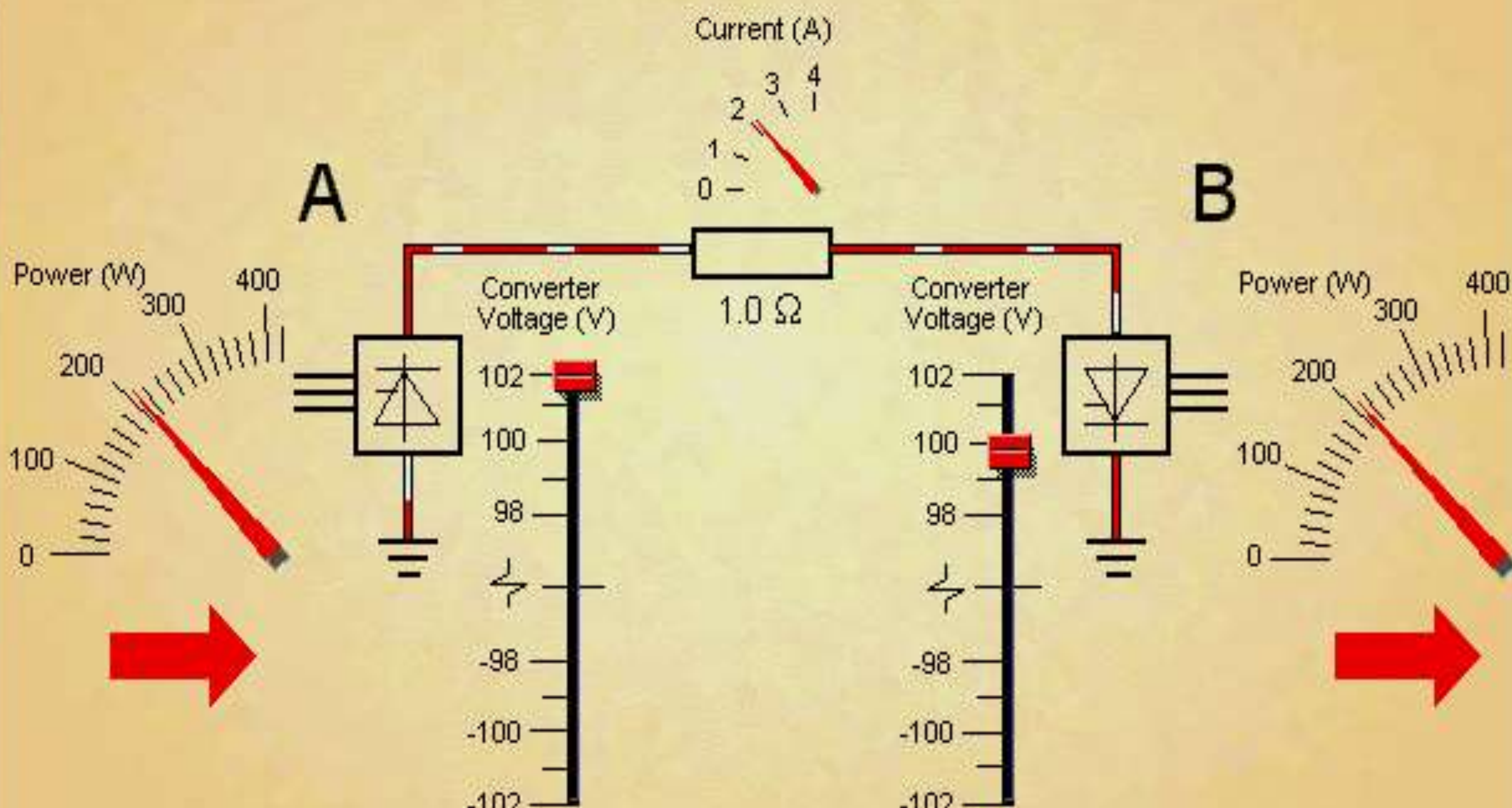
7. HVDC link itself is also very complicated.


Week-13
Page:112-119

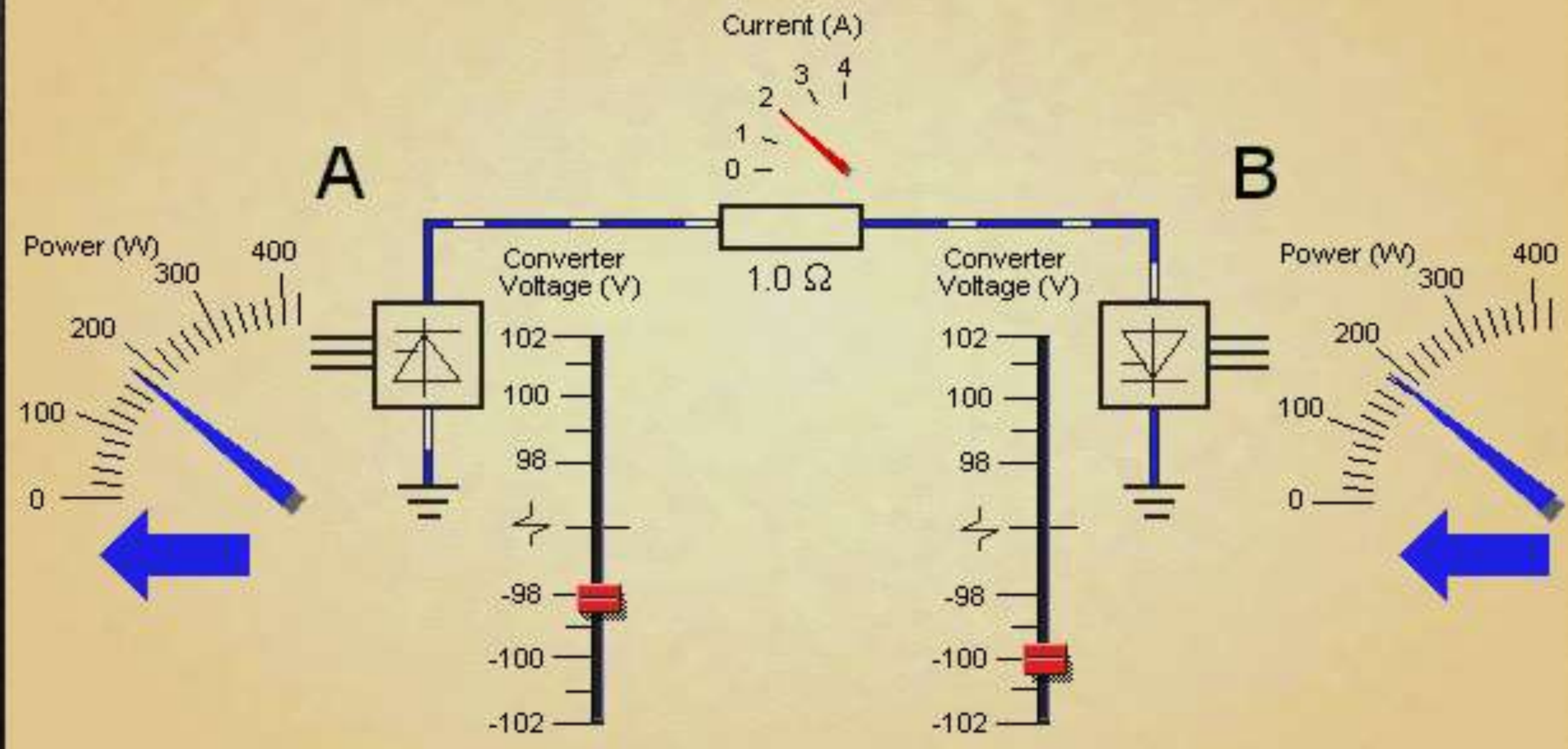


Decrease voltage at station B or increase voltage at station A. power flows from A→ B Normal direction

How does HVDC work?



