GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY
Department of Electrical and Electronics Engineering

Course Title: HVDC TRANSMISSION(GR20A3094)

Following documents are available in Course File.

S.No.	Points	Yes	No
1	Institute and Department Vision and Mission Statements	Y	
2	PEO & PO Mapping	Y	
3	Academic Calendar	Y	
4	Syllabus Copy	Y	
5	Course Outcomes	Y	
6	CO-PO Mapping	Y	
7	Course Schedule	Y	
8	Course Unit Schedule	Y	
9	Guidelines to Study Course and Teaching Strategic Plan	Y	
10	Lecture Notes (Soft Copy of Notes/PPT/Slides)	Y	
11	Tutorial/Assignment Sheets with Solution	Y	
12	Best, Average and Weak Answer Scripts for Each Sessional Exam.		N
13	Sessional Question Paper and Scheme of Evaluation (Internal and External)	Y	
14	Previous University Question Papers		N
15	Result Analysis	Y	
16	Feedback from Students	Y	
17	Course Exit Survey		N
18	CO Attainment for All Mids.		N
19	CO-Cognitive Level Mapping	Y	
20	Remedial Action plan.	Y	

J. SRIDEVI
Professor
EEE Department

HOD, EEE

Vision of the Institute

To be among the best of the institutions for engineers and technologists with attitudes, skills and knowledge and to become an epicenter of creative solutions.

Mission of the Institute

To achieve and impart quality education with an emphasis on practical skills and social relevance.

Vision of the Department

To impart technical knowledge and skills required to succeed in life, career and help society to achieve self-sufficiency.

Mission of the Department

- To become an internationally leading department for higher learning.
- To build upon the culture and values of universal science and contemporary education.
- To be a center of research and education generating knowledge and technologies which lay groundwork in shaping the future in the fields of electrical and electronics engineering.
- To develop partnership with industrial, R&D and government agencies and actively participate in conferences, technical and community activities.

Program Educational Objectives (B.Tech-EEE)

This programme is meant to prepare our students to professionally thrive and to lead. During their progression:

PEO-1: Graduates will have a successful technical or professional career, including supportive and leadership roles on multidisciplinary teams.

PEO-2: Graduates will be able to acquire, use and develop skills as required for effective professional practices.

PEO-3: Graduates will be able to attain holistic education that is an essential prerequisite for being a responsible member of society.

PEO-4: Graduates will be engaged in life-long learning, to remain abreast in their profession and be leaders in our technologically vibrant society.

Program Outcomes (B.Tech-EEE)

- **a.** Ability to apply knowledge of mathematics, science, and engineering.
- **b.** Ability to design and conduct experiments, as well as to analyze and interpret data.
- **c.** Ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.
- **d.** Ability to function on multi-disciplinary teams.
- **e.** Ability to identify, formulates, and solves engineering problems.
- **f.** Understanding of professional and ethical responsibility.
- **g.** Ability to communicate effectively.
- **h.** Broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.
- **i.** Recognition of the need for, and an ability to engage in life-long learning.
- **j.** Knowledge of contemporary issues.

k. Ability to utilize experimental, statistical and computational methods and tools necessary for engineering practice.

l. Graduates will demonstrate an ability to design electrical and electronic circuits, power electronics, power systems; electrical machines analyze and interpret data and also an ability to design digital and analog systems and programming them.

Program Educational Objectives (PEOs) - Program Outcomes (POs) Relationship Matrix

	POs	a	b	c	d	e	f	g	h	i	j	k	l
PEOs	PEO 1: Graduates will have a successful technical or professional careers, including supportive and leadership roles on multidisciplinary teams.	M	M			H			H	H		H	H
	PEO 2: Graduates will be able to acquire, use and develop skills as required for effective professional practices.			M	M	H	H	H					H
	PEO 3: Graduates will be able to attain holistic education that is an essential prerequisite for being a responsible member of society.					H	H	M	M	M	M	H	H
	PEO 4: Graduates will be engaged in life-long learning, to remain abreast in their profession and be leaders in our technologically vibrant society.				M	M	H	M	H	H		M	H

Gokaraju Rangaraju Institute of Engineering and Technology
(Autonomous)
Bachupally, Kukatpally, Hyderabad – 500 090, India

GRIET/DAA/1H/G/22-23 19 July 2022

Academic Calendar
Academic Year 2022-23

III B.Tech. –First Semester

S. No.	EVENT	PERIOD	DURATION
1	Commencement of First Semester class work	08-08-2022	
2	I Spell of Instructions	08-08-2022 to 08-10-2022	9 Weeks
3	I Mid-term Examinations	10-10-2022 to 13-10-2022	3 Days
4	II Spell of Instructions	14-10-2022 to 12-12-2022	9 Weeks
5	II Mid-term Examinations	13-12-2022 to 15-12-2022	3 Days
6	Preparation	16-12-2022 to 22-12-2022	1 Week
7	End Semester Examinations (Theory/ Practical) Regular/ Supplementary	23-12-2022 to 13-01-2023	3 Weeks
8	Commencement of Second Semester, AY 2022-23	16-01-2023	

III B.Tech. – Second Semester

S. No.	EVENT	PERIOD	DURATION
1	Commencement of Second Semester class work	16-01-2023	
2	I Spell of Instructions	16-01-2023 to 16-03-2023	9 Weeks
3	I Mid-term Examinations	17-03-2023 to 20-03-2023	3 Days
4	II Spell of Instructions	21-03-2023 to 29-04-2023	6 Weeks
5	Summer Vacation	01-05-2023 to 20-05-2023	3 Weeks
6	II Spell of Instructions Contd	22-05-2023 to 12-06-2023	3 Weeks
7	II Mid-term Examinations	13-06-2023 to 15-06-2023	3 Days
8	Preparation	16-06-2023 to 22-06-2023	1 Week
9	End Semester Examinations (Theory/ Practical) Regular / Supplementary	23-06-2023 to 15-07-2023	3 Weeks
10	Commencement of IV B.Tech First Semester, AY 2023-24	17-07-2023	

Dean Academic Affairs

Copy to Principal, All HoDs, CoE

Syllabus – HVDC TRANSMISSION

COURSECODE:GR20A3094 **LTPC**
IV Year I Semester **3 0 0 3**

UNIT-I
HVDC TRANSMISSION:
Introduction, equipment required for HVDC systems, Comparison of AC and DC Transmission, Limitations of HVDC transmission lines, reliability of HVDC systems, comparison of HVDC link with EHVAC link, HVDC convertors, HVDC –VSC transmission System: VSC system components, Control of Active and reactive power, Applications of VSC systems.
UNIT-II
HVDC CONVERTER OPERATION AND ANALYSIS:
Thyristors and their characteristics, silicon rectifier, 6 pulse convertor configuration, ideal communication process without gate control, DC output voltage , gate control of valves, analysis of voltage wave forms with overlap angle, analysis of communication circuits , equivalent circuit of rectifier, Inverter operation with overlap, Equivalent circuit of inverter , complete equivalent circuit of HVDC link, power factor and reactive power of converters
UNIT-III
HVDC CONVERTER CONTROL:
AC transmission and its control , necessary of dc link control, rectifier control , inverter control , constant beta control, constant gamma control, compounding of rectifiers, current compounding of inverter , complete HVDC system characteristics , power reversal in DC link, voltage dependent current order limit(VDCOL), system control hierarchy ,individual phase control, cosine control of phase delay, linear control phase delay , equidistance pulse control, pulse frequency control , constant current control
UNIT-IV
HARMONICS IN HVDC SYSTEM:
Harmonics due to converter, characteristic current harmonics in the 12-pulse converter, harmonic model and equivalent circuit, design of AC filters, single tune and double tuned high pass filters, second order filters and C-Type filter, Reactive power considerations of AC filters
UNIT-V
FAULTS ON AC SIDE OF CONVERTER STATION:
3-phase symmetrical fault and asymmetrical faults, commutation failure, DC circuit breaker, Ground Electrodes for HVDC system: Advantage and problems with ground return, HVDC system grounding, Resistance of electrodes- Electric current field, resistance of electrodes in uniform earth and non-uniform earth, distribution of current field between electrodes.

TEXTBOOKS:
1. HVDC transmission by S Kamakshaiah and V Kamaraju, Tata McGraw Hills Publications.

REFERENCE BOOKS:
1. K.R.Padiyar., HVDC Power Transmission System(English) 2nd edition.
2. Arillaga., High Voltage Direct Transmission, (London)Peter Peregrinus, 1981.

S.No	Course Outcomes
1	Compare the differences between HVDC and HVAC transmission.
2	Analyze the rectifier and inverter commutating circuits.
3	Discuss the different control strategies.
4	Estimate the requirement of HVDC filters.
5	Explain the role of AC system faults on HVDC system.

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY
Department of Electrical and Electronics Engineering

COURSE OUTCOME AND PROGRAM OUTCOME MAPPING

		P-Outcomes / C-Outcomes	a	b	c	d	e	f	g	h	i	j	k	l
GR20A3094	HVDC Transmissions	1. Compare the differences between HVDC and HVAC transmission.	H	H	M	M		H	H	H			H	M
		2. Analyze the rectifier and inverter commutating circuits.		H	H	M	M	H	H	M	H	M	H	H
		3. Discuss the different control strategies.	H		H	M		H		M	H		H	H
		4. Estimate the requirement of HVDC filters.		H	H	M		H	M	M	H		H	H
		5. Explain the role of AC system faults on HVDC system.	H	H	H	M		H		M	H		H	H

Academic **Y**ear : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

The Schedule for the whole Course / Subject is:

S. No.	Description	Total number of Periods
1	Unit-I: HVDC TRANSMISSION	10
2	Unit-II: HVDC CONVERTER OPERATION AND ANALYSIS	12
3	Unit-III: HVDC CONVERTER CONTROL	12
4	Unit-IV: HARMONICS IN HVDC SYSTEM	10
5	Unit-V: FAULTS ON AC SIDE OF CONVERTER STATION	12

Total No. of Instructional periods available for the course: ……56……. Periods

SCHEDULE OF INSTRUCTIONS

UNIT PLAN

Academic **Y**ear : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

S.NO	UNIT	NO: OF PERIODS	TOPIC/SUBTOPICS
1	I	2	Introduction, equipment required for HVDC systems
2	I	2	Comparison of AC and DC Transmission.
3	I	2	Limitations of HVDC transmission lines, reliability of HVDC systems, comparison of HVDC link with EHVAC link
4	I	2	HVDC convertors, HVDC –VSC transmission System, VSC system components
5	I	2	Control of Active and reactive power, Applications of VSC systems

No of Instructional Periods required to complete the lesson ....10.... periods

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY
Department of Electrical and Electronics Engineering

SCHEDULE OF INSTRUCTIONS

UNIT PLAN

Academic **Y**ear : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

S.NO	UNIT	NO: OF PERIODS	TOPIC/SUBTOPICS
1	II	2	Thyristors and their characteristics, silicon rectifier, 6 pulse convertor configuration
2	II	2	ideal communication process without gate control, DC output voltage
3	II	2	gate control of valves, analysis of voltage wave forms with overlap angle
4	II	2	analysis of communication circuits , equivalent circuit of rectifier, Inverter operation with overlap
5	II	2	Equivalent circuit of inverter
6	II	2	complete equivalent circuit of HVDC link, power factor and reactive power of converters

No of Instructional Periods required to complete the lesson ....12.... periods

SCHEDULE OF INSTRUCTIONS

UNIT PLAN

Academic Year : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

S.NO	UNIT	NO: OF PERIODS	TOPIC/SUBTOPICS
1	III	2	AC transmission and its control , necessary of dc link control
2	III	2	rectifier control , inverter control , constant beta control, constant gamma control
3	III	2	compounding of rectifiers, current compounding of inverter , complete HVDC system characteristics
4	III	2	power reversal in DC link, voltage dependent current order limit(VDCOL)
5	III	2	system control hierarchy ,individual phase control, cosine control of phase delay
6	III	2	linear control phase delay , equidistance pulse control, pulse frequency control , constant current control

No of Instructional Periods required to complete the lesson ….12…. periods

SCHEDULE OF INSTRUCTIONS

UNIT PLAN

Academic **Y**ear : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

S.NO	UNIT	NO: OF PERIODS	TOPIC/SUBTOPICS
1	IV	2	Harmonics due to converter , characteristic current harmonics in the 12 pulse converter
2	IV	2	harmonic model and equivalent circuit ,design of AC filters
3	IV	2	single tune and double tuned high pass filters
4	IV	2	second order filters and C-Type filter
5	IV	2	Reactive power considerations of AC filters

No of Instructional Periods required to complete the lesson ….10…. periods

SCHEDULE OF INSTRUCTIONS

UNIT PLAN

Academic **Y**ear : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

S.NO	UNIT	NO: OF PERIODS	TOPIC/SUBTOPICS
1	V	2	3-phase symmetrical fault and asymmetrical faults
2	V	2	commutation failure, DC circuit breaker
3	V	2	Ground Electrodes for HVDC system
4	V	2	Advantage and problems with ground return, HVDC system grounding
5	V	2	Resistance of electrodes- Electric current field, resistance of electrodes in uniform earth and non-uniform earth
6	V	2	distribution of current field between electrodes.

No of Instructional Periods required to complete the lesson ….12…. periods

LESSON PLAN

Academic Year : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

S.NO	UNIT	NO: OF PERIOD	DATE	TOPIC/SUBTOPICS	CO No.
1	I	2	18-Jan-23	Introduction, equipment required for HVDC systems	1
2	I	1	20- Jan-23	Comparison of AC and DC Transmission.	1
3	I	2	25-Jan-23	Limitations of HVDC transmission lines, reliability of HVDC systems, comparison of HVDC link with EHVAC link	1
4	I	2	27-Jan-23	HVDC convertors, HVDC –VSC transmission System, VSC system components	1
5	I	1	01-Feb-23	Control of Active and reactive power, Applications of VSC systems	1
6	I	2	03-Feb-23	Revision	
7	II	1	08-Feb-23	Thyristors and their characteristics, silicon rectifier, 6 pulse convertor configuration	2
8	II	2	10-Feb-23	ideal communication process without gate control, DC output voltage	2
9	II	2	15-Feb-23	gate control of valves, analysis of voltage wave forms with overlap angle	2
10	II	1	16-Feb-23	analysis of communication circuits , equivalent circuit of rectifier, Inverter operation with overlap	2
11	II	2	22-Feb-23	Equivalent circuit of inverter	2
12	II	2	24-Feb-23	complete equivalent circuit of HVDC link, power factor and reactive power of converters	2
13	II	1	27-Feb-23	Revision	
14	III	2	02-Mar-23	AC transmission and its control , necessary of dc link control	3

15	III	2	08-Mar-23	rectifier control, inverter control, constant beta control, constant gamma control	3
16		1	10-Mar-23	Revision	
17		2	14-Mar-23	Revision	
18			16-Mar-23	Mid Exam	
19			18-Mar-23	Mid Exam	
20	III	2	20-Mar-23	compounding of rectifiers, current compounding of inverter, complete HVDC system characteristics	3
21	III	1	22-Mar-23	power reversal in DC link, voltage dependent current order limit (VDCOL)	3
22	III	2	27-Mar-23	system control hierarchy, individual phase control, cosine control of phase delay	3
23	III	1	31-Mar-23	linear control phase delay, equidistance pulse control, pulse frequency control, constant current control	3
24	IV	2	04-Apr-23	Harmonics due to converter, characteristic current harmonics in the 12-pulse converter	4
25	IV	2	08-Apr-23	harmonic model and equivalent circuit, design of AC filters	4
26	IV	2	16-Apr-23	single tune and double tuned high pass filters	4
27	IV	2	18-Apr-23	Revision	4
28	IV	1	21-Apr-23	second order filters and C-Type filter	4
29	IV	2	24-Apr-23	Reactive power considerations of AC filters	4
30	IV	1	27-Apr-23	Revision	4
Summer Vacation (01-05-2023 to 20-05-2023)					
31	V	2	24-May-23	3-phase symmetrical fault and asymmetrical faults	5
32	V	1	26-May-23	commutation failure, DC circuit breaker	5
33	V	2	02-Jun-23	Ground Electrodes for HVDC system	5
34	V	2	04-Jun-23	Advantage and problems with ground return, HVDC system grounding	5
35	V	2	08-Jun-23	Resistance of electrodes- Electric current field, resistance of electrodes in uniform earth and non-uniform earth	5
36	V	2	10-Jun-23	distribution of current field between electrodes.	5
37	V	1	12-Jun-23	Revision	

GUIDELINES TO STUDY THE COURSE/SUBJECT

Academic Year : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

Course Design and Delivery System (CDD):

- The Course syllabus is written into number of learning objectives and outcomes.
- These learning objectives and outcomes will be achieved through lectures, assessments, assignments, seminars, presentations.
- Every student will be given an assessment plan, criteria for assessment, scheme of evaluation and grading method.
- The Learning Process will be carried out through assessments of Knowledge, Skills and Attitude by various methods and the students will be given guidance to refer to the text books, reference books.