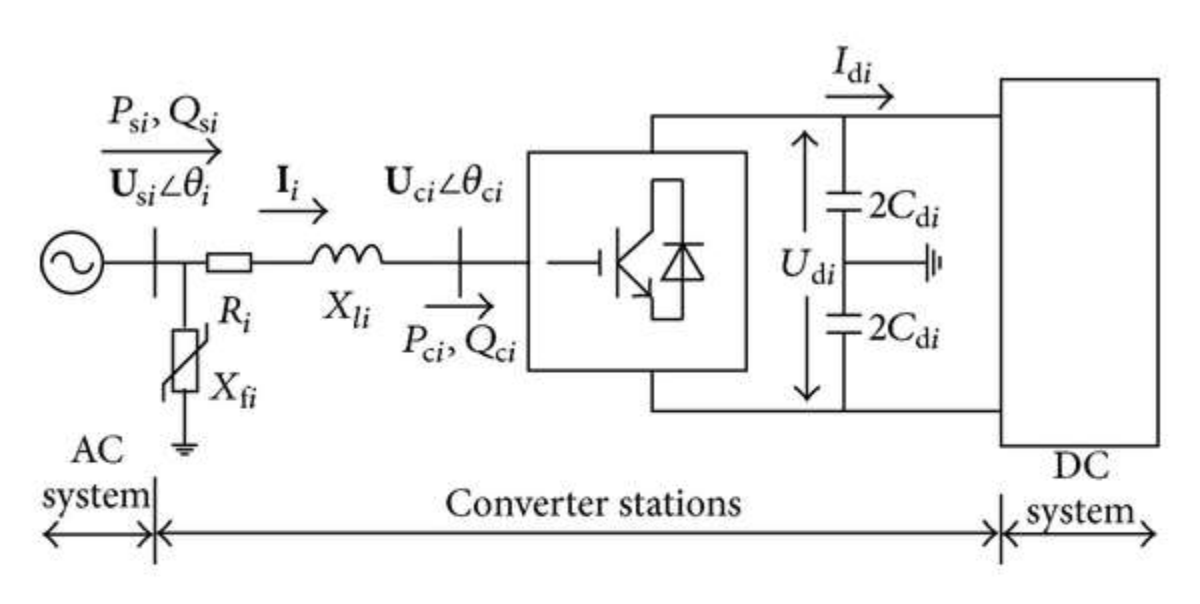
How does HVDC work?



Power reversal is obtained by reversal of polarity of direct voltages at both ends.

Voltage Source Converter 300MW

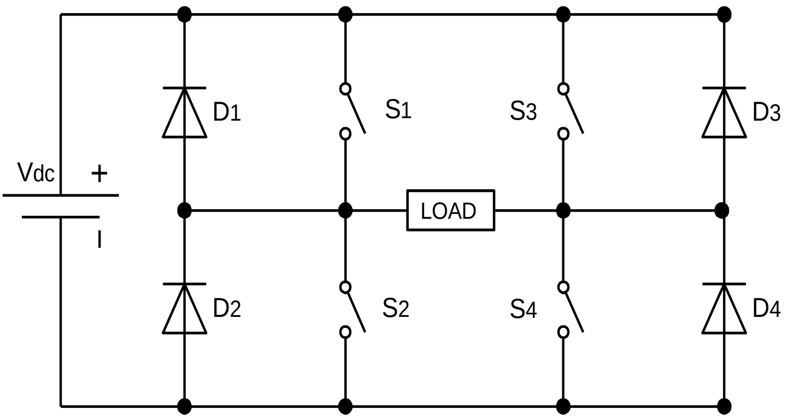
Can generate and absorb reactive power. Power flow is changed by shift voltage waveform (changing power angle)



$$P = \frac{U_{ci} U_{si} \sin(\theta_i - \theta_{ci})}{X_{li}}$$

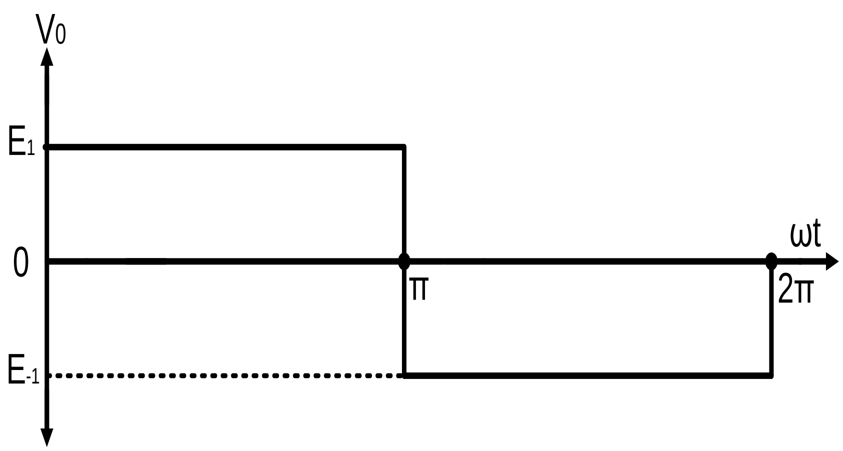
VSC Based HVDC

Inverter Topologies

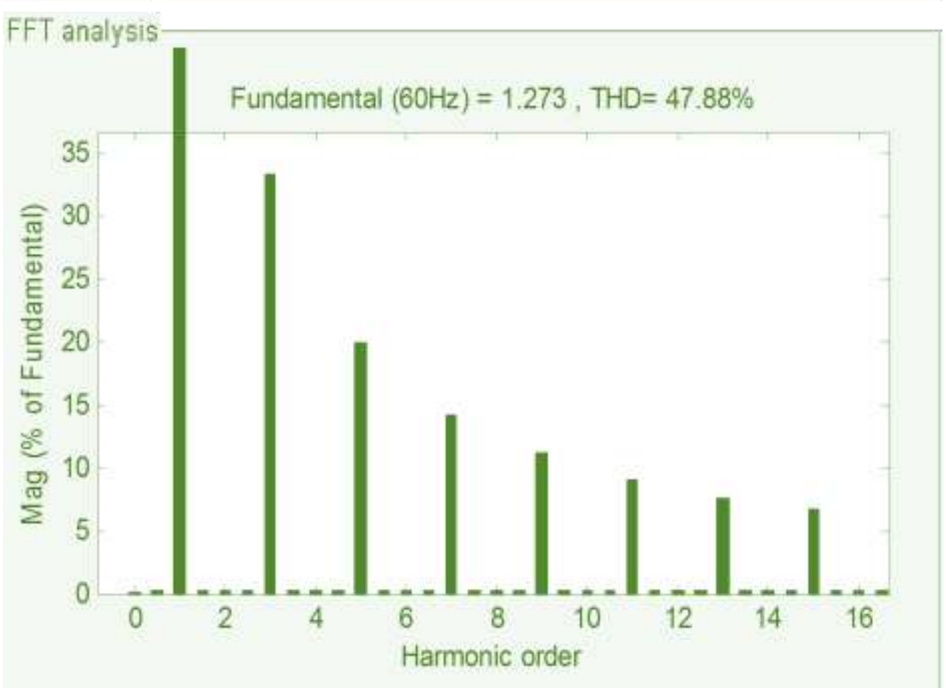


Simple Square-Wave Inverter

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} H_{(n)}^{2}}}{H_1}$$



Output voltage waveform of Square-Wave inverter



Inverter Topologies

The harmonic free sinusoidal output is a major area that has been investigated for many years as it is highly desirable in most inverter applications.

- Some switching techniques are utilized for the purpose of enhancing the magnitude of the fundamental component and reducing the harmonics to obtain minimized total harmonic distortion.

The techniques regarding harmonic Elimination are

- Diode Clamped Multilevel Inverter (DCMLI) technique.
- Pulse Width Modulation (PWM) technique.
- PWM technique in DCMLI.

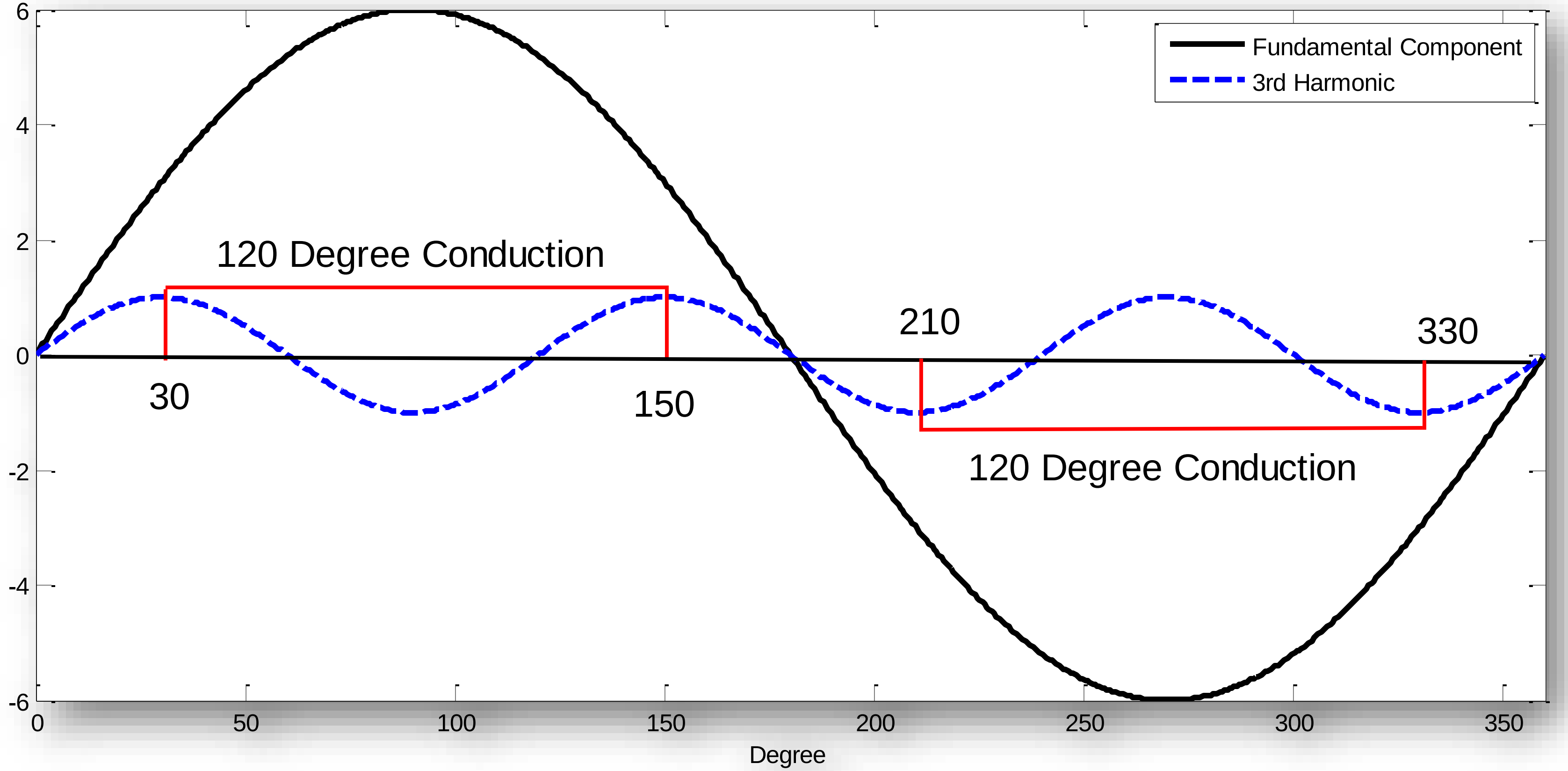
In these harmonic elimination techniques the lower order harmonics are effectively reduced from output voltage by fundamental switching, so smaller output filters can easily be used to eliminate the remaining higher order harmonics.

The topologies are explained in the following sequence:

- Circuit Diagram.
- Output Voltage waveform.
- Fourier Analysis.
- Switching Angles Calculation.
- Spectrum of Output Sinusoidal waveform.
- Calculation of Total Harmonic Distortion

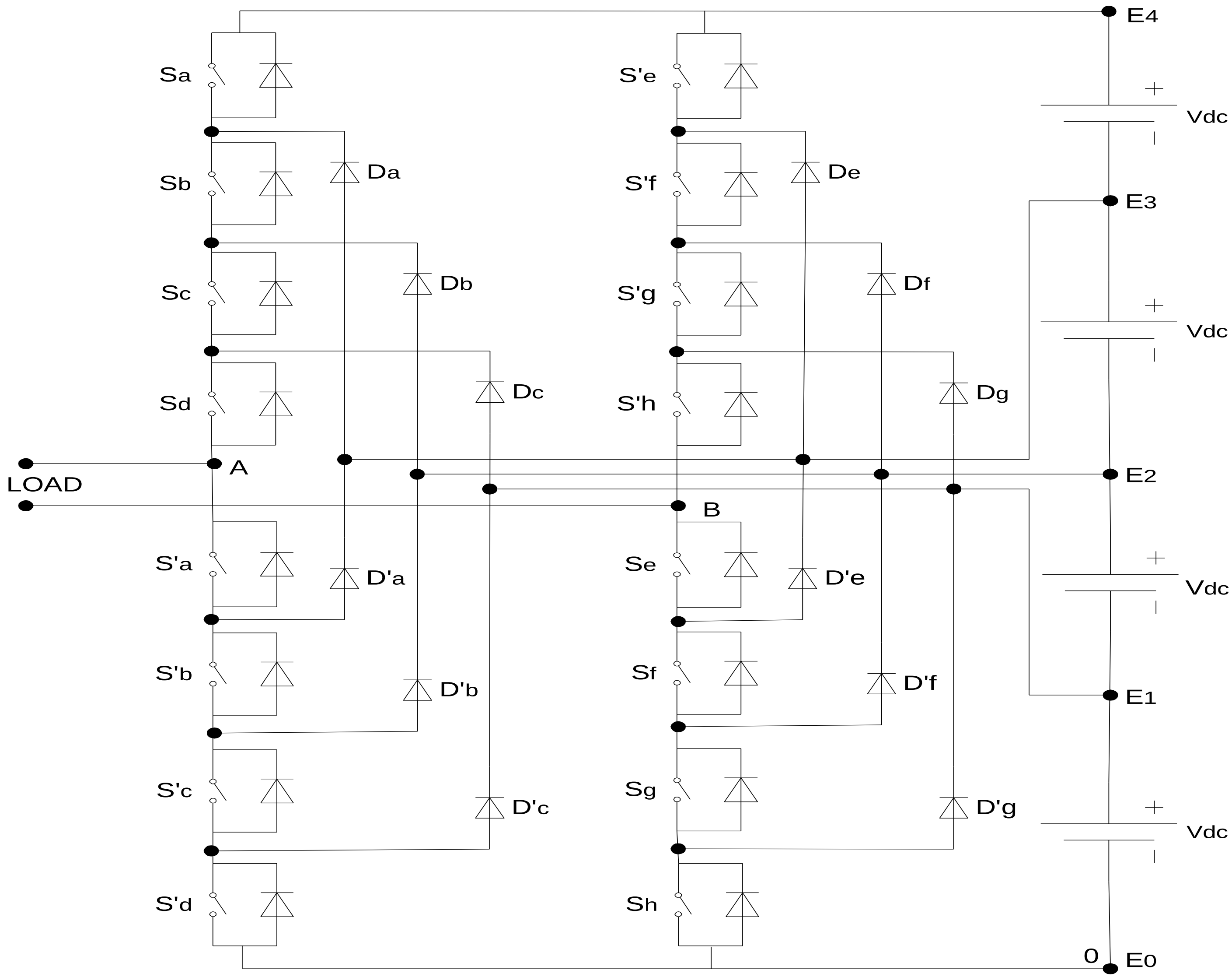

Week-14
Page:121-126

Fundamental idea of harmonic Elimination



Elimination of 3rd Harmonic via Switching

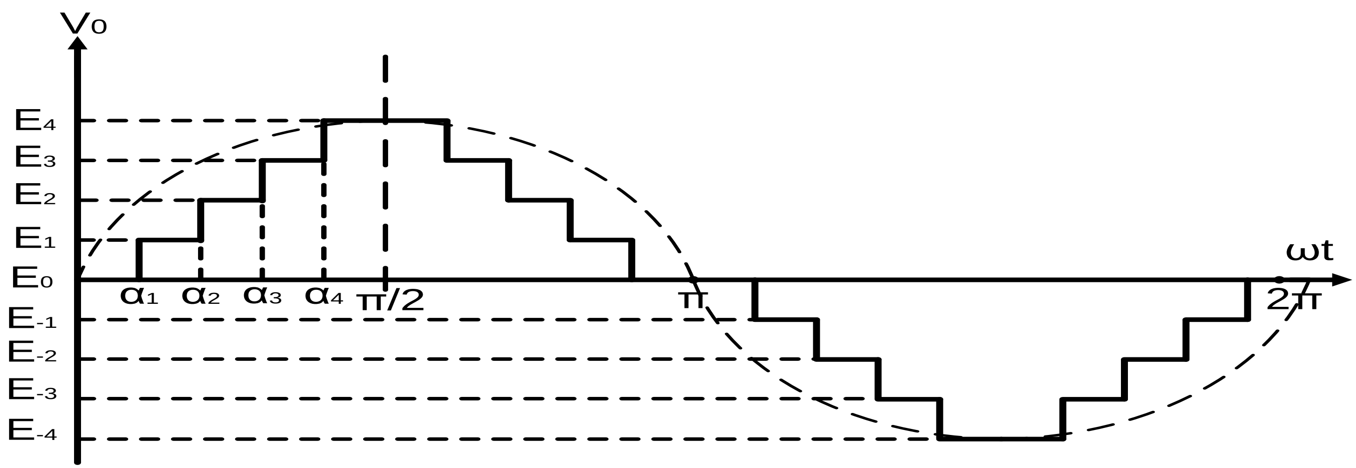
Diode Clamped Multilevel Inverter (DCMLI)



Diode Five-Level Bridge Multilevel Inverter

Five-level DCMLI voltage levels and their corresponding switch states.