The faculty be able to –

- Understand the principles of Learning
- Develop instructional objectives for a given topic
- Prepare course, unit and lesson plans
- Use appropriate teaching and learning aids like Slides and Paper Presentation.
- Plan and deliver lectures effectively.
- Provide the students of availability of the content in the textbooks and Internet.
- Provide feedback to students using various methods of Assessments and tools of Evaluation
- Act as a guide, advisor, counselor, facilitator, and motivator and not just as a teacher alone.

TEACHING STARTEGIC PLAN

Academic Year : **2022 - 23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

1. TARGET:

a) Percentage for pass: 100%

b) Percentage of class: 100%

2. COURSE PLAN & CONTENT DELIVERY

- PPT presentation of the Lectures
- Solving exercise programs
- Model questions

3. METHOD OF EVALUATION

1. Continuous Assessment Examinations (CAE-I, CAE-II)
2. Assignments
3. Quiz in Moodle
4. Class tests
5. Semester/End Examination

UNIT-I

COMPARISON OF AC AND DC TRANSMISSION:-

Economic Factors:-

⇒ The cost of a transmission line includes the investment and operational costs.

⇒ The investment includes cost of Right of way (ROW), transmission towers, conductors, insulators and terminal equipment.

⇒ The operational costs include mainly the cost of losses.

⇒ Lines designed with the same insulation level, a DC line can carry as much power with two conductors as an AC line with 3 conductors of the same size.

⇒ For a given power level, DC lines requires less ROW, simpler and cheaper towers and reduced conductor and insulator costs.

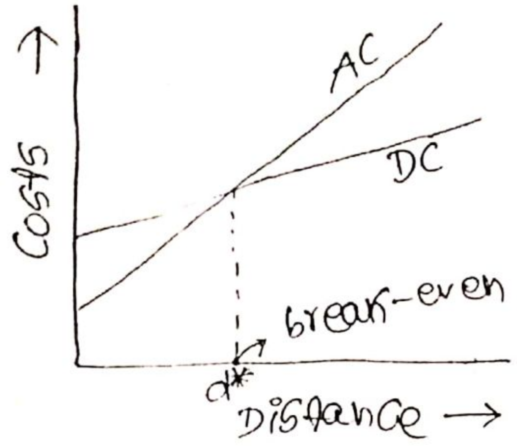
⇒ The power losses are also reduced with DC as there are only two conductors.

⇒ The absence of skin effect with DC is also beneficial in reducing power losses marginally.

⇒ the dielectric losses in case of power cables is also very less for DC transmission.

⇒ The corona effects tend to be less significant on DC conductors than for AC and this also leads to the choice of economic size of conductors with DC transmission.

⇒ DC lines donot require compensation but the terminal equipment costs are increased due to the presence of converters and filters.



• Fig. Variation of costs with line length.

⇒ If the transmission distance is shorter than the break-even distance, ac transmission is chealer than DC.

⇒ If the transmission distance is longer than the break-even distance, dc transmission is chealer than ac.

⇒ The break even distances can vary from 500 to 800km in overhead lines depending on the per unit line costs.

Advantages and disadvantages of HVDC transmission:

1). Greater power per conductor.

2). Simpler line construction.

3). Ground return can be used.

4). Hence each conductor can be operated as an independent circuit.

5). No charging current.

6). No skin effect.

7). Cables can be worked at a higher voltage gradient.

8). Line power factor is always unity; line does not require reactive compensation.

9). Less corona loss and radio interference, especially in foul weather, for certain conductor diameter and rms voltage.

10). Synchronous operation is not required.

11). Hence distance is not limited by stability.

12). May interconnect ac systems of different frequencies.

13). Low short-circuit current on dc line.

14). Tie-line power is easily controlled.

Disadvantages:—

1). Converters are expensive.

2). Converters require much reactive power.

3). Converters generate harmonics, requiring filters.

4). Converters have little overload capability.

5). Power-tapping is not possible in DC transmission.

6). Inability to use transformers to change voltage levels.

Reliability:—

⇒ The reliability of DC transmission systems is quite good and comparable to that of AC systems.

⇒ The performance of thyristor valves is much more reliable than mercury arc values and further developments in devices, control and protection is likely to improve the reliability level.

⇒ There are two measures of overall system reliability - energy availability and transient reliability.

Energy availability:-

$$\text{Energy availability} = 100\left(1 - \frac{\text{equivalent outage time}}{\text{total time}}\right)\%$$

Transient reliability:-

$$\text{Transient reliability} = \frac{100 \times \text{No. of times HVDC systems performed as designed}}{\text{No. of recordable AC faults}}$$

⇒ Both energy availability and transient reliability of existing DC systems with thyristor valves is 95% or more.

Applications of HVDC system:-

⇒ The main areas of application based on the economics and technical performances, are

1. Long distance bulk power transmission.
2. The underground or submarine cables.

Scanned by CamScanner

3. Asynchronous connection of AC system with different frequencies.

4. Control and stabilize the power system with power flow control.

5. Based on the interconnection, three types of HVDC links are possible.

6. HVDC transmission system where bulk power is transmitted from ~~the~~ one point to another point over long distance.

7. Back-to-back DC link where rectification and inversion is carried out in the same converter station with very small or no DC lines.

8. This is basically used to control the power and stabilize the system. It is also used, sometimes, to connect two different frequencies systems.

9. Parallel connection of AC and DC links where both AC and DC lines run parallel. It is mainly used to modulate the power of AC line.

10. Due to its fast control DC line can improve the transient stability of the system.

<u>Terminal equipment of HVDC transmission system.</u>

Essential requirements of HVDC system are

(a) 6/12-pulse converters.

(b) Converter transformer with suitable ratio and tap changing.

(c) Filters both on the AC side and on the DC side to take care of the harmonic generation at the converters and to reduce the harmonics

(d) A smoothing reactor in the DC side to reduce the harmonic currents in the DC line and possible transient over currents.

(e) shunt capacitors to complement the reactive power generated by the converters as they operate on lagging power factor and take lagging current

(f) DC transmission line or DC cables for power transmission.

⇒ A typical layout of HVDC transmission system is shown in below fig.

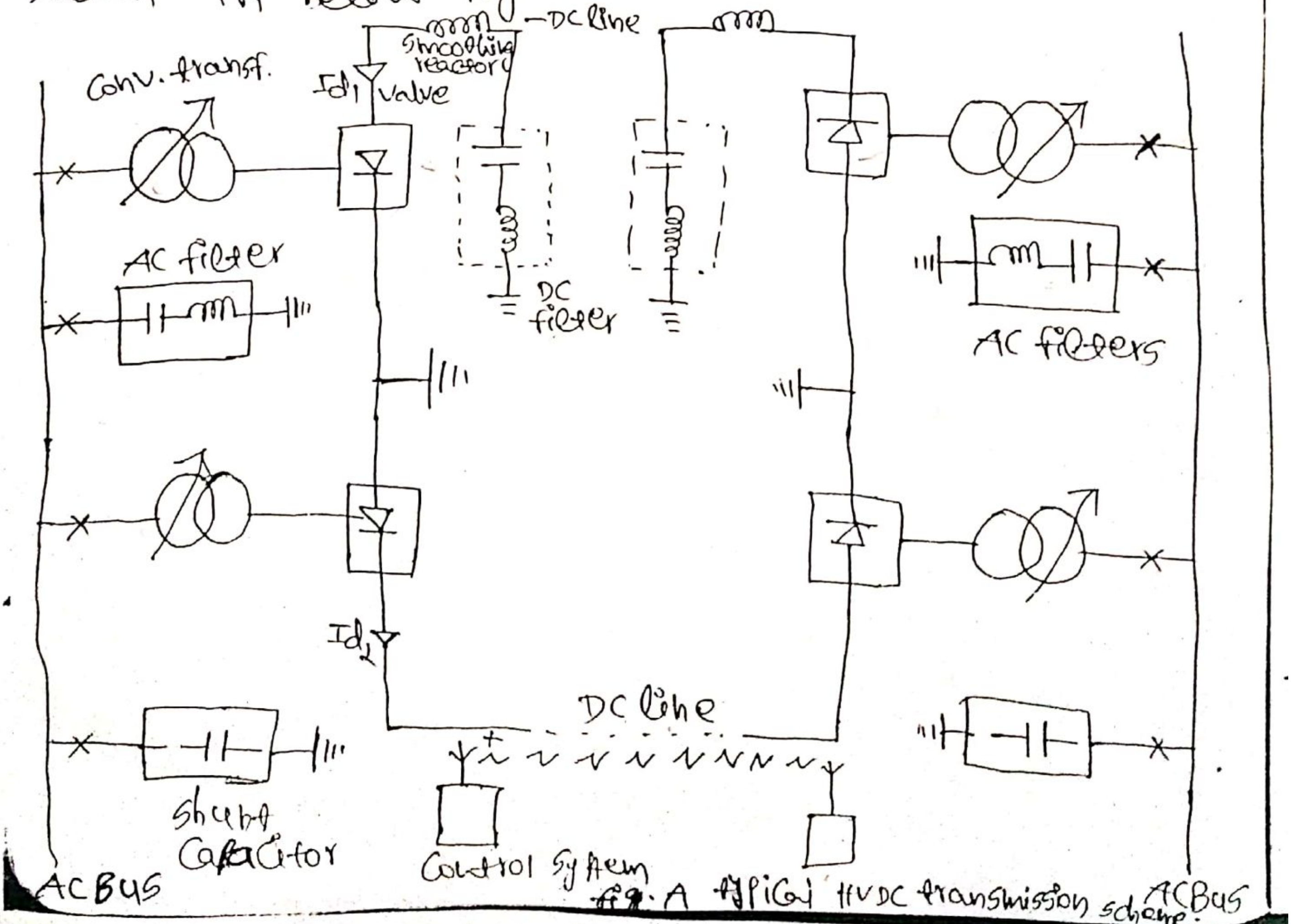


fig. A typical HVDC transmission scheme.

UNIT- I

Parts of HVDC system

1) Converters :-

⇒ Converters are the main Part of the HVDC System.

⇒ each HVDC line has at least two Converters, One at each end.

⇒ Sending end Converter works as rectifier (Converts AC Power to DC Power) however Converter at receiving end works as inverter (Converts DC Power to AC Power).

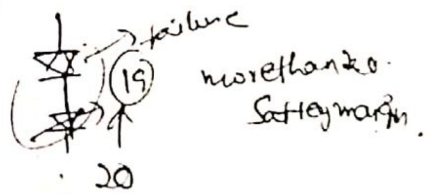
⇒ Several thyristors are Connected in series and/or Parallel to form a valve to achieve higher voltage / Current ratings.

Switches are → Thyristors, GTO, IGBT, MCT, MOSFET.

100KV , IKA.
↓ ↓
series Thyristor — Parallel Thyristors

(1) switch rating 5KV, IKA.

$\frac{100}{5} = 20$ Switches



⇒ The Current rating of Converter Stations Can be increased by putting

- Valves in Parallel
- Thyristors in Parallel
- Bridges in Parallel
- Some Combinations of above.

⇒ Voltage rating of Converter Station Can be increased by

- valves in series
- Bridges in series
- Combination of above.

⇒ Bridge Converters are normally used for HVDC transmission systems.

The main requirements of the valves are:

⇒ To allow current flow with low voltage drop across it during the conduction phase and to offer high resistance during non-conducting phase.

⇒ To withstand high peak inverse voltage (PIV) during non-conducting period.

⇒ To allow a reasonably short-commutation margin angle during inverter operation.

⇒ smooth control of conducting and non conducting phases.

⇒ Two versions of switching converters are feasible depending on whether the DC storage device utilized is

- an inductor → Called Current source converter (CSC), or
- a Capacitor → Called voltage source converter (VSC)

⇒ CSC is used in traditional HVDC transmission.

⇒ VSC is used in SVC, STATCOM, active filters etc.

CSC	VSC
⇒ inductor is used in DC side	⇒ Capacitor is used in dc side
⇒ Constant Current	⇒ Constant voltage

⇒ Higher losses (I^2R constant — I constant)	⇒ more efficient (I^2R variable I variable)
⇒ Fast accurate control	⇒ slow control
⇒ Larger and more expensive	⇒ smaller and less expensive
⇒ More fault tolerant and more reliable	⇒ Less fault tolerant and less reliable.
⇒ simpler control	⇒ complex control
⇒ not easily expandable in series	⇒ Easily expanded in parallel for increased rating

Converter Transformer :—

⇒ For six-pulse converter, a conventional 3-phase or three single-phase transformers are used.

⇒ However for 12-pulse converter configuration, following transformers are used

- six single-phase two winding
- three single-phase three winding
- Two 3-phase two winding

⇒ In converter transformer it is not possible to use winding close to yoke since the potential of its winding connection is determined by conducting valves.

⇒ Hence entire winding is completely insulated.

⇒ As leakage flux of a converter transformer contains very high harmonic contents, it produces greater eddy current loss and hot spots in the transformer tank.

⇒ In case of 12-pulse configuration, if two three-phase transformers are used, one will have Y-Y connection and second will have Y-Δ Connection to give phase shift of 30°.

⇒ Since fault current due to fault across value is predominantly controlled by transformer impedance, the leakage impedance of converter transformer is higher than the conventional transformer.

⇒ On-line tap changing is used to control the voltage and reactive power demand.

Smoothing Reactors:-

⇒ As its name, these reactors are used for smoothing the DC current output in the DC line.

⇒ It also limits the rate of rise of the fault current in the case of DC line short circuit.

⇒ Normally partial or ~~total~~ air cored magnetically shielded reactors are used

⇒ Disc coil type winding are used and braced to withstand the short circuit current.

⇒ The saturation inductance should not be too low.

Harmonic Filters:-

⇒ Harmonics generated by converters are of the order of $np \pm 1$ in AC side and np in DC side. where p is number of pulses and n is integer.

⇒ Filters are used to provide low impedance path to the ground for the harmonic currents.

⇒ They are connected to the Converter terminals so that harmonics should not enter to AC system.
⇒ However, it is not possible to protect all harmonics from entering into AC system.
⇒ ~~However~~ Magnitudes of some harmonics are high and filters are used for them only.
⇒ These filters also provide some reactive power compensation at the terminals.

Overhead Lines:-

⇒ As monopolar transmission scheme is most economical and the first consideration is to use ground as return path for DC current.
⇒ But use of ground as conductors is not permitted for longer use and a bipolar arrangement is used with equal and opposite currents in both poles.
⇒ In the case of failure in any poles, ground is used as a return path temporarily.
⇒ The basic principle of design of DC overhead lines is almost same as AC lines (design) design such as configurations, towers, insulators, etc.
⇒ The number of insulators and clearances are determined based on DC voltage.
⇒ The choice of conductors depends mainly on corona and field effect considerations.

⇒ Reactive Power Source :-

⇒ As such converter does not consume reactive power but due to phase displacement of current drawn by converter and the voltage in AC system, reactive power requirement at a converter station is about 50-60% of real power transfer, which is supplied by filters, capacitors and synchronous condensers.

⇒ Synchronous condensers are not only supplying the reactive power but also provide AC voltages for natural commutation of the inverter.

⇒ Due to harmonics and transients, a special designed machine is used.

Earth electrodes :-

⇒ The earth resistivity at upper layer is higher (~ 4000 ohm-m) and electrodes cannot be kept directly on the earth surface.