Output Voltage Levels	Switching States															
	S_a	S_b	S_c	S_d	S_e	S_f	S_g	S_h	S'_a	S'_b	S'_c	S'_d	S'_e	S'_f	S'_g	S'_h
$E_4 = 4V_{dc}$	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
$E_3 = 3V_{dc}$	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
$E_2 = 2V_{dc}$	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
$E_1 = V_{dc}$	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0
$E_0 = 0$	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
$E_{-1} = -V_{dc}$	0	0	0	0	1	1	1	0	1	1	1	1	0	0	0	1
$E_{-2} = -2V_{dc}$	0	0	0	0	1	1	0	0	1	1	1	1	0	0	1	1
$E_{-3} = -3V_{dc}$	0	0	0	0	1	0	0	0	1	1	1	1	0	1	1	1
$E_{-4} = -4V_{dc}$	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1



Phase voltage waveform of 5-level inverter

Fourier Analysis

The Fourier series of the quarter-wave symmetric 5-level DCMLI multilevel waveform

$$V_o(\omega t) = \sum_{n=1}^{\infty}\left[\frac{4V_{dc}}{n\pi}\sum_{k=1}^{m-1}\cos(n\alpha_k)\right]\sin(n\omega t)$$

Switching Angles Computation

The equations used to calculate switching angles are:

$$\cos(\alpha_1)+\cos(\alpha_2)+\cos(\alpha_3)+\cos(\alpha_4) = \frac{(m-1)M\pi}{4}$$

$$\cos(3\alpha_1)+\cos(3\alpha_2)+\cos(3\alpha_3)+\cos(3\alpha_4)=0$$

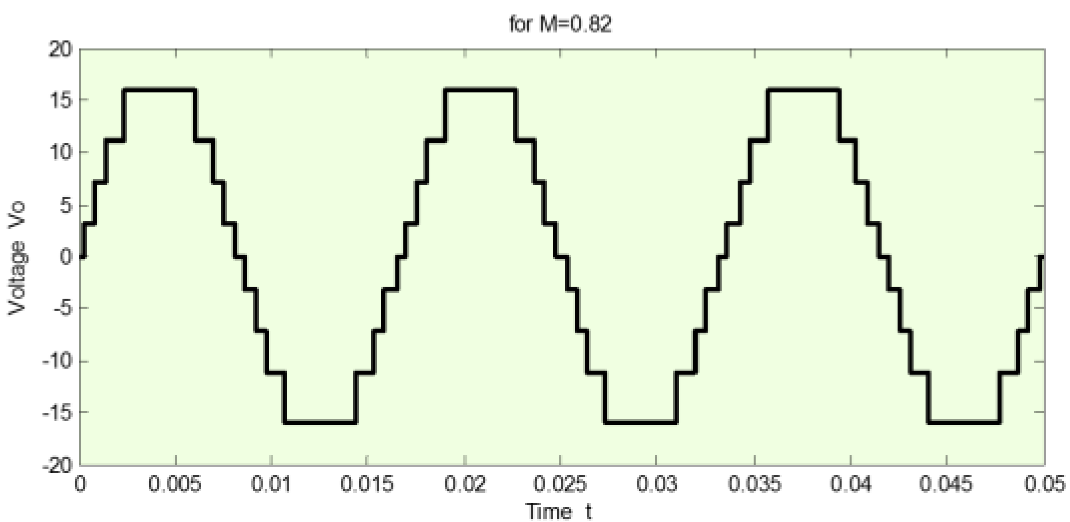
$$\cos(5\alpha_1)+\cos(5\alpha_2)+\cos(5\alpha_3)+\cos(5\alpha_4)=0$$

$$\cos(7\alpha_1)+\cos(7\alpha_2)+\cos(7\alpha_3)+\cos(7\alpha_4)=0$$

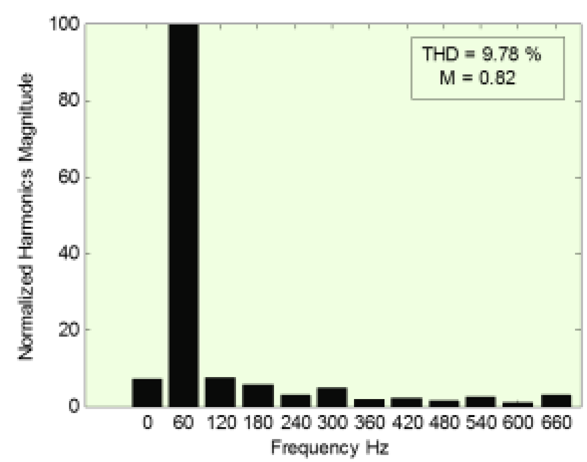
$$M=\frac{V_1}{V_{max}}$$

Table 2: Five-level DCMLI Switching angles for different values of modulation index and corresponding THD

M	α_1	α_2	α_3	α_4	THD (%)
0.82	5.3973	18.3862	29.9027	50.0994	9.78
0.85	5.7926	17.3835	37.6089	55.7373	10.29
0.87	5.7754	13.4645	31.4153	44.7595	11.17
0.9	5.7754	13.3385	32.8649	56.5509	10.68

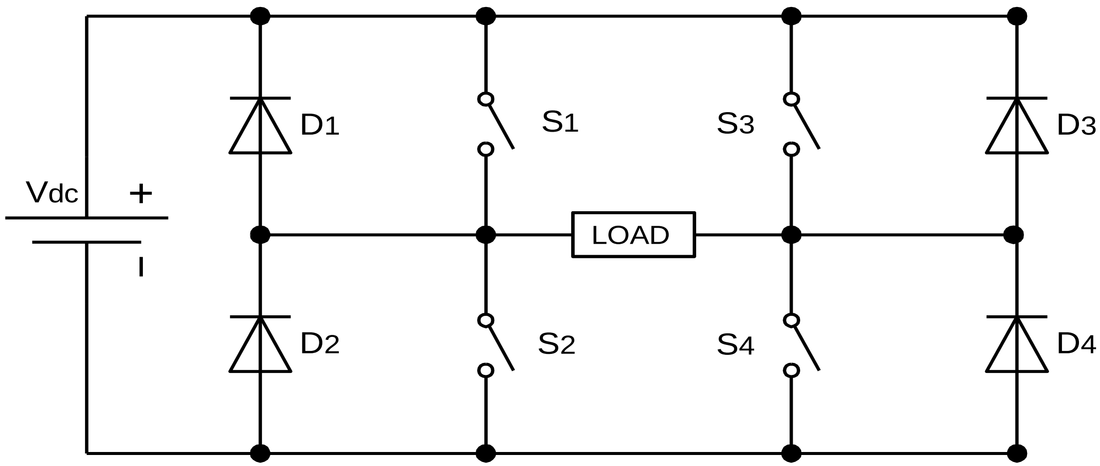


5-Level DCMLI Output Voltage Waveform for M=0.82

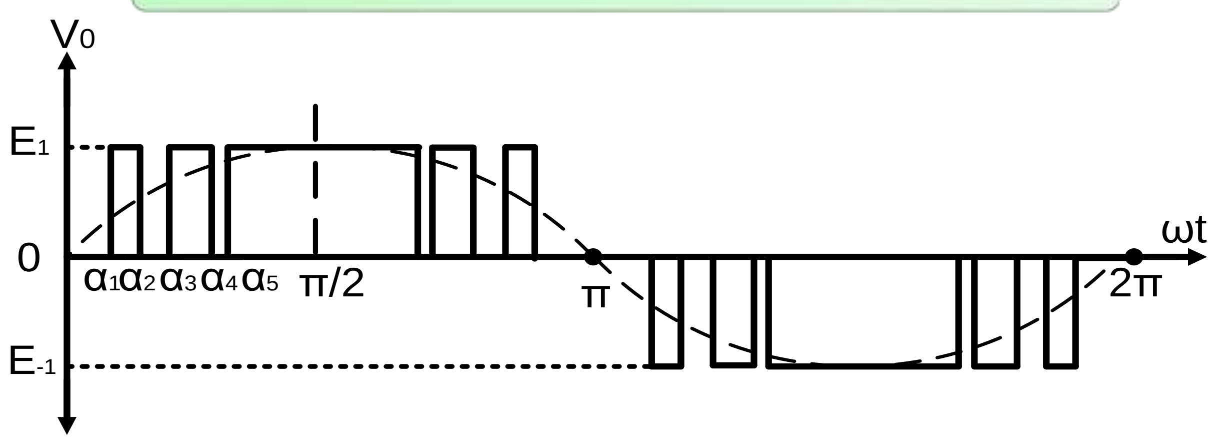


Voltage Spectrums Normalized to Fundamental Component

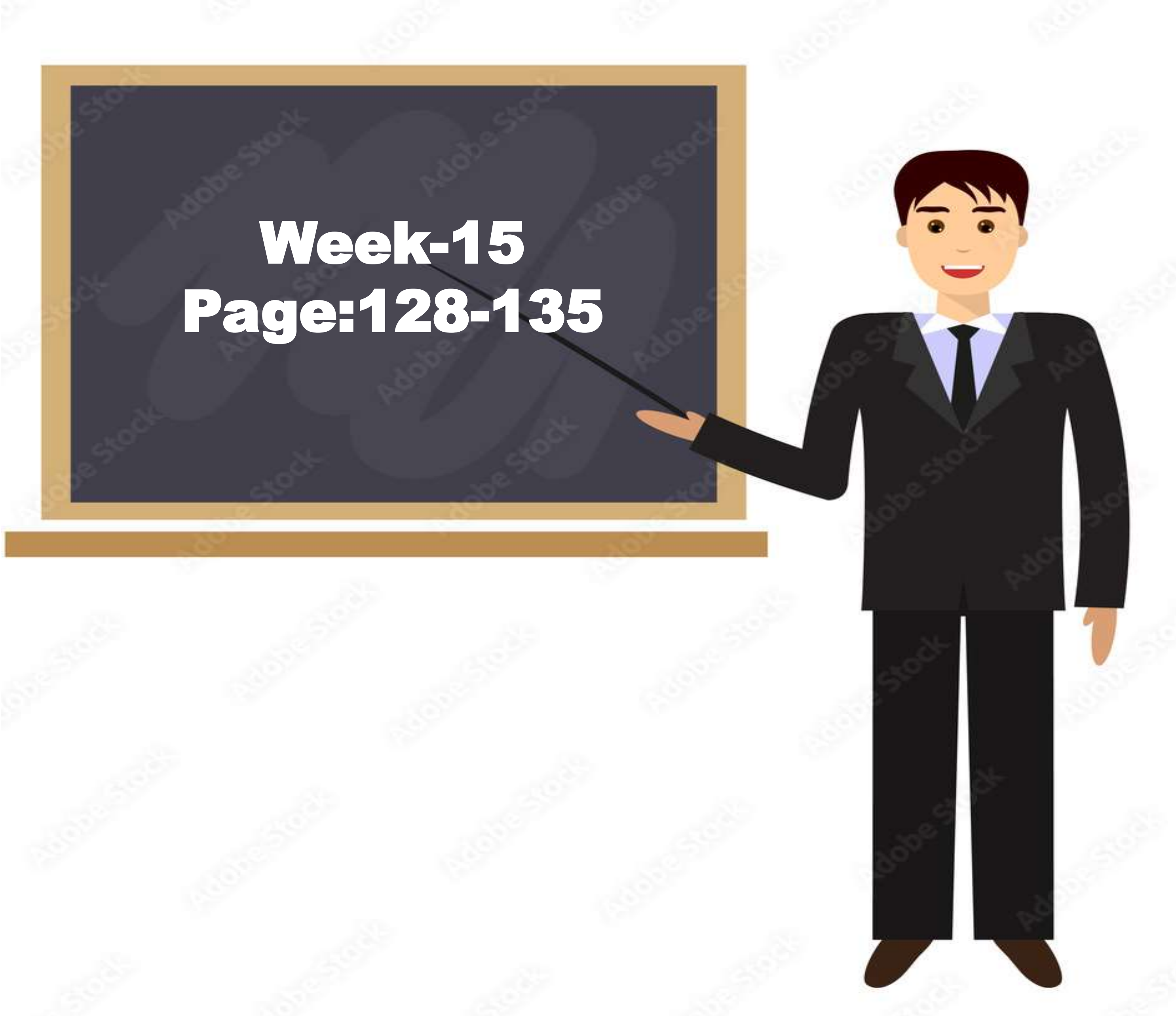
Pulse Width Modulated Inverter (PWM)



Single-phase Full- Bridge PWM inverter



Phase voltage waveform of PWM inverter


Week-15
Page:128-135

Fourier Analysis

The Fourier series of the quarter-wave symmetric *m*-pulse PW waveform is:

$$V_o(\omega t) = \sum_{n=1}^{\infty}\left[\frac{4V_{dc}}{n\pi}\sum_{k=1}^{m}(-1)^{k+1}\cos(n\alpha_k)\right]\sin(n\omega t)$$

Switching Angles Computation

The equations used to calculate switching angles are:

$$\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \cos(\alpha_4) + \cos(\alpha_5) = \frac{M\pi}{4}$$

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) + \cos(3\alpha_5) = 0$$

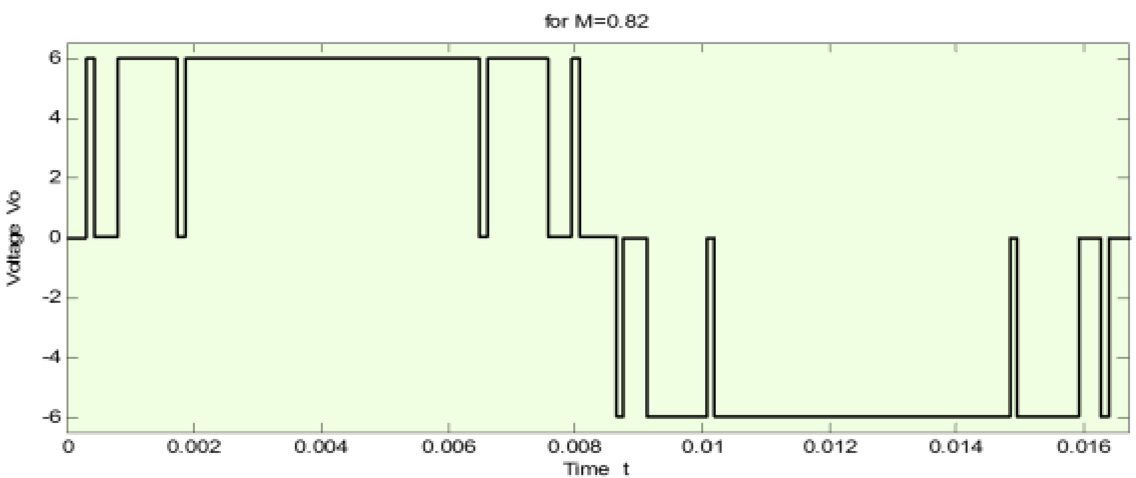
$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) + \cos(5\alpha_5) = 0$$

$$\cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) + \cos(7\alpha_5) = 0$$