⇒ The electrodes are buried into the earth where resistivity is around 3-10 ohm-m to reduce transient over-voltages during line faults and also gives low DC electric potential and potential gradient at the surface of earth.

⇒ The location of earth electrodes is also important due to

• Possible interference of DC current ripple to power lines, communication systems of telephone and railway signals etc.

• metallic corrosion of pipes, cable sheaths etc

• public safety.

⇒ The electrodes must have low resistance (less than 0.1 ohm) and buried up to 500 meters into the earth.

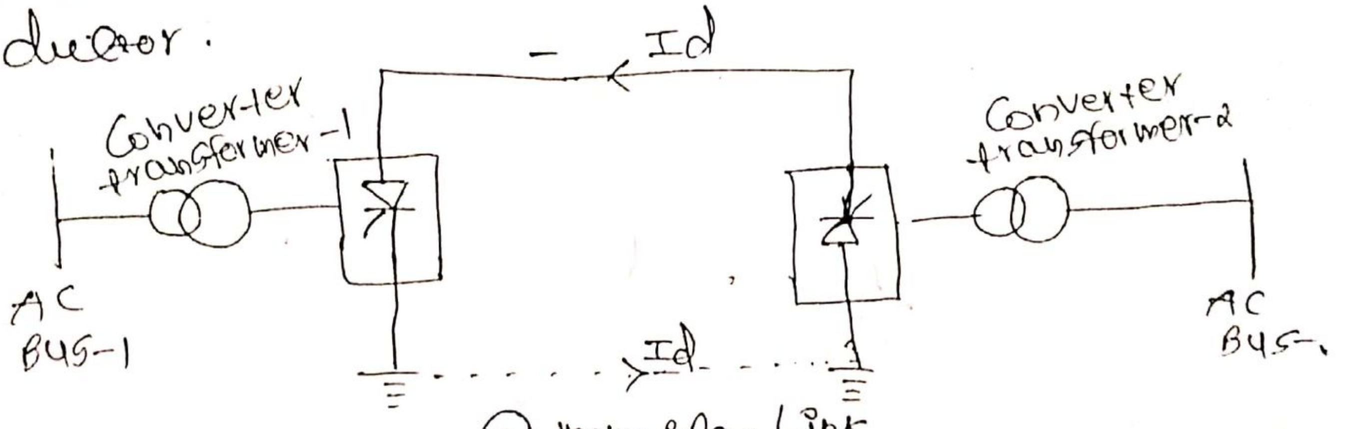
Types of HVDC links: —

There are mainly three types of HVDC links they are:

1. Monopolar Link.
2. Bipolar Link
3. Homopolar Link

1. Monopolar Link: —

⇒ A monopolar system has only one conductor with ground as return conductor, and it is usually of a negative polarity. It is suitable in submarine systems where sea water can be used as a return conductor.



(a) monopolar Link

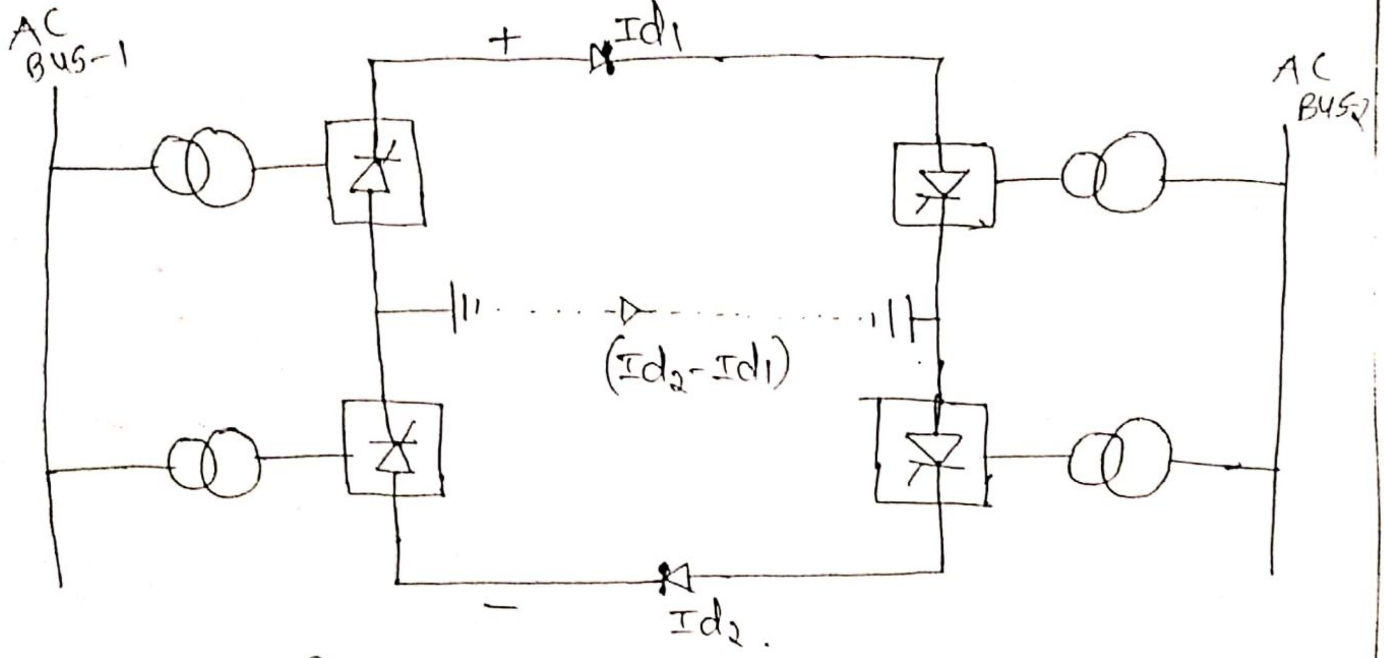
2. Bipolar Link: —

→ A bipolar system has two conductors, one of positive and other of negative polarity. The mutual or ground point is maintained at the mid-potential.

⇒ Each terminal of a bipolar system has two converters of equal voltage ratings connected in series.

⇒ If both neutrals are grounded then two poles operate at equal current and there is no ground current.

⇒ In the event of fault in one conductor, the other conductor with ground return can be used up to half the rated load or power with the rated current of the pole.



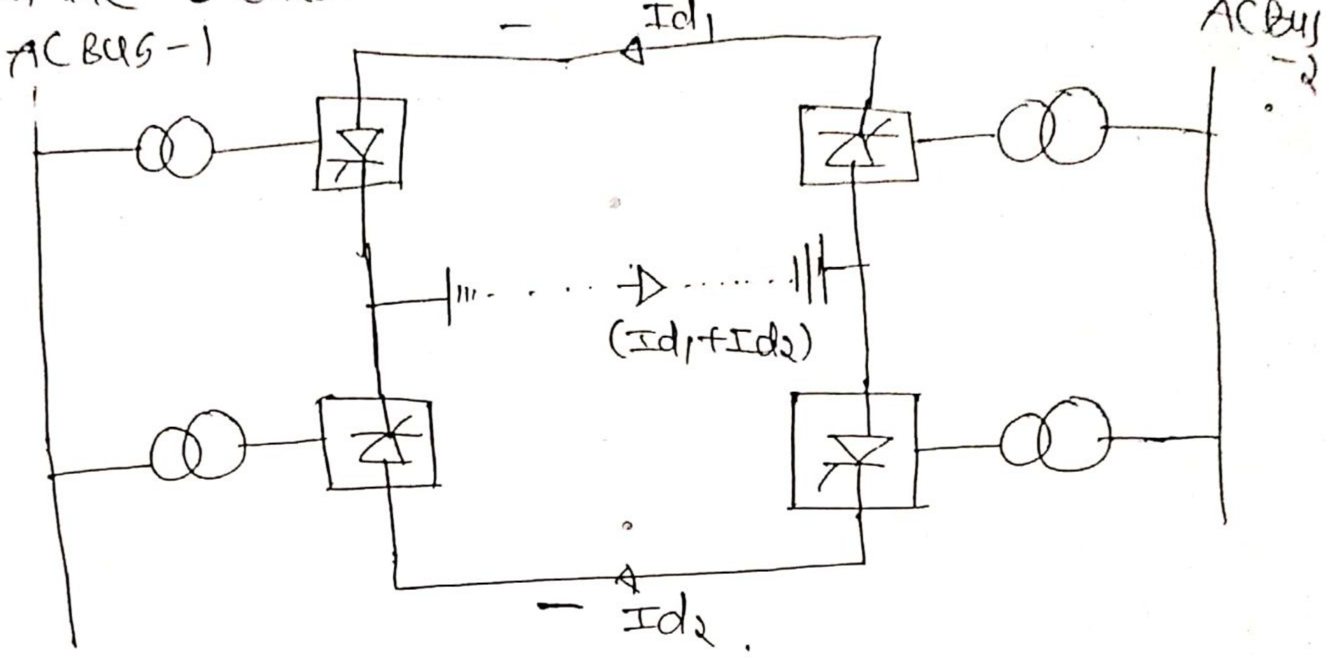
(b) Bipolar Link (unbalanced operation).

3. Homopolar Link

⇒ Homopolar system has two or more conductors with the same polarity, usually negative, and they always operate with ground return.

⇒ In the event of fault in one conductor, the whole converter can be connected to a healthy pole and can carry more than half the power (2-pole) by over-loading but at the expense of increased line loss.

⇒ The additional advantage is lower corona loss and radio interference due to negative polarity on the lines.



(c) Homopolar Link.

Planning for HVDC Transmission:—

⇒ The system planner the factors to be considered are i) Cost ii) technical performance, and iii) reliability

⇒ The considerations in the planning for DC depends on the application. Two applications can be considered as representative.

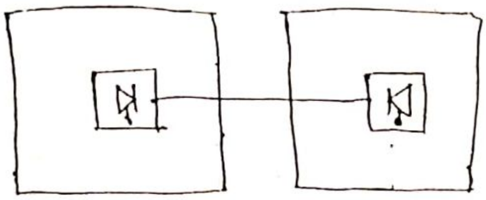
These are:

1. Long distance bulk power transmission.
2. Interconnection between two adjacent systems

⇒ In the first application, the DC and AC alternatives for the same level of system

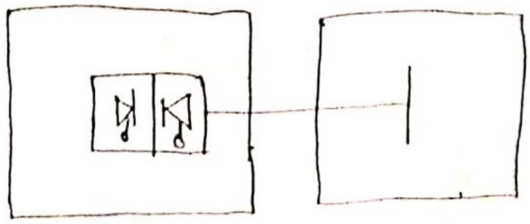
curity and reliability are likely to have the
ie power carrying capability. thus the cost
mparisons would form the basis for the selec-
ion of the DC (or AC) alternative, if the requir-
ements regarding technical performance are not
critical.

In the second application, ~~thus the choice for
e interconnection will be based on the foll~~
having settled on the DC link for interconnection,
there are three configurations for interconnection.
these are:



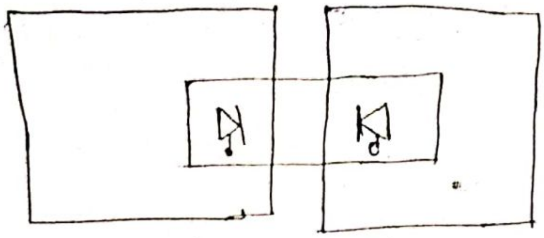
ⓐ Two terminal DC link.

⇒ A two terminal transmission where each terminal is located at a suitable place somewhere within the network and connected by a DC overhead line or cable.



ⓑ Back-to back DC link along with AC feeder.

→ a back to back HVDC station (also called HVDC coupling station) located somewhere within one of the network and an AC line from the other network to the common station.



(c) back to back DC link at Border.

=> A back to back station located close to the border between the two systems.

=> In the choice between the first and second configuration, it is to be noted that converter costs are less for the common coupling station and the AC line costs are greater than the DC line costs.

=> If the distances involved are less than 200km, the second configuration is to be prefered.

=> If the short circuit ratio (SCR) is acceptable, then the third alternative will be the most economic.

=> The following aspects also require a detailed study of the system interactions.

1. Var requirements of converter stations.
2. Dynamic over voltages
3. Harmonic generation and design of filters.
4. Damping of low frequency and subsynchronous torsional oscillations.

Modern trends in DC Transmission:—

⇒ The continuing technological developments in the areas of power semiconductor devices, digital electronics, adaptive control, DC protection equipment have increased the pace of application of DC transmission.

⇒ The major contribution of these developments is to reduce the cost of converter stations while improving the reliability and performance.

Power semiconductors and valves:—

⇒ The cost of the converters can come down if the number of devices to be connected in series and parallel can be brought down.

⇒ The power rating of thyristors is increased by better cooling methods.

⇒ As forced commutated converters operating at high voltages are uneconomic.

⇒ The development of devices that can be turned off by application of a gate signal would be desirable.

⇒ Gate turn off (GTO) thyristors are already available at 2500V and 2000A. However, the main disadvantage of GTO's is the large gate current needed to turn them off.

⇒ MOS (metal oxide semiconductor) controlled thyristor or MCT appears to be a promising technology.

⇒ In this device, a very large line current can be switched off by a small gate current.

⇒ The turn off time of MCT is also less than one third that of GTO's.

Converter Control:—

⇒ The development of micro-computer based converter control equipment has now made it possible to design systems with completely redundant converter control with automatic transfer between systems in the case of a malfunction.

⇒ Not only is the forced outage rate of control equipment reduced but it is also possible to perform scheduled preventive maintenance on the stand-by system when the converter is in operation.

⇒ The micro computer based control also has the flexibility to try adaptive control algorithms or even the use of expert systems for fault diagnosis and protection.

DC breakers:—

⇒ With the development and testing of prototype DC breakers, it will be possible to go in for tapping an existing DC link or the development of new MTDC systems.

⇒ The DC breaker ratings are not likely to exceed the full load ratings as the control intervention is expected to limit the fault current.

⇒ The possibility of decentralized control necessitated by communication failure, the coordination of control and protection are some of the issues currently being studied.

Conversion of existing AC lines:—

⇒ The constraints on ROW are forcing some utilities to look into the option of converting existing AC circuits to DC in order to increase the power transfer limit. The could be some operationals problems due to electromagnetic induction from AC circuits operating in the same ROW.

⇒ An experimental project of converting a single circuit of a double circuit 220KV line is currently under commissioning stage in india.

Operation with weak AC systems:—

⇒ The strength of AC systems connected to the terminal of a DC link is measured in terms of short circuit ratio (SCR) which is defined as

$$SCR = \frac{\text{Short Circuit level at the Converter bus}}{\text{Rated DC power}}$$

⇒ If SCR is less than 3, the AC system is said to be weak.

1.9 COMPARISON OF HVDC LINK WITH EHVAC LINK

HVDC links technically are superior to EHVAC links and are preferred for interconnection between two individually controlled AC systems. Table 1.13 shows the superiority of DC link to AC link.

Table 1.13 Comparison between DC and AC interconnection

S. No.	*Characteristics*	*HVDC Link*	*EHVAC Link*	*Criterion for Preference*
1.	Power transfer ability	High, limited by temperature rise	Lower, limited by power angle and the reactance	HVDC Link for higher power
2.	Control of power flow	Fast, accurate and bi-directional	Slow and difficult	HVDC is preferred
3.	Frequency disturbance	Reduced	Communicated between the system	HVDC is preferred
4.	System support	Excellent, power flow is quickly modulated for damping oscillation	Poor, oscillations continue for long time	HVDC is better
5.	Transient performance	Excellent	Poor	HVDC is preferred
6.	Fault levels	Remains unchanged after interconnection	Get added after the interconnection	HVDC is better
7.	Power swings	Damped quickly	Continue for long time	HVDC is better
8.	Interconnection	Asynchronous	Synchronous	HVDC is preferred
9.	Frequency conversion	Possible	Not possible	HVDC is preferred
10.	Cascade tripping of AC systems	Avoided	Likely	HVDC is preferred
11.	Spinning reserves of AC Network	Reduced	Not much reduced	HVDC is preferred
12.	Transient stability limit	Very high, limited, by thermal capacity of the equipment	Less than half of the thermal limit of line conductor	HVDC is preferred

UNIT – II

Analysis of simple Rectifier Circuits:—

Assumptions and Justifications:—

→ AC source has no impedance and delivers constant voltage of sinusoidal wave form and constant frequency.

→ If poly-phase source, it delivers balance voltages.

→ Transformers have no leakage impedance or exciting admittance.

→ The dc load has infinite inductance (i.e. dc current is constant and ripple free).

→ Valve is ideal (i.e. offers zero resistance during conduction and infinite resistance during on non-conduction state).

Some Definitions:—

→ The volt-ampere rating of valve is taken as the product of its average current and peak inverse voltage. ($P = PIV \times I_{avg}$)
I_{dc}

→ Peak inverse voltage (PIV) is the peak voltage occurs across the valve during non-conduction

Scanned by CamScanner

State.

⇒ Rating (VA) of transformer is the product of rms voltage and rms current. ($V_{rms} \times I_{rms} = P$)

⇒ Pulse number of a converter is the number of pulsations (cycle of ripples) of dc voltage per cycle of ac voltage.

⇒ A group of valves in which only one valve conducts at a time (neglecting overlap) is known as a commutation group (q)

⇒ V_{do} is the average dc voltage the terminal of converter when delay angle is zero.

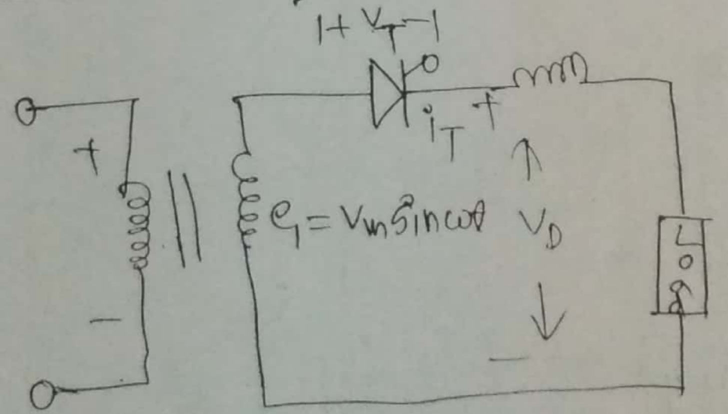
⇒ Number of series valves is represented as s.

⇒ Number of parallel valves is represented as r.

⇒ Thus,

$$P = q \times s \times r.$$

<u>Half-wave</u> <u>Rectifier</u> <u>(Single-phase)</u>.

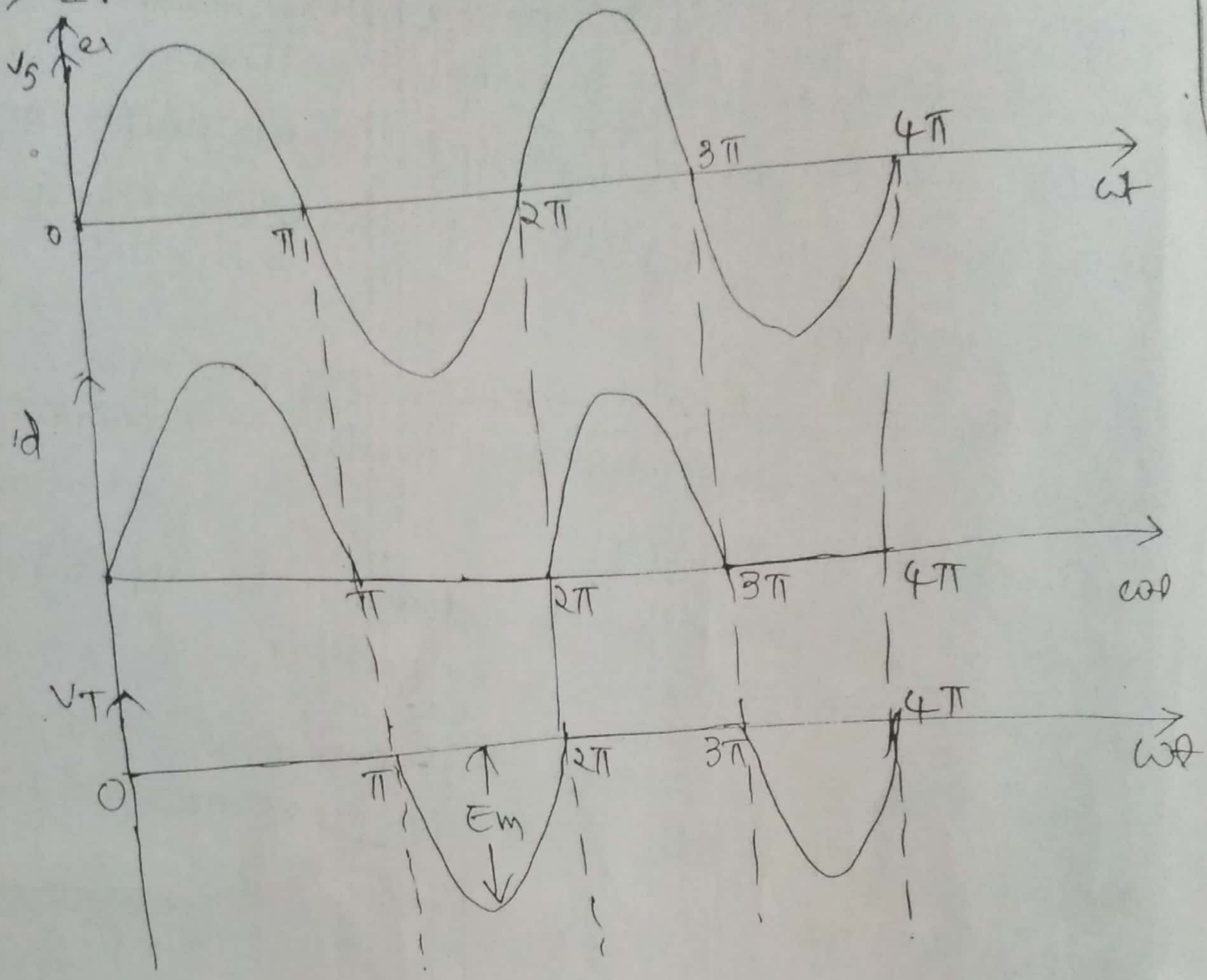


⇒ It is the simplest rectifier.

⇒ Current is inherently intermittent and thus dc current cannot be constant

⇒ DC current and voltage pulsate as the same frequency as the ac voltage and current.

> It is useful for the small power applications.



$$v_T = v_s - v_d$$

PIV = V_m.

$$V_{do} = \frac{1}{2\pi}\int_0^{\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{1}{2\pi}\left[-\cos\omega t\right]_0^{\pi} = \frac{V_m}{\pi}$$

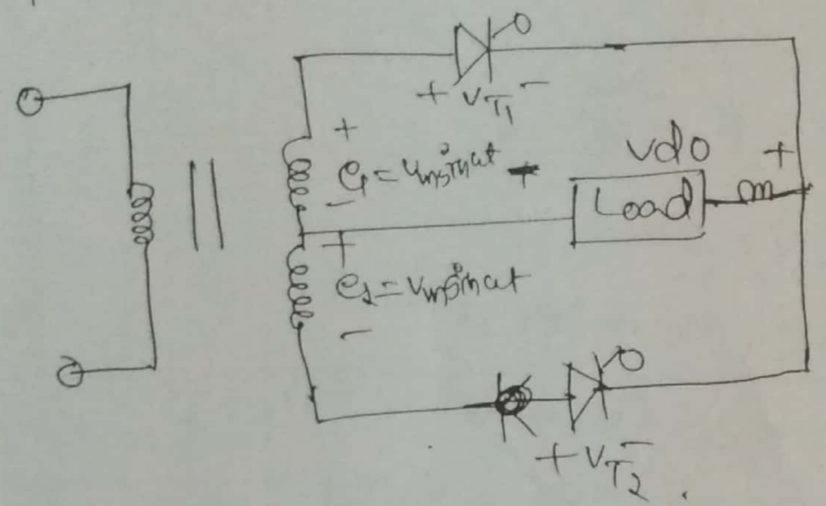
PIV = V_m.

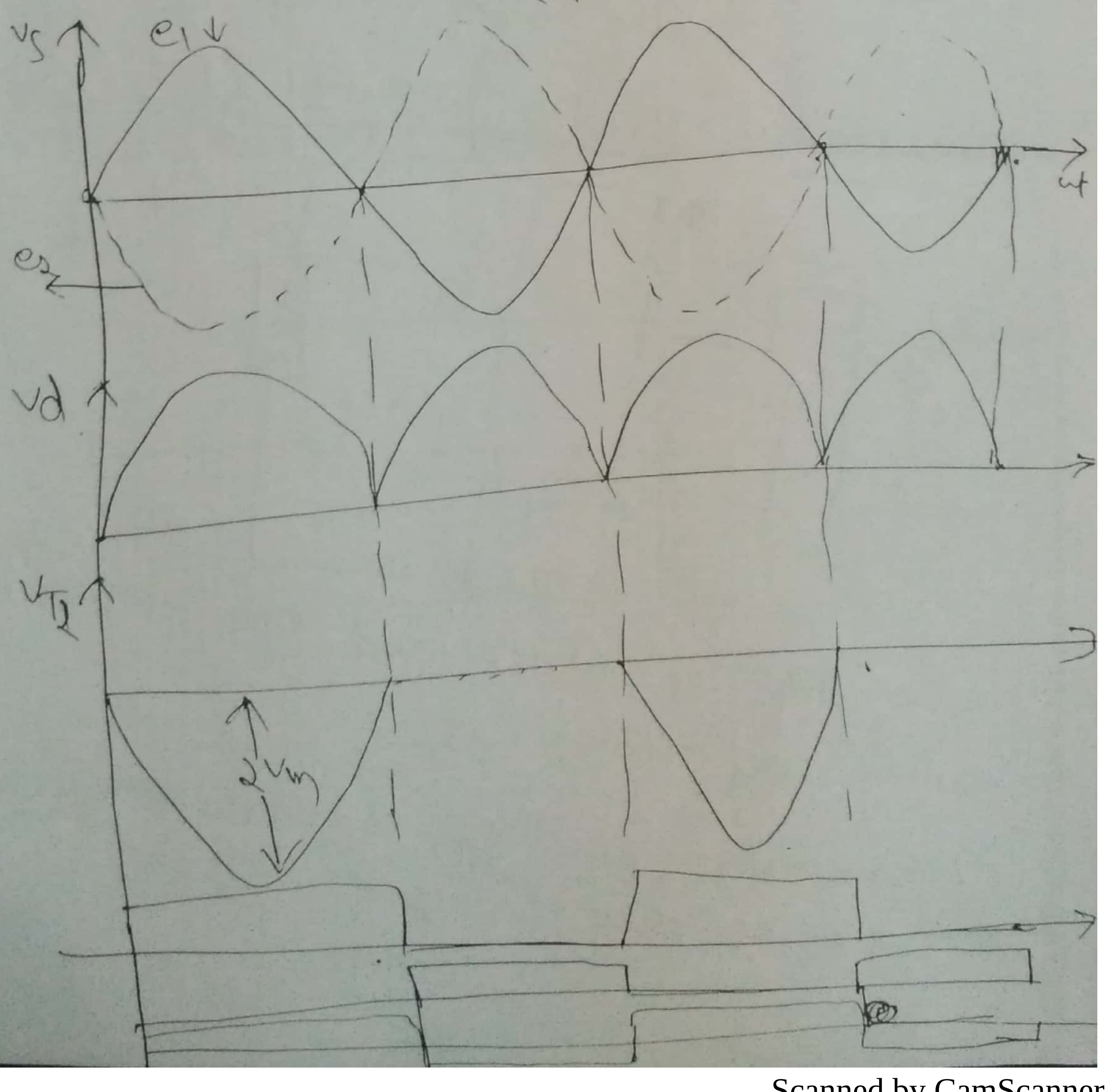
Pulse number (P) = 1

Full-wave Rectifier (single-phase):—

⇒ It has two valves and one transformer with center-tapped secondary (T:1:1).

⇒ e_1 and e_2 are having phase difference of 180°.





Scanned by CamScanner

$V_{T_2} = e_2 - V_d$

$$V_{do} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \, d\omega t$$

$$= \frac{1}{\pi}\left(-\cos\omega t\right)_0^{\pi}$$

$$= \frac{2V_m}{\pi}$$

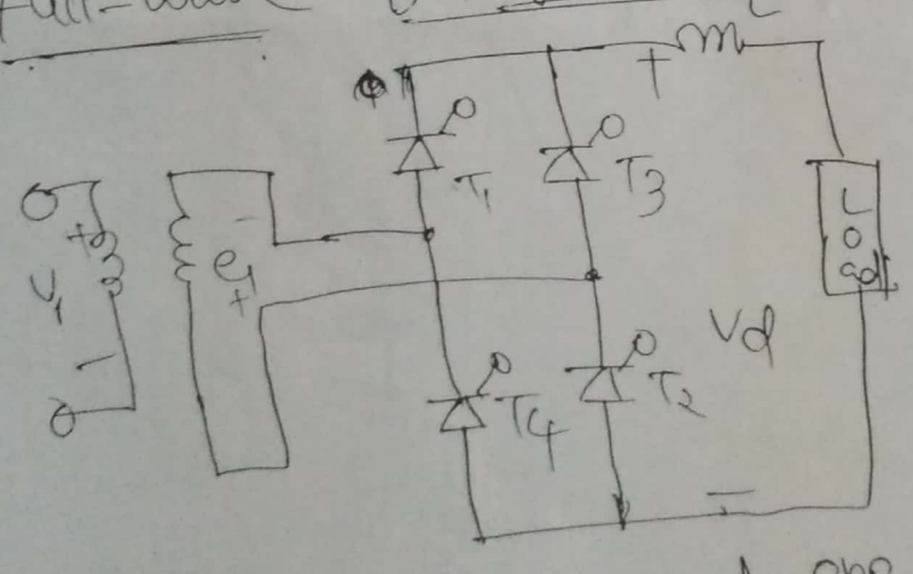
PIV = $2V_m$.

Pulse number (P) = 2.

Average Current = $I_d/2$.

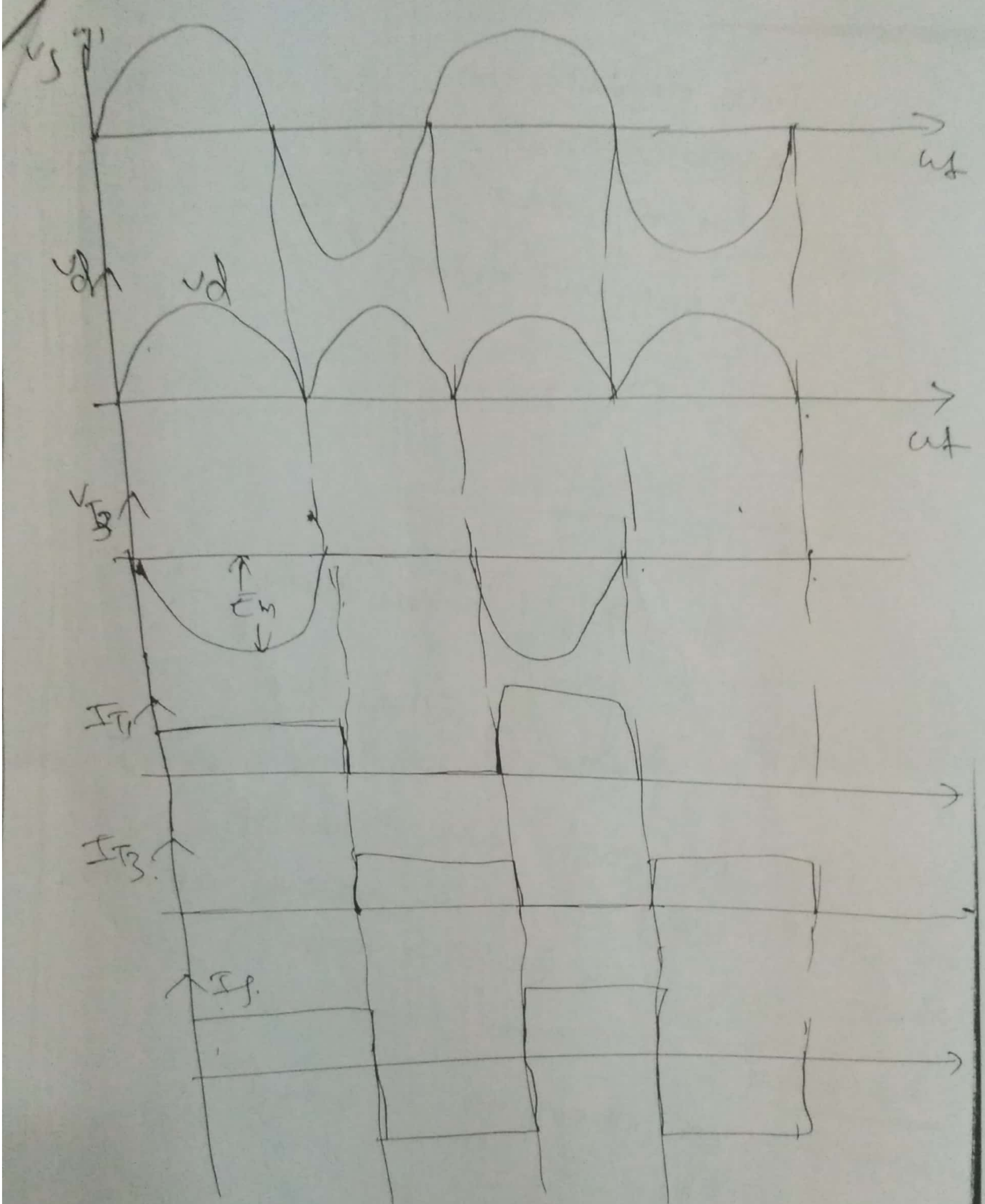
Valve rating = $V_m I_d$.