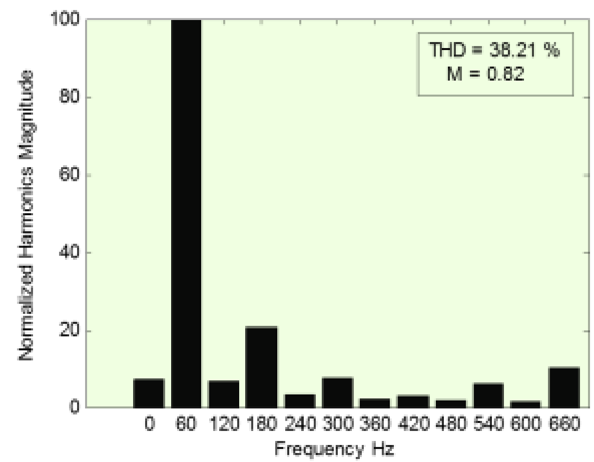
$$\cos(11\alpha_1) - \cos(11\alpha_2) + \cos(11\alpha_3) - \cos(11\alpha_4) + \cos(11\alpha_5) = 0$$

Table 3: PWM Inverter switching angles for different values of modulation index and corresponding THD

M	α_1	α_2	α_3	α_4	α_5	THD (%)
0.82	6.0963	8.9038	16.5069	37.1277	40.14	38.22
0.85	7.4485	10.6456	19.3087	37.2824	39.4768	35.19
0.87	6.2223	7.8037	14.6964	36.9844	37.9012	34.3
0.9	6.8698	8.4511	12.7655	35.7411	37.4286	36.48

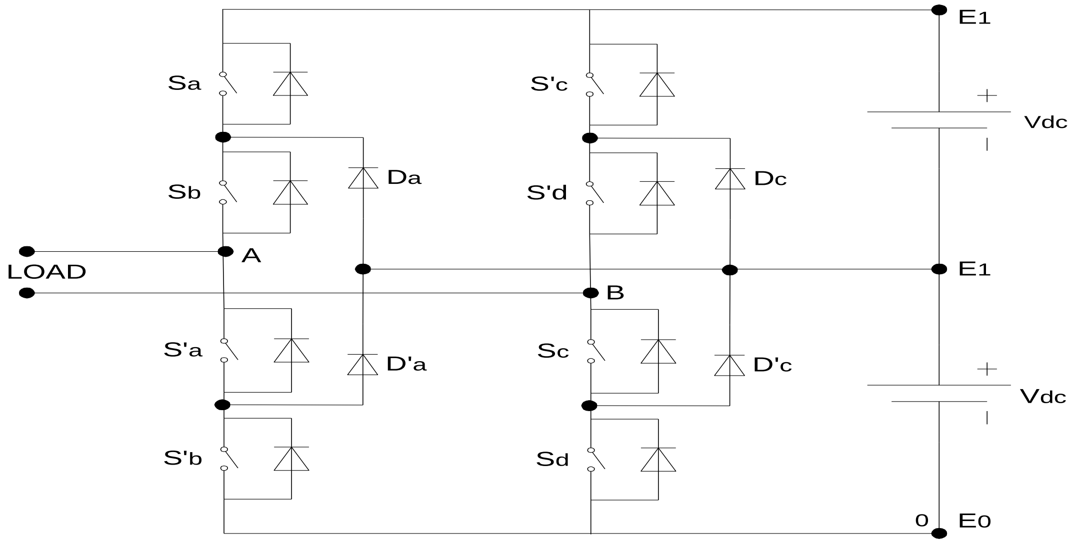


PWM Inverter Output Voltage Waveform for M=0.82



Voltage Spectrums Normalized to Fundamental Component

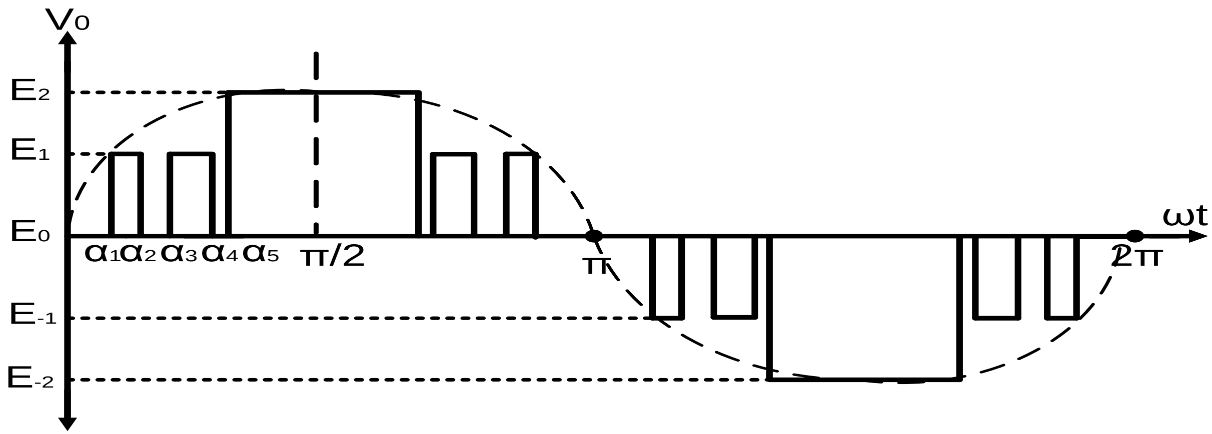
Pulse Width Modulated (PWM) multilevel Inverters



Single-phase Full- Bridge PWM inverter

Output Voltage Levels	Switching States							
	S_a	S_b	S_c	S_d	S'_a	S'_b	S'_c	S'_d
$E_2 = 2V_{dc}$	1	1	1	1	0	0	0	0
$E_1 = V_{dc}$	0	1	1	1	1	0	0	0
$E_0 = 0$	0	0	1	1	1	1	0	0
$E_{-1} = -V_{dc}$	0	0	1	0	1	1	0	1
$E_{-2} = -2V_{dc}$	0	0	0	0	1	1	1	1

3-level PWM DCMLI voltage levels and corresponding switch states.



3-level PWM output voltage waveform

Fourier Analysis

The Fourier series of the quarter-wave symmetric *3-level PWM* output voltage waveform is:

$$V_o(\omega t) = \sum_{n=1}^{\infty}\left[\frac{4V_{dc}}{n\pi}\left\{\begin{matrix}\cos(n\alpha_1) - \cos(n\alpha_2) + \cos(n\alpha_3) - \cos(n\alpha_4) \\ +2\cos(n\alpha_5)\end{matrix}\right\}\right] \sin(n\omega t)$$

Switching Angles Computation

The equations used to calculate switching angles are:

$$\cos(\alpha_1) - \cos(\alpha_2) + \cos(\alpha_3) - \cos(\alpha_4) + 2\cos(\alpha_5) = \frac{M\pi}{4}$$

$$\cos(3\alpha_1) - \cos(3\alpha_2) + \cos(3\alpha_3) - \cos(3\alpha_4) + 2\cos(3\alpha_5) = 0$$

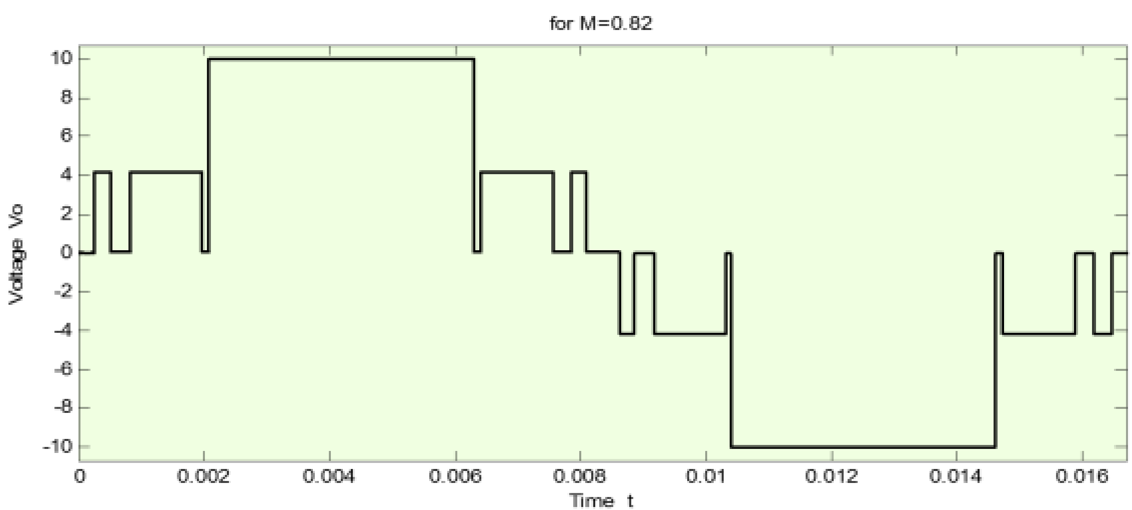
$$\cos(5\alpha_1) - \cos(5\alpha_2) + \cos(5\alpha_3) - \cos(5\alpha_4) + 2\cos(5\alpha_5) = 0$$

$$\cos(7\alpha_1) - \cos(7\alpha_2) + \cos(7\alpha_3) - \cos(7\alpha_4) + 2\cos(7\alpha_5) = 0$$