Full-wave Bridge Rectifier (1-ϕ)



⇒ It has 4 valves and one transformer having ratio T:1

→ secondary winding of Transformer is used more effectively.



$PIV = V_m$

$V_{d0} = \frac{1}{\pi}\int_0^{\pi} V_m \sin\omega t \, d\omega t$

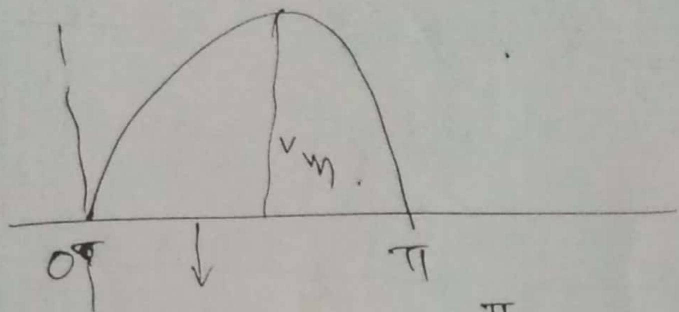
$= \frac{2V_m}{\pi}$

Pulse number = 2.

Average current = $\frac{I_d}{2}$.

⇒ Valve rating = $0.5 V_m I_d$.

⇒ But four valves.



$V_{do} = \frac{1}{\pi} \int_0^{\pi} V_m \sin\omega t \, d\omega t$.

$= \frac{1}{\pi} \int_{-\pi/2}^{\pi/2} V_m \cos\omega t \, d\omega t$

⇒ PIV of each valve is halved.

⇒ It is used for high voltage application where PIV is a limiting factor.

3-ϕ Rectifier :-

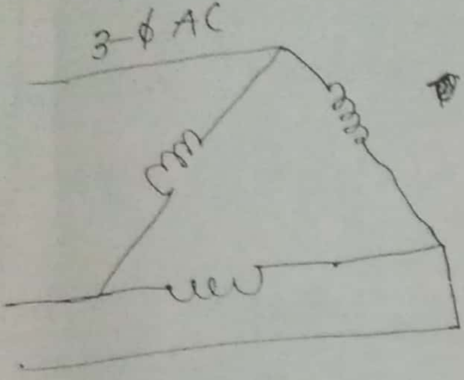
⇒ Current rating of transformer is given by

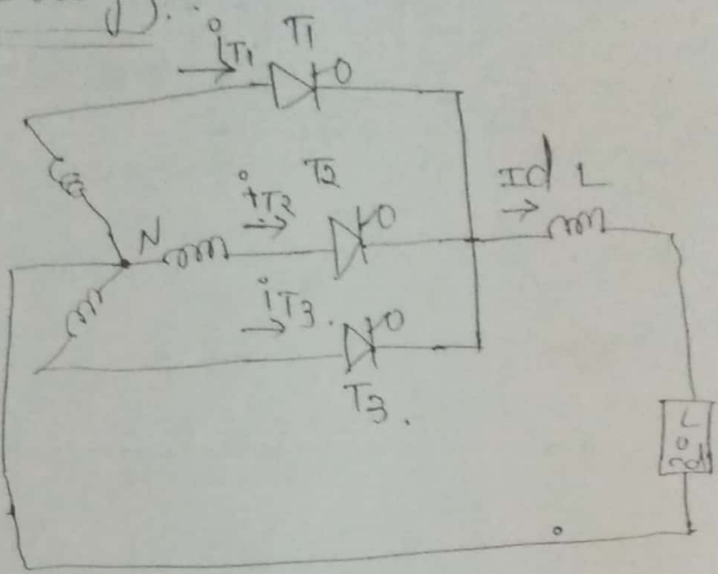
$$I_t = \frac{I_d}{r\sqrt{q}}$$

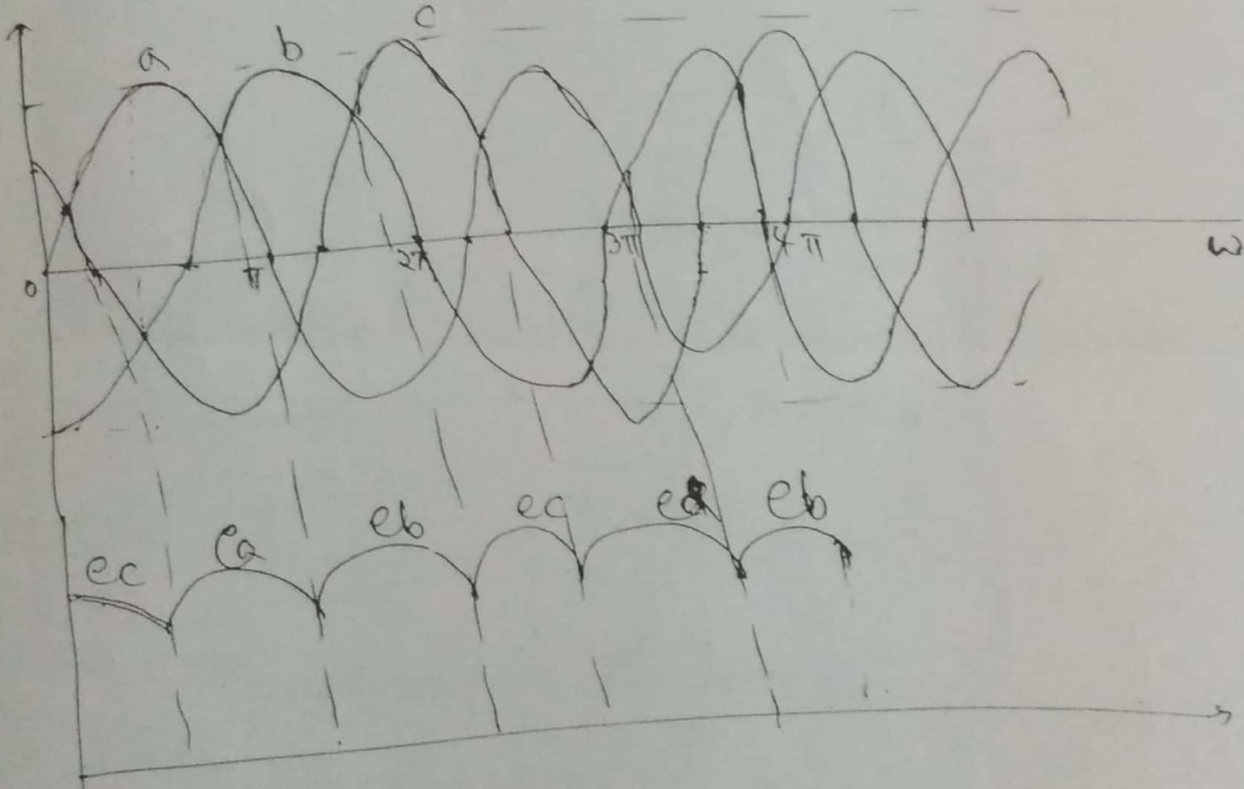
⇒ The transformer rating will be

$$P_t = p \frac{E_m}{\sqrt{2}} I_t = p \frac{E_m I_d}{r\sqrt{2q}}$$

3-ϕ Rectifier (one-way) :-





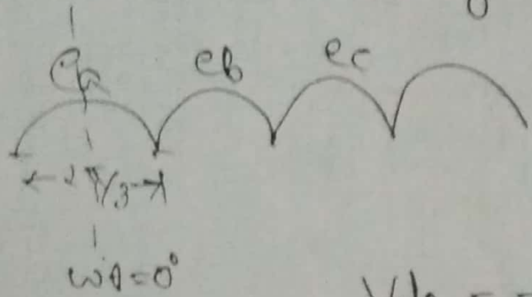


$$TUF = \frac{Pt}{V_{do}\, I_d} = \frac{p\,\dfrac{E_m I_d}{r\sqrt{2q}}}{\dfrac{q\, s\, I_d}{\pi} E_m \sin \pi/q}$$

$$= \frac{\pi}{\sqrt{2}\sqrt{q}\, \sin \pi/q}$$

$e_a = E_m \sin(\omega t + 30^\circ)$.

$$V_{do} = \frac{1}{2\pi/3} \int_0^{120} V_m \sin(\omega t + 30^\circ)\, d\omega t$$



$$V_{do} = \frac{1}{2\pi/3} \int_{-\pi/3}^{\pi/3} V_m \cos\omega t \, d\omega t .$$

$$a = \frac{1}{2\pi/3} V_m \left[\sin\omega t\right]_{-\pi/3}^{\pi/3}$$

$$V_{do} = \frac{3\sqrt{3}\, V_m}{2\pi}.$$

$$\frac{PIV}{V_{do}} = \begin{cases} \dfrac{2\pi}{q \sin \pi/q} & \text{for } q \text{ even} \\ \dfrac{\pi}{S q \sin \frac{\pi}{2q}} & \text{for } q \text{ odd} \end{cases}$$

$P = q \times r \times s$

$= 3 \times 1 \times 1$

Pulse number = 3.

$PIV = \sqrt{3}\, E_m$.

$$\text{valve-1 voltage } V_{T_1} = \begin{cases} 0 & 0 \le \omega t \le 120^\circ \\ e_a - e_b & 120^\circ \le \omega t \le 240^\circ \\ e_a - e_c & 240^\circ \le \omega t \le 360^\circ \end{cases}$$

$$V_{do} = \frac{1}{2\pi/q} \int_{-\pi/q}^{\pi/q} V_m \cos\omega t \, d\omega t$$

$$= \frac{q\, V_m}{\pi} \sin(\pi/q)$$

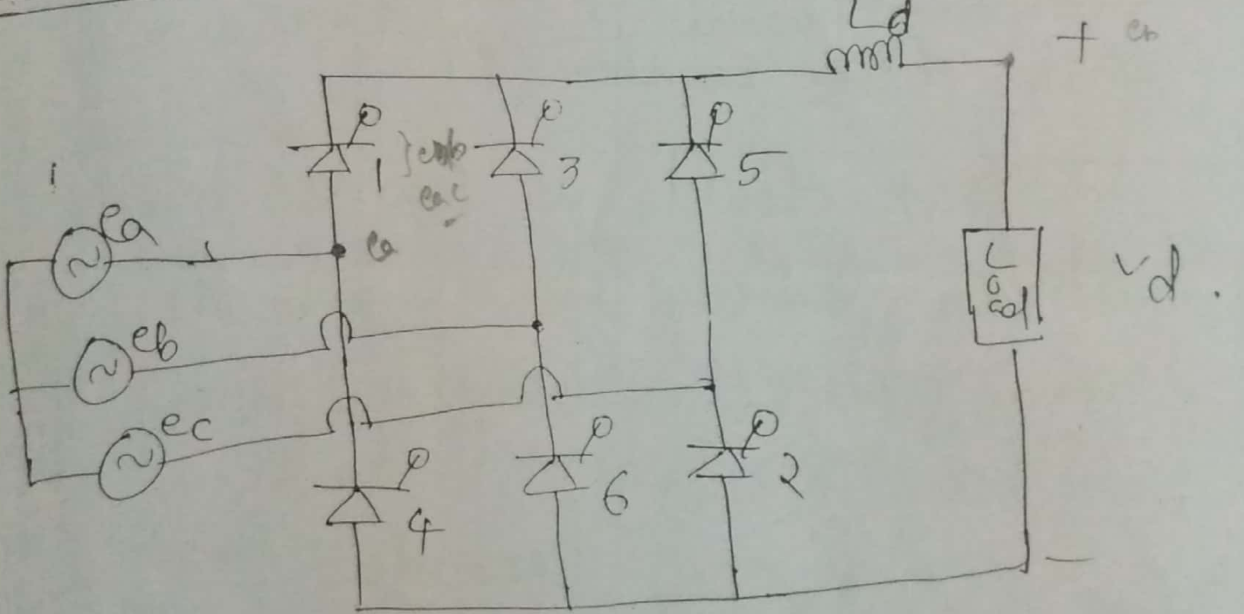
$$\frac{V_{do}}{E} = \frac{\sqrt{2}\, q s}{\pi} \sin \pi/q$$

$$V_{do} = \frac{sq\, V_m}{\pi} \sin(\pi/q).$$

Peak inverse voltage (PIV) in general terms

$$PIV = \begin{cases} 2V_m & q \text{ is even} \\ 2V_m \cos \pi/2q & q \text{ is odd.} \end{cases}$$

Three phase Two-way or 3-ϕ Bridge Rectifier:—



=) In circuit (3-ϕ, one way), if the Three valves are reversed, the circuit operates as before except the directions of dc voltage and current are reversed.

=) In the bridge converter, the same transformer is feeding two one-way rect.

-ifiers of opposite connections.

⇒ The output voltage is doubled and thus power for the same current but PIV is same. Thus useful for high voltage and high power applications.

⇒ No dc current in the transformer windings.