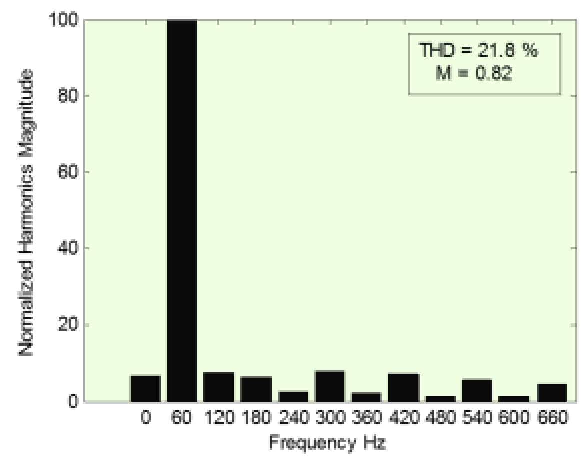
$$\cos(11\alpha_1) - \cos(11\alpha_2) + \cos(11\alpha_3) - \cos(11\alpha_4) + 2\cos(11\alpha_5) = 0$$

Table 5: 3-level PWM Inverter switching angles for different values of modulation index & corresponding THD.

M	α_1	α_2	α_3	α_4	α_5	THD (%)
0.82	5.3056	11.1669	17.5783	43.0750	44.2896	21.8
0.85	5.1165	12.2957	18.4836	40.1758	41.2570	22.84
0.87	5.7640	9.3850	13.3499	36.0104	37.6319	20.3
0.9	5.6494	9.3850	13.3499	36.0104	37.1162	19.23



3-level PWM Inverter Output Voltage Waveform for M=0.82



Voltage Spectrums Normalized to Fundamental Component

Conclusion

Simulation results of three different 1-ϕ inverters were presented

- The PWM inverter though took four switches for implementation (less than other two) but resulting THD is greater of all.
- The DCMLI resulting THD is lowest of all but it took too many devices for implementation.
- The PWM in DCMLI (Combination of PWM and DCMLI) have less number of switches than the DCMLI and low THD than PWM inverter, implying that this technique is economically and technically best to implement


Week-16
Page:136-146

Advantages of Proposed Inverter technique

- Improved efficiency due to modified sine wave.
- Reduction in power losses, Electromagnetic Interference (EMI).
- Well suited for renewable energy systems.
- Frequency adaptive inverter-System's AC output can be easily reconfigured after installation
- Cost effective- With simple structure and fewer components.
- Requires low output filter values to attenuate the undesired harmonics.

Disadvantages of HVDC Transmission

- The disadvantages of HVDC are in conversion, switching and control.
- Expensive inverters with limited overload capacity.
- Higher losses in static inverters at smaller transmission distances.
- The cost of the inverters may not be offset by reductions in line construction cost and lower line loss.
- High voltage DC circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching.
- HVDC is less reliable and has lower availability than AC systems, mainly due to the extra conversion equipment.

Control of HVDC Systems

Objectives of Control	• Efficient and stable operation. • Maximum flexibility of power control without compromising the safety of equipment.
Content	• Principle of operation of various control systems. • Implementation and their performance during normal and abnormal system conditions.

Basic principles of control

- Direct current from the rectifier to the inverter

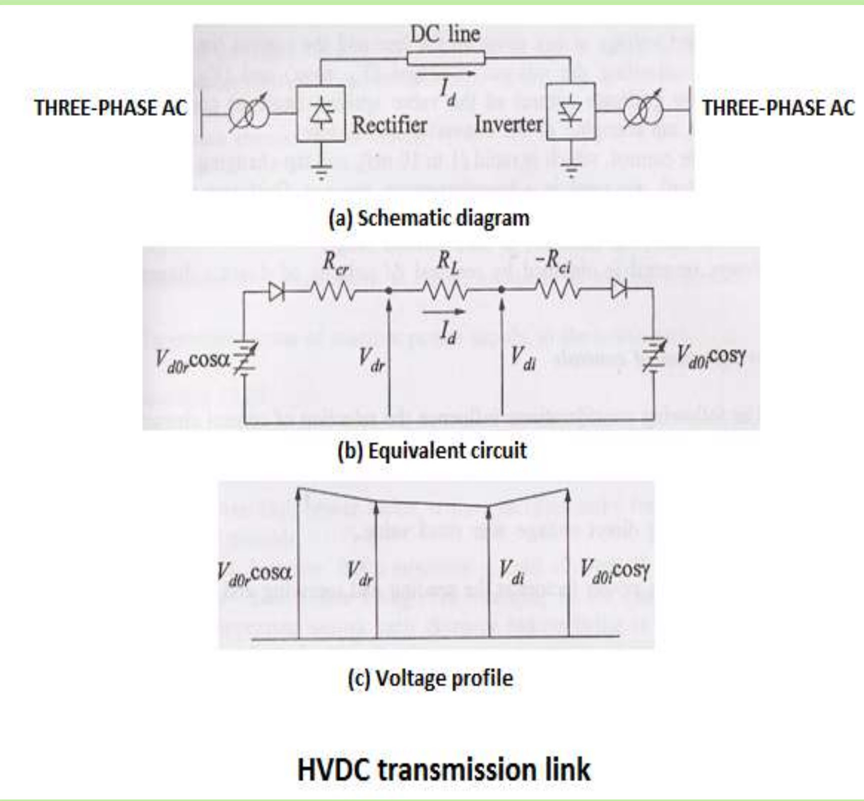
$$I_d = \frac{V_{dor} \cos\alpha - V_{doi} \cos\beta}{R_{cr} + R_l - R_{ci}}$$

- Power at the rectifier terminal

$$P_{dr} = V_{dr} I_d$$

- Power at the inverter terminal

$$P_{di} = V_{di} I_d = P_{dr} - R_L I_d^{\,2}$$



Schematic diagram of control

Basic Means of control

- Internal voltages $V_{dor} \cos\alpha$ and $V_{doi} \cos\beta$ can used be controlled to control the voltages at any point on the line and the current flow (power).

- This can be accomplished by:
  - Controlling firing angles of the rectifier and inverter (for fast action).
  - Changing taps on the transformers on the AC side (slow response).

- Power reversal is obtained by reversal of polarity of direct voltages at both ends.

Control Implementation

- Power control

  To transmit a scheduled power, the corresponding current order is determined by:

$$I_{ord} = P_o / V_d$$

- Rectifier control and protection

  Determines firing angles and sets their limits.