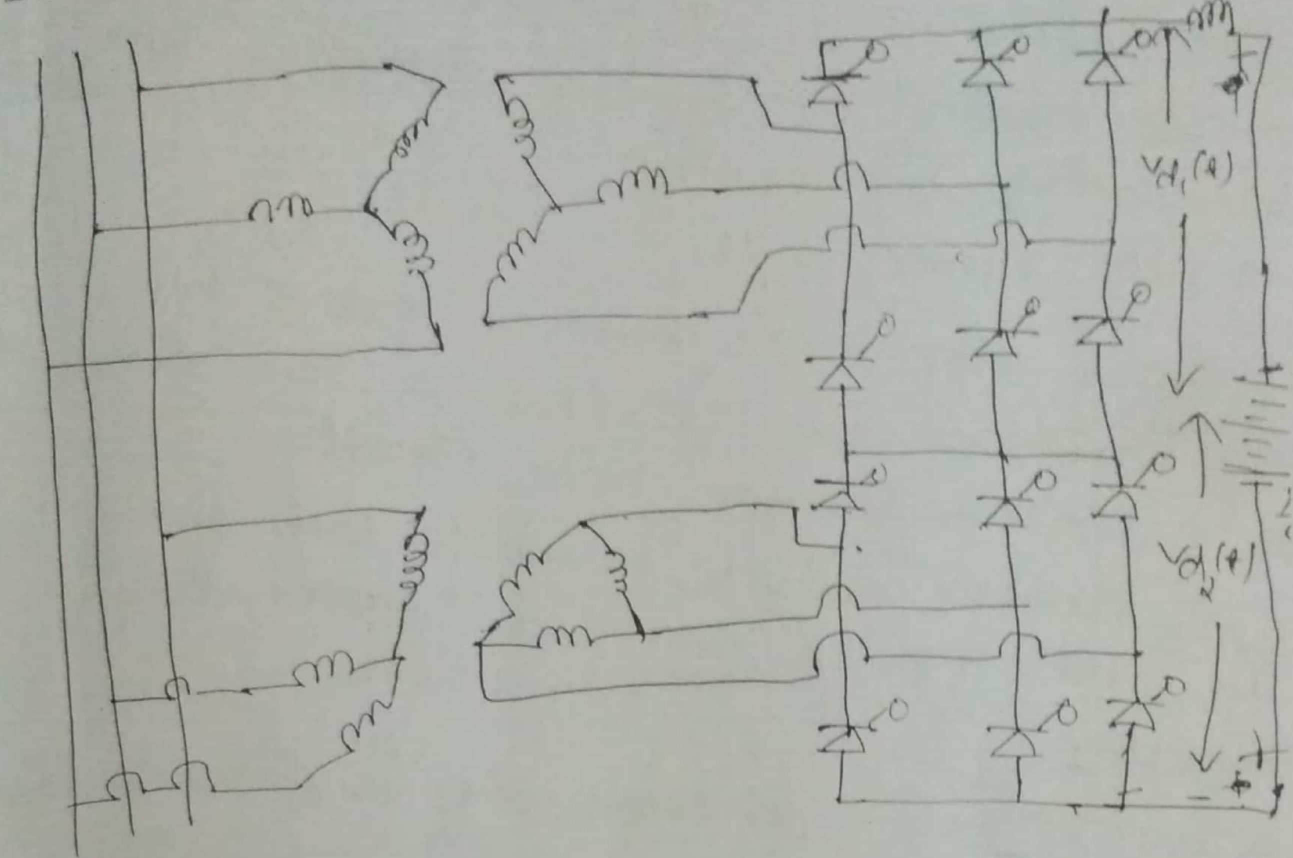
⇒ Pulse becomes six.

Desired Features of Converter Circuit :—

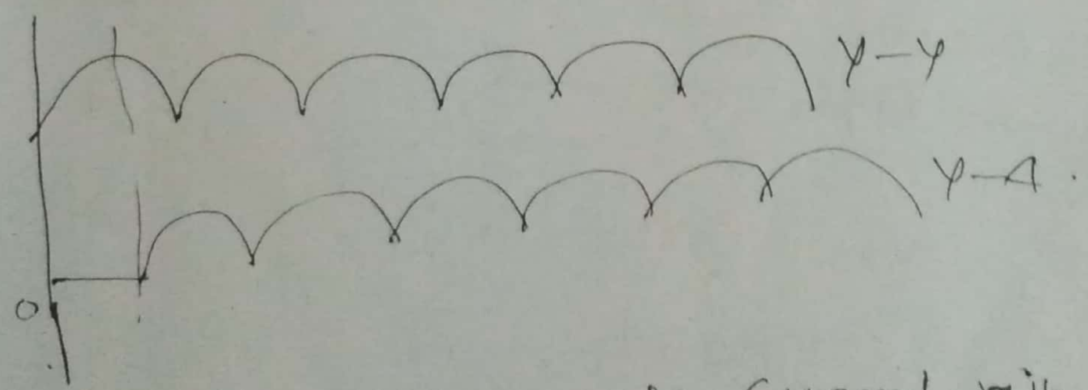
1. High pulse number (P).
2. PIV/Vdo should as low as possible.
3. Vdo/E should be as high as possible.
4. Transformer utilization factor should be near to unity.

S.NO	q	r	s	PIV/Vdo	Vdo/E	TUF
1	2	1	3	1.047	2.700	1.571
2	2	3	1	3.142	0.900	1.571
3	3	1	2	1.047	2.340	1.481
4	3	2	1	2.094	1.169	1.481
5	6	1	1	2.094	1.350	1.814

12-Pulse Converter:—



⇒ we can make the two six pulses and we will shift by certain angle means 30 degree, we will get the twelve pulse.



⇒ one Transformer is connected in Y-Y another is connected in Y-Δ. There two are putting in series we are getting in the twelve pulse.

⇒ most of the HVDC links they are operating on the twelve pulse converter basis.

transformers

⇒ due to the star-delta ~~[struck]~~. phase shift

some there is a 30 degree

⇒ This leading or lagging depending upon the winding configurations.

⇒ pulse number is 12.

⇒ going for large number of pulses here, the harmonics are less. like a here the

⇒ DC output becomes more smooth.

⇒ AC harmonics and DC harmonics both in this case the twelve pulses are better than six pulses.

⇒ For p pulse converter the harmonics components are $np \pm 1$.

6 pulse case → 5, 7, 11, 13 . . . .

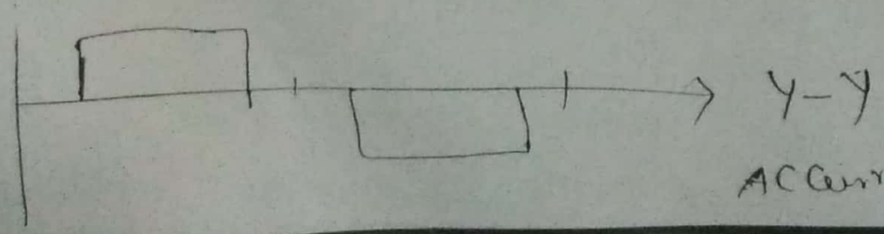
12 pulse case → ~~X~~ , 11, 13, ...

⇒ Those are the lower harmonics component having the higher magnitude

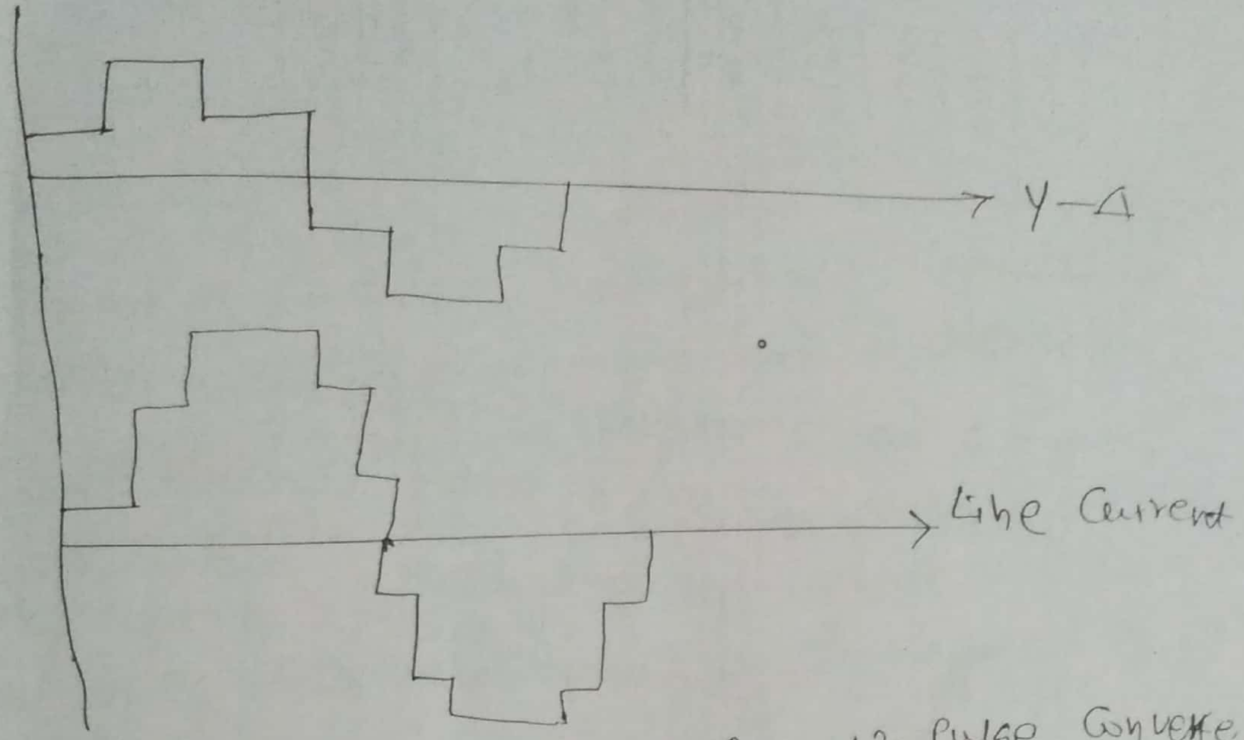
$$V_{do} = V_{d1} + V_{d2}.$$

$$= 2V_{d1}$$

$$= 2 \times \frac{3\sqrt{3}}{\pi} V_m.$$

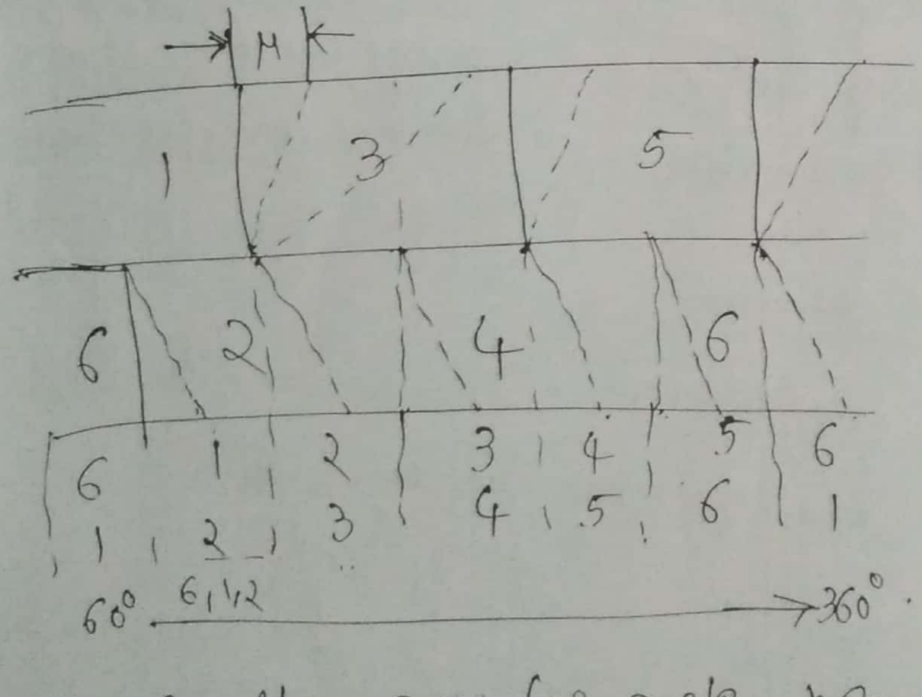


AC current waveform



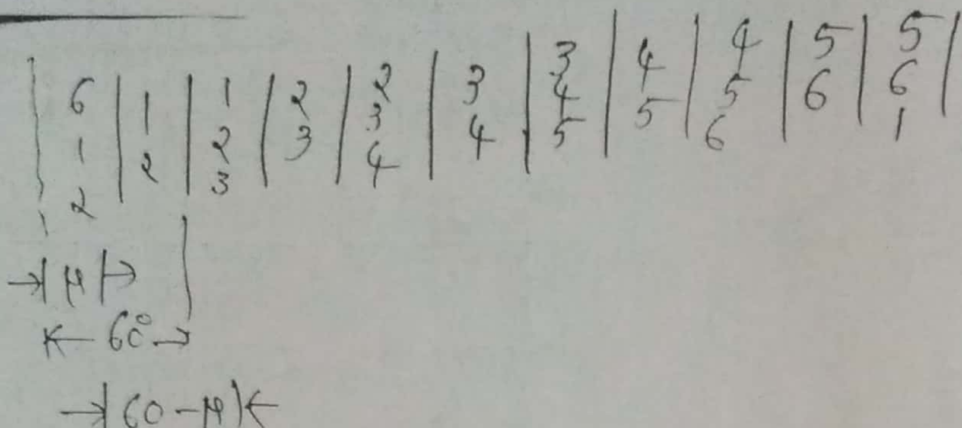
AC current waveform in a 12-Pulse Converter.

Effect of Source inductance on the system:—



⇒ μ is the over lap angle. means this is the period in the degree that the current sum 1 is going to be shift to 3 means this period taking

⇒ both 1 & 3 are conducting during this period.



μ = 0 ⇒ 2 valves conducting at a time.

μ < 60° ⇒ 2 or 3 valve conducting means some times 2 and some times 3.

μ = 60° ⇒ 3 valves conducting always.

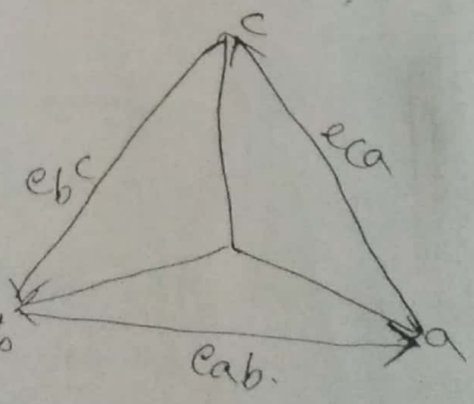
μ > 60° ⇒ 3 or 4 valves are conducting.

⇒ 4 valves conducting at a time means dead short circuit in your converter circuit

⇒ always we try to operate our converter circuit that should be less than 60° degrees. overlap angle.

Three-phase voltages:—

⇒ Taking e_{ba} as reference voltage as shown in figure, the other voltages can be written



$e_{ba} = \sqrt{3} E_m \sin \omega t$

$e_a = E_m \sin(\omega t + 5\pi/6)$

$e_b = E_m \sin(\omega t + \pi/6)$

$e_c = E_m \sin(\omega t - \pi/2)$

$e_{cb} = e_c - e_b = \sqrt{3} E_m \sin(\omega t - 120°)$.

$e_{ac} = \sqrt{3} E_m \sin(\omega t + 120^\circ)$

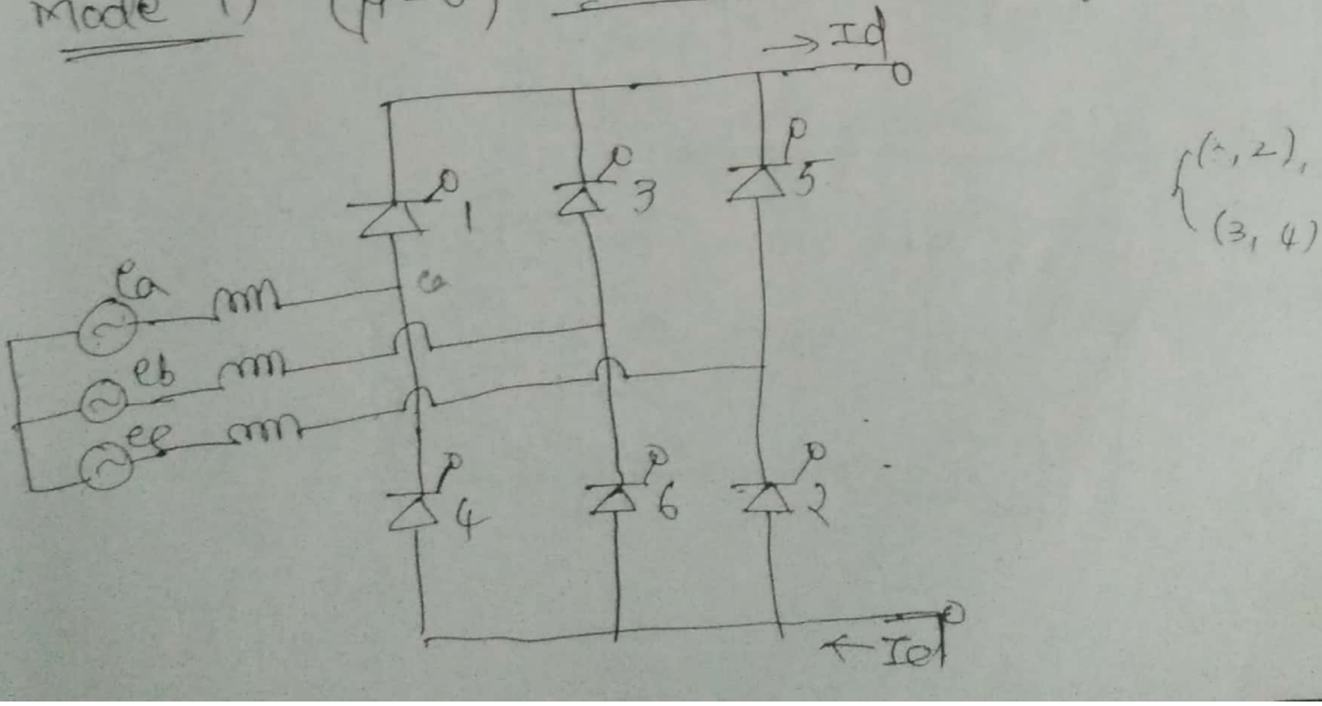
$e_{bc} = \sqrt{3} E_m \sin(\omega t + 60^\circ)$

Overlap angle (μ):- The duration when the current is shared by conducting valves in a commutation group is called overlap angle and is measured by the overlap (commutation) angle μ.