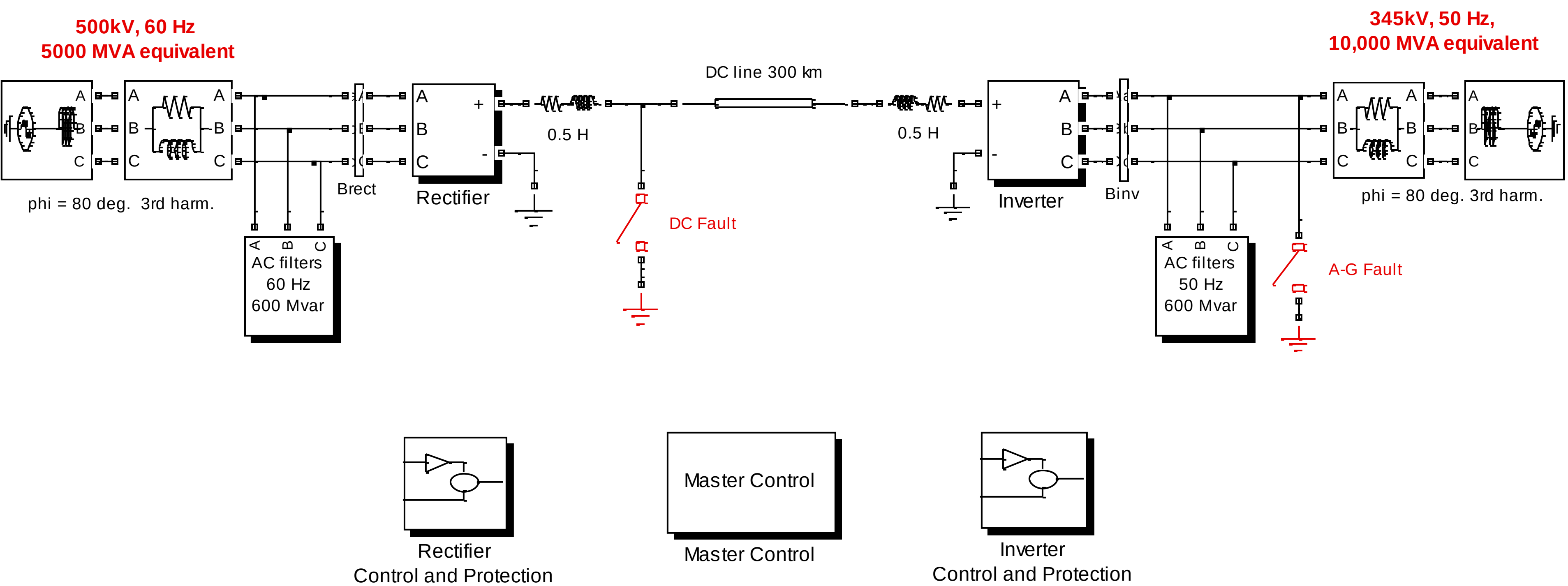
- Inverter control and protection

  Determines firing angles and set frequency of resulting AC.

- Master Control

  It coordinates the conversion of current order to a firing angle order, tap changer control and other protection sequences.

Control Implementation



HVDC 12-pulse Transmission System 1000 MW (500kV-2kA) 50/60 Hz

A 1000 MW (500 kV, 2 kA) DC interconnection is used to transmit power from a 500 kV, 5000 MVA, 60 Hz system to a 345 kV, 10000 MVA, 50 Hz system.

The rectifier and the inverter are 12-pulse converters

Control Implementation

- A 1000 MW (500 kV, 2 kA) DC interconnection is used to transmit power from a 500 kV, 5000 MVA, 60 Hz system to a 345 kV, 10000 MVA, 50 Hz system.
- The rectifier and the inverter are 12-pulse converters
- The converters are interconnected through a 300-km line and 0.5 H smoothing reactors
- Frequency adaptive inverter-System's AC is used.
- From the AC point of view, an HVDC converter acts as a source of harmonic currents. From the DC point of view, it is a source of harmonic voltages.
- Two circuit breakers are used to apply faults: one on the rectifier DC side and the other on the inverter AC side..

Conclusion

- HVDC is very important issue in transmission energy.
- Very large investments in e.g in China and India shows that high-voltage direct current will very important in the future, especially in big, new-industries countries
- Recent studies indicate that HVDC systems are very reliable.
- The data collected from 31 utilities says that forced unavailability of energy due to the converter station is 1.62%.
- The scheduled unavailability of energy is about 5.39%.
- HVDC offers powerful alternative to increase stability of a power system as well as to improve system operating flexibility and loss reduction
- To keep the losses to a minimum, the control system shall be designed to keep as high voltage as possible.

More power can be transmitted per conductor per circuit.

The capabilities of power transmission of an a.c. link and a d.c. link are different.

For the same insulation, the direct voltage V_d is equal to the peak value ($\sqrt{2}$ x rms value) of the alternating voltage V_d.

$$V_d = \sqrt{2}\, V_a$$

For the same conductor size, the same current can transmitted with both d.c. and a.c. if skin effect is not considered.

$$I_d = I_a$$

Thus the corresponding power transmission using 2 conductors with d.c. and a.c. are as follows.

d c power per conductor $P_d = V_d I_d$

a c power per conductor $P_a = V_a I_a \cos\varphi$

The greater power transmission with d.c. over a.c. is given by the ratio of powers.

$$\frac{P_d}{P_a} = \frac{\sqrt{2}}{\cos\varphi} = \begin{cases} 1.414 & \text{at p.f} = \text{unity} \\ 1.768 & \text{at p.f} = 0.8 \end{cases}$$

In practice, a.c. transmission is carried out using either single circuit or double circuit 3 phase transmission using 3 or 6 conductors. In such a case the above ratio for power must be multiplied by 2/3 or by 4/3.

Comparison

In general, we are interested in transmitting a given quantity of power at a given insulation level, at a given efficiency of transmission. Thus for the same power transmitted P, same losses P_L and same peak voltage V, we can determine the reduction of conductor cross-section A_d over A_a.

Let R_d and R_a be the corresponding values of conductor resistance for d.c. and a.c. respectively, neglecting skin resistance.

For d.c current $= \dfrac{P}{V_m}$

power loss $P_L = (P/V_m)^2 R_d = (P/V_m)^2.(\rho l/A_d)$

For a.c current $= \dfrac{P}{(V_m/\sqrt{2})\cos\varphi} = \dfrac{\sqrt{2}P}{V_m \cos\varphi}$

power loss $P_L = [\sqrt{2}P/(V_m \cos\varphi)]^2 R_a$

$= 2\,(P/V_m)^2.(\rho l/A_a \cos^2\varphi)$

Equating power loss for d.c. and a.c.

$$(P/V_m)^2.(\rho l/A_d) = 2\,(P/V_m)^2.(\rho l/A_a \cos^2\varphi)$$

This gives the result for the ratio of areas as

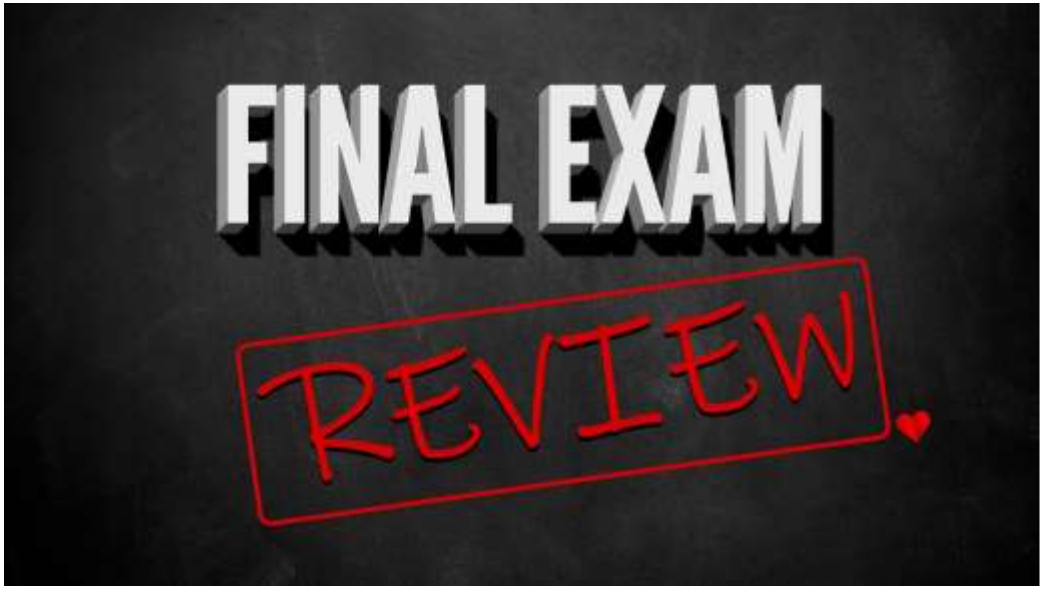
$$\frac{A_d}{A_a} = \frac{\cos^2\varphi}{2} = \begin{cases} 0.5 & \text{at p.f. = unity} \\ 0.32 & \text{at p.f. = 0.8} \end{cases}$$

The result has been calculated at unity power factor and at 0.8 lag to illustrate the effect of power factor on the ratio. It is seen that only one-half the amount of copper is required for the same power transmission at unity power factor, and less than one-third is required at the power factor of 0.8 lag.


Week-17

- **Revision and Final Review**

Revision and Final Review

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