⇒ Let us consider the valves 1 and 2 are conducting. voltage appearing at the cathode of valve 3 will be e_a since valve 1 is conducting and e_b at the anode of valve 3.

⇒ The valve 3 will only conduct when voltage e_b is greater or equal to e_a i.e. when voltage e_{ba} is positive. This is known as the commutation voltage of valve 3. valve 3 can now be fired using gate pulse with any delay angle α which is α° after the zero crossing of commutation voltage of valve 3.

Mode 1) ($\mu = 0$) without overlaping :—



⇒ here two Commutation groups are there. They are upper Commutation group and lower Commutation group.

⇒ when the valve Current here 1 and 3 this from 1 and 3, it is going to share that duration. is called the overlap angle and we are assu-ming the overlap angle here is 0.

~~⇒ It means whenever~~

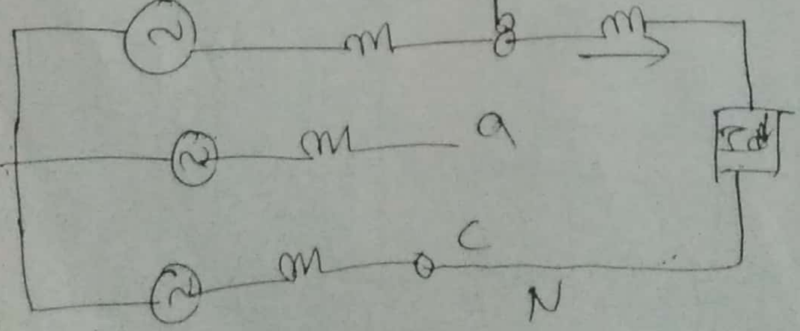
⇒ In this analysis we all assume the valve 1 and 2 are conducting and then 3 is getting the pulse and then there by we are starting.

⇒ we are analyzing our Circuit when your 3 and 2 are going to conduct to know.

⇒ eba is known as the Commutation voltage of valve 3.

→ $e_{cb} = e_c - e_b$ is the Commutation voltage of valve 5 similarly, you can calculate for others as well.

<u>Valves 2, 3 Conduction Case:—</u>



$i_a = 0$; $i_b = I_d$; $i_c = -I_d$.

$i_1 = 0$; $i_2 = I_d$; $i_3 = I_d$; $i_4 = 0$; $i_5 = 0$; $i_6 = 0$.

$$V_d = e_{bc}.$$

⇒ Since the pair of valves 2 and 3 will conduct for 60° and valves 3 & 4 will conduct for next 60°. for the DC output voltage only one interval can be considered.

→ If the delay angle is $\alpha°$. the instantaneous DC voltage e_{bc} will appear across DC terminal from α to $60+\alpha$. The average DC voltage will be given by

$$V_d = \frac{1}{\pi/3} \int_{\alpha}^{\pi/3+\alpha} e_{bc} \, d\omega t$$

$$= \frac{3\sqrt{3}}{\pi} E_m \int_{\alpha}^{\pi/3+\alpha} \sin(\omega t + \pi/3) \, d\omega t.$$

$$= \frac{3\sqrt{3} E_m}{\pi} \left[-\cos(\omega t + \pi/3) \right]_{\alpha}^{\pi/3+\alpha}$$

$$= \frac{3\sqrt{3} E_m}{\pi} \left[-\cos(2\pi/3 + \alpha) + \cos(\pi/3 + \alpha) \right]$$

$$= \frac{3\sqrt{3} E_m}{\pi} \left[2 \sin(\pi/2 + \alpha) \sin(\pi/6) \right]$$

$$\left[\cos A - \cos B = -2 \sin\left(\frac{A+B}{2}\right) \sin\left(\frac{A-B}{2}\right) \right]$$

$$V_d = \frac{3\sqrt{3} E_m}{\pi} \cos\alpha$$

$$V_d = V_{d0} \cos\alpha.$$

⇒ α once it 180. So, we are getting the highest voltage as usual in rectifier circuit

⇒ α is 90 degree output voltage is 0.

⇒ It is again further delayed then this voltage becomes negative.

⇒ If you're delaying from 90 degree onwards it becomes inverter operation voltage becomes negative for this case.

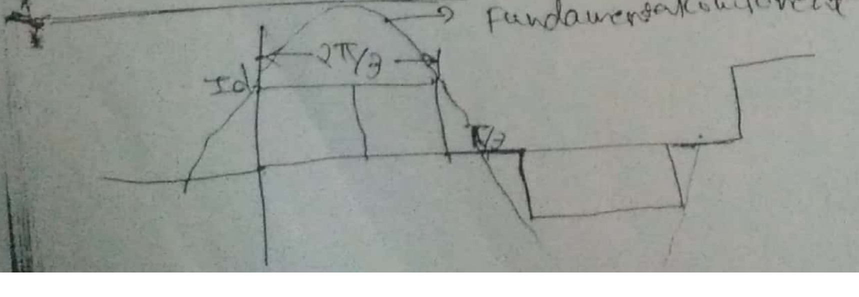
⇒ Although delay angle α can vary from 0 to 180°, delay angle can not be less than certain minimum limit (say 5°) in order to ensure the firing of all the series connected thyristors.

⇒ Similarly the upper limit of delay angle is also restricted due to the turnoff time of a valve.

⇒ the delay angle α is not allowed to go beyond (180° − γ) where γ is called extinction angle.

⇒ It is also known as minimum margin angle, which is typically 15°.

Phase b Current! —



peak value

$$I_{m1} = \frac{2}{\pi} \int_{-\pi/3}^{\pi/3} I_d \cos\theta \, d\theta$$

$$= \frac{2 I_d}{\pi} \left[\sin\theta \right]_{-\pi/3}^{\pi/3}$$

$$I_{m1} = \frac{2\sqrt{3} I_d}{\pi}$$

rms value $I_1 = \frac{\sqrt{6}}{\pi} I_d$.

$$I_h = \frac{I_1}{h}.$$

h is harmonic component.

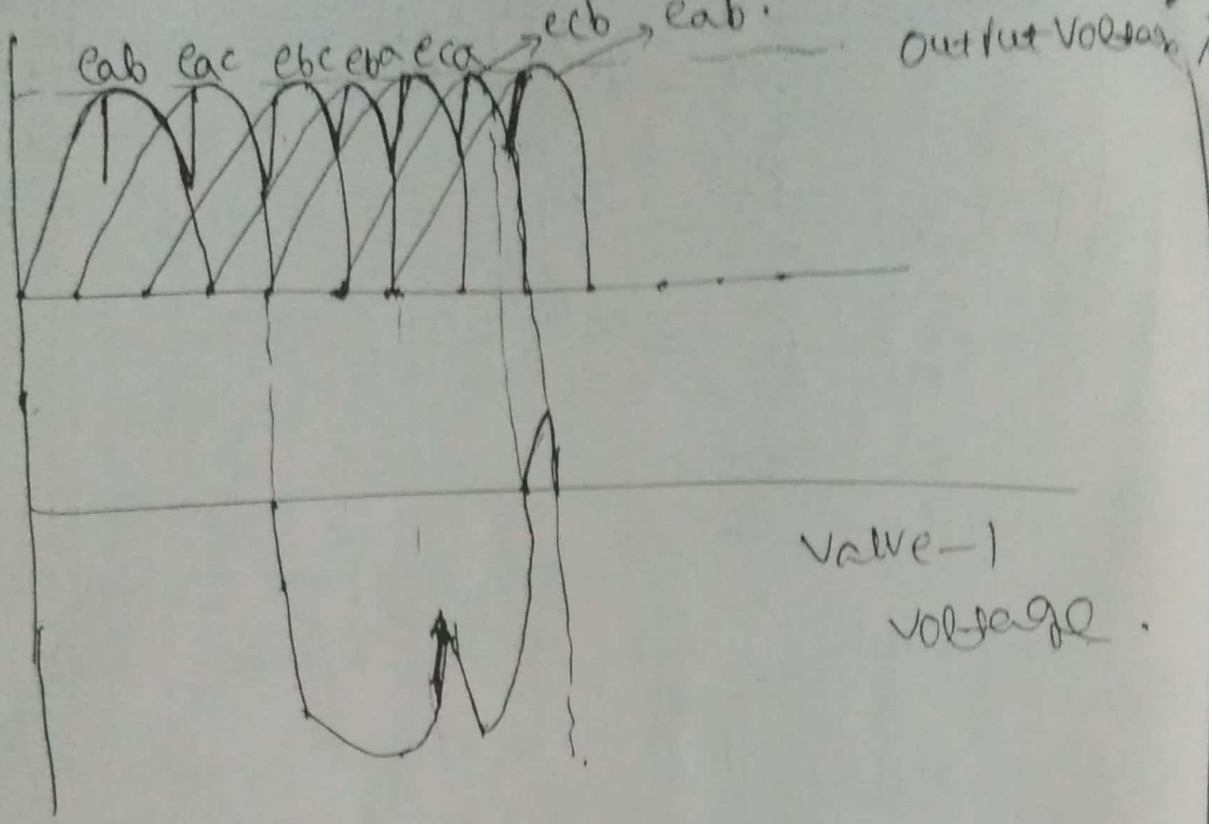
$$I = \left[\frac{1}{2\pi} \int_0^{2\pi} I_d^2 \, d\theta \right]^{1/2}.$$

$$= \left[\frac{1}{2\pi} \int_0^{2\pi/3} I_d^2 \, d\theta + 0 + \int_{\pi}^{5\pi/6} I_d^2 \, d\theta \right]^{1/2}.$$

$$= \left[\frac{1}{2\pi} I_d^2 \cdot 2 \cdot 2\pi/3 \right]^{1/2}$$

$$\boxed{I = \sqrt{\frac{2}{3}} I_d.}$$

Scanned by CamScanner



Power Factor:— Neglecting other harmonic component, the AC power supplied by the converter will be

$$P_{ac} = \sqrt{3}\, E_{LL} I_1 \cos\phi \qquad \left[E_m = \sqrt{2} E_{ph} = \sqrt{2} \times \frac{E_{LL}}{\sqrt{3}} \right]$$

⇒ The DC output power is given

$$P_{dc} = V_d I_d = \frac{3\sqrt{2}}{\pi} E_{LL} I_d \cos\alpha$$

⇒ Ignoring the losses in the converters, AC power will be equal to D.C power

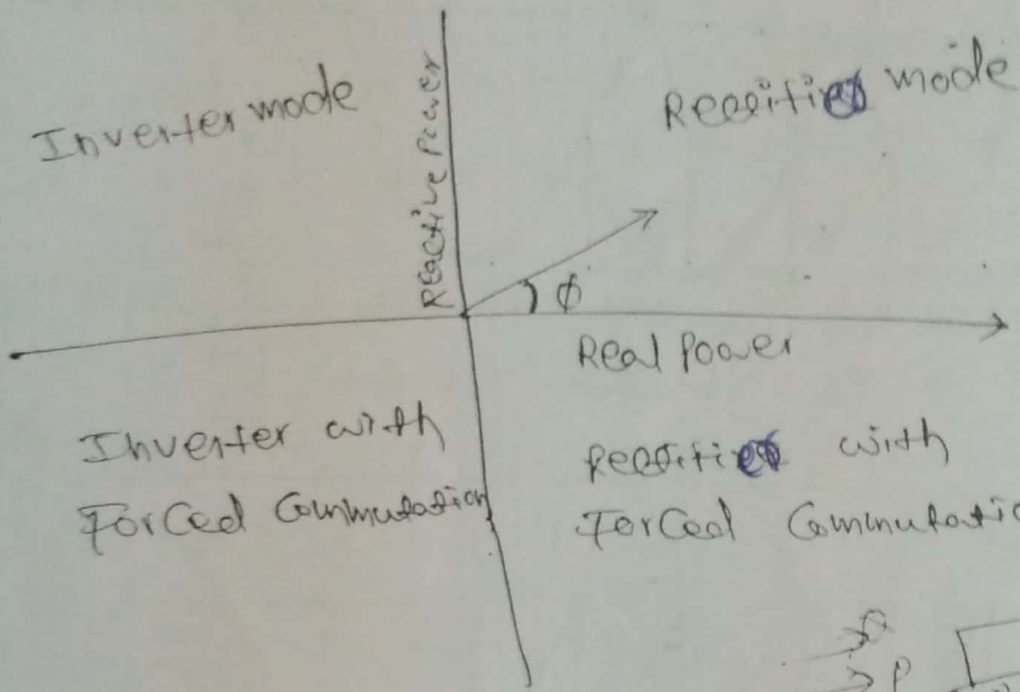
$$\sqrt{3}\, E_{LL} I_1 \cos\phi = \frac{3\sqrt{2}}{\pi} E_{LL} I_d \cos\alpha$$

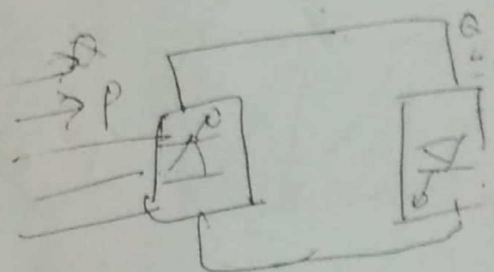
$$\sqrt{3}\, E_{LL} \frac{\sqrt{6}}{\pi} I_d \cos\phi = \frac{3\sqrt{2}}{\pi} E_{LL} I_d \cos\alpha$$

$$\boxed{\cos\phi = \cos\alpha} \Rightarrow \boxed{\cos\alpha = \cos\phi}$$

Scanned by CamScanner

This shows that when delay angle an increase, the power factor reduces and thus more reactive power requirement.

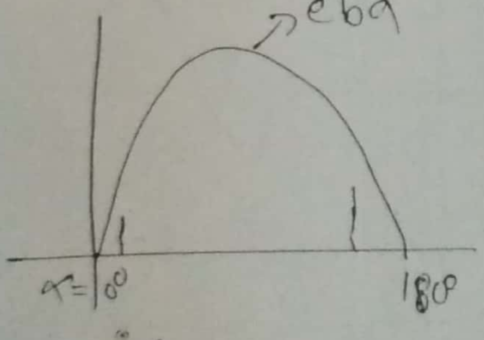




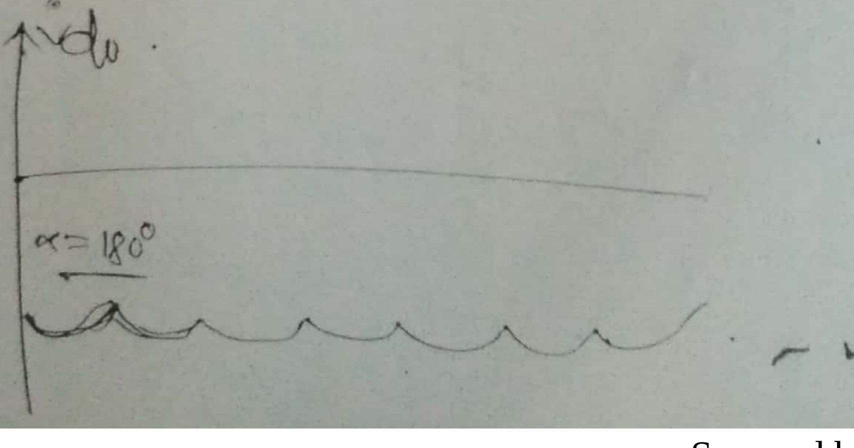
Power factor.

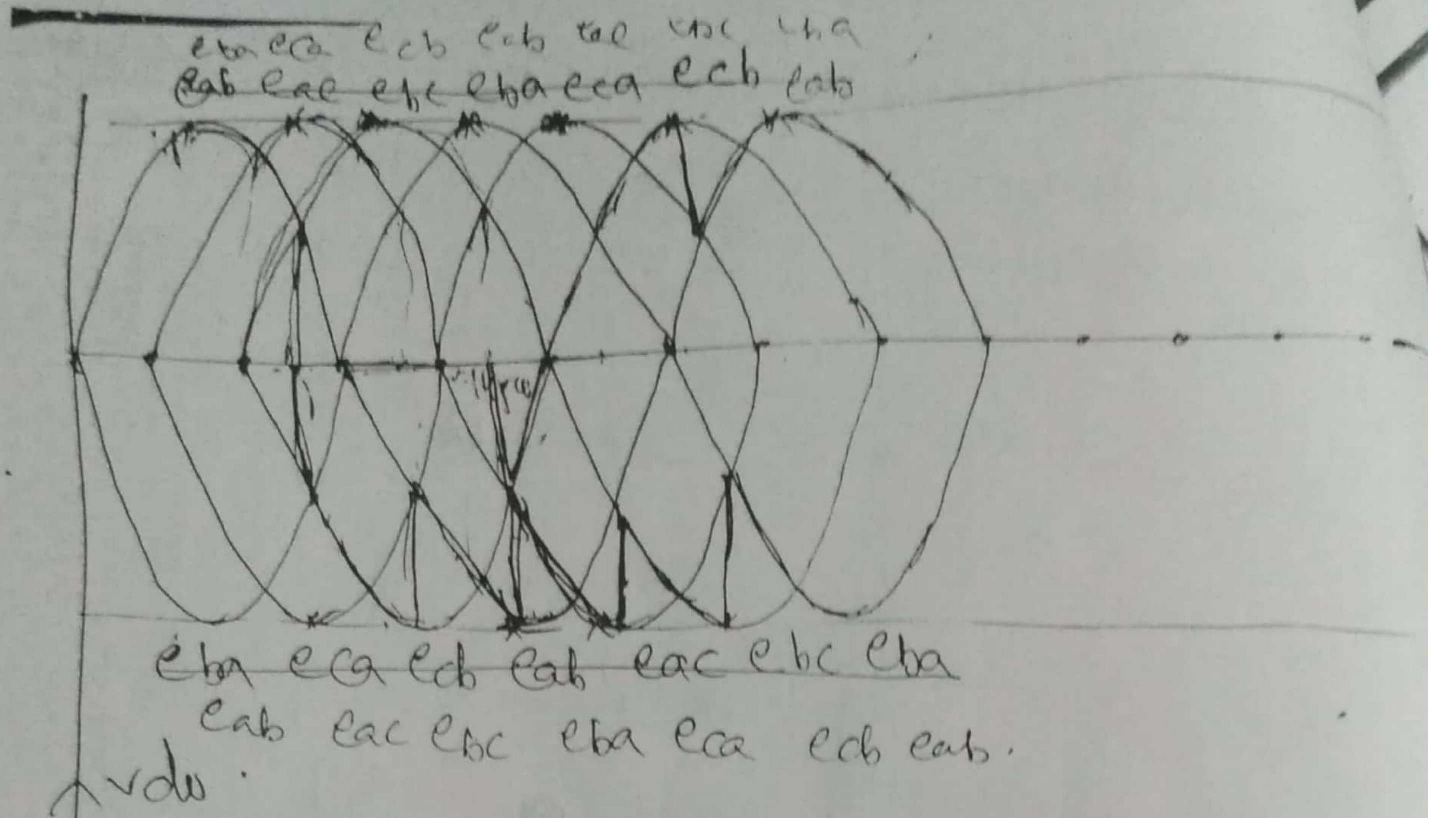
Inverter mode operation:-

$\alpha > 90^\circ$

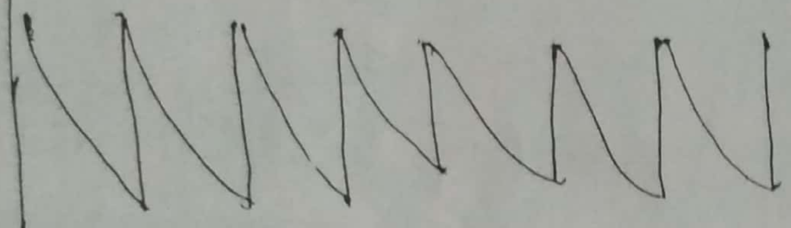


$\alpha = 180^\circ$

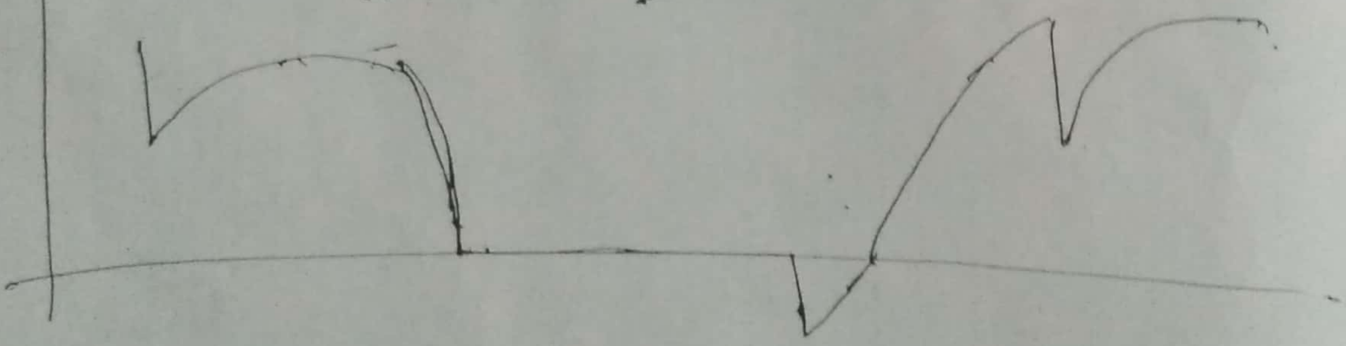


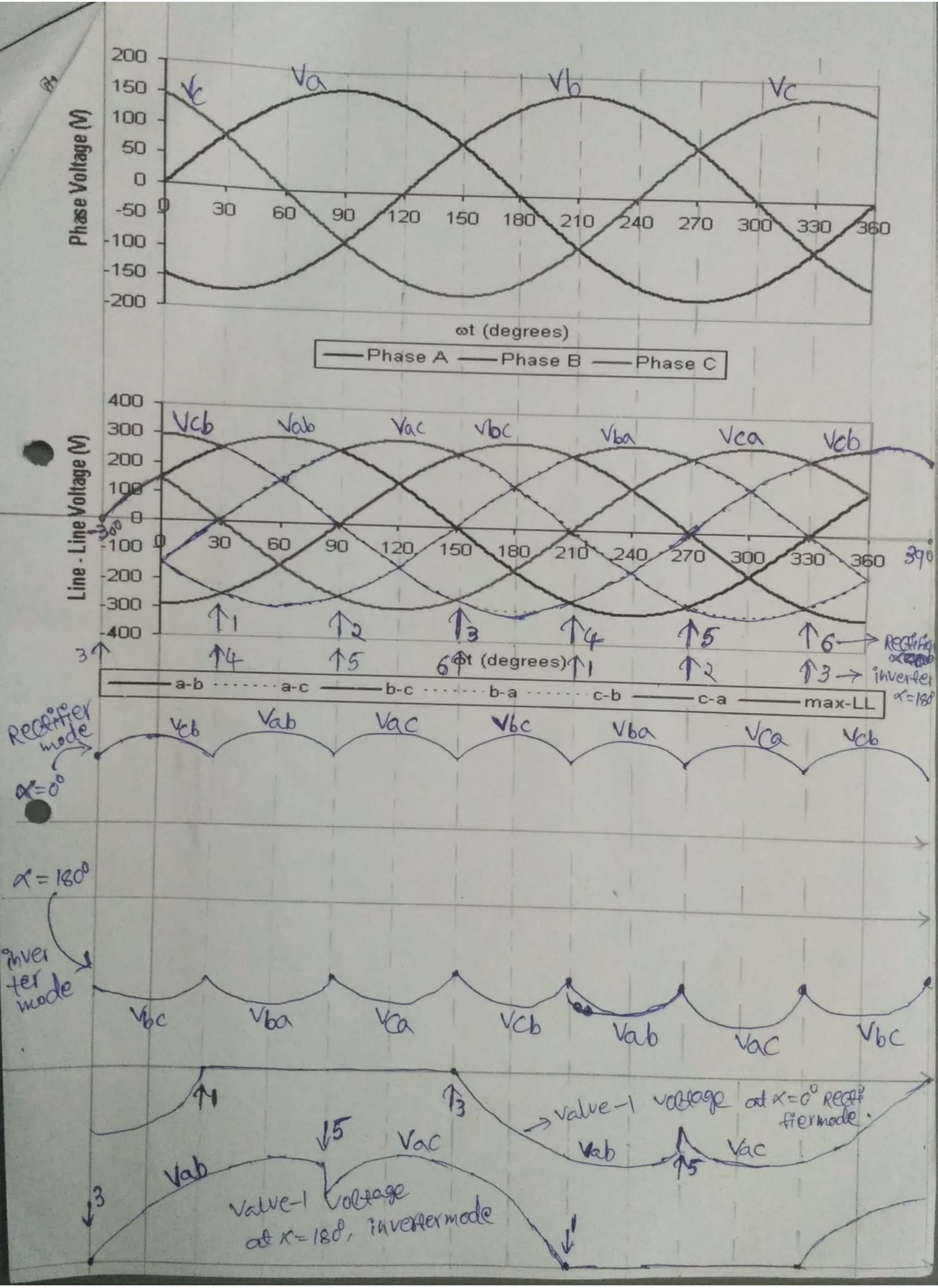


$\alpha = 150^\circ$



Valve -3 voltage

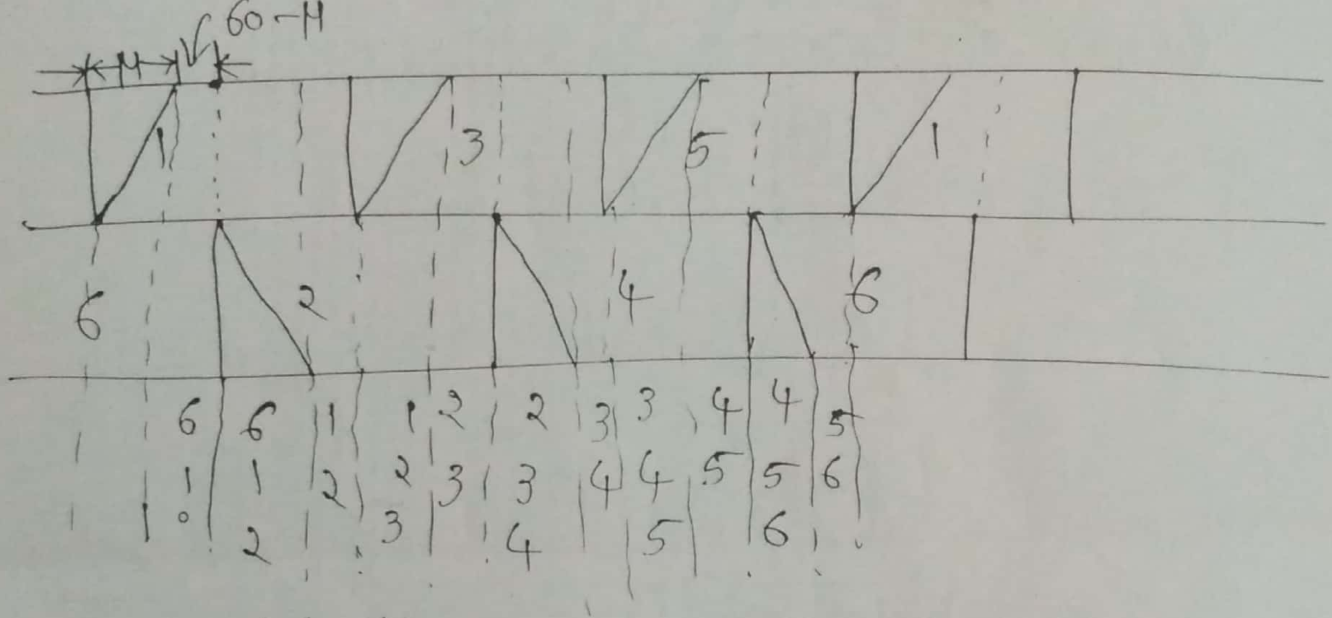



Phase Voltage (V)
ωt (degrees)
Phase A
Phase B
Phase C
Va
Vb
Vc
Line - Line Voltage (V)
a-b
a-c
b-c
b-a
c-b
c-a
max-LL
Vcb
Vab
Vac
Vbc
Vba
Vca
Rectifier mode
α=0°
α=180°
inverter mode
valve-1 voltage at α=0° rectifiermode
Valve-1 voltage at α=180°, invertermode

Mode-2 :- $\mu < 60^\circ$:-

Two and three valves conduction:-

⇒ where two valves conduct for $60^\circ - \mu$ and three valves conduct for μ degree.



| 1, 2 | 1, 2, 3 | 2, 3 |

For 1, 2 ↓:

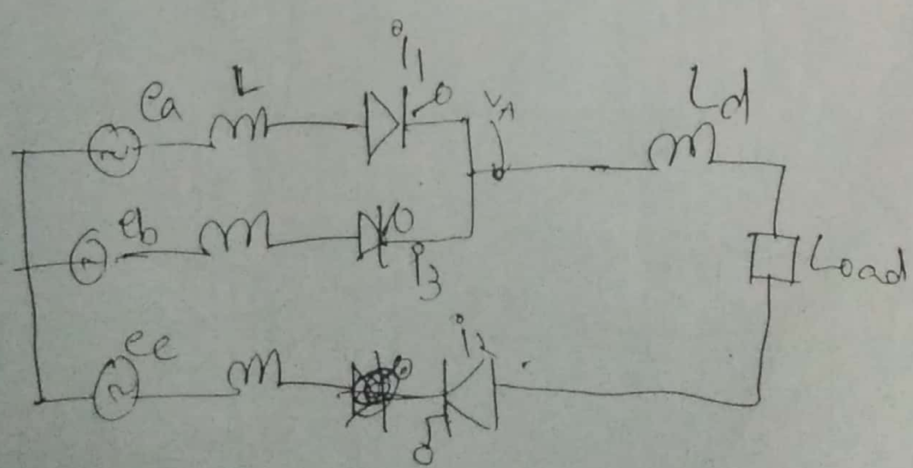
$i_1 = I_d$

$i_2 = -I_d$

For 1, 2, 3 →:

$i_1 + i_3 = I_d$

$i_2 = -I_d$.



$$e_a - L\frac{di_1}{dt} = V_A$$

$$e_b - L\frac{di_3}{dt} = V_A .$$

$$e_a + e_b - L\left(\frac{di_1}{dt} + \frac{di_3}{dt}\right) = 2V_A .$$

$$\frac{di_1}{dt} + \frac{di_3}{dt} = 0 .$$

$$e_a + e_b = 2V_A$$

$$\frac{e_a + e_b}{2} = V_A .$$

For balanced circuit

$$e_a + e_b + e_c = 0$$

$$\therefore \frac{e_a + e_b}{2} = -\frac{e_c}{2} .$$

$$V_d = \begin{cases} \frac{e_a + e_b}{2} - e_c = \frac{-3}{2} e_c & 0 \le \omega t \le \mu \\ e_{bc} & \mu \le \omega t \le 60 - \mu^\circ , \end{cases}$$

$$V_d = \frac{1}{\pi/3}\left[\int_{\alpha}^{\mu + \alpha} \frac{-3}{2} e_c \, d\omega t + \int_{\mu + \alpha}^{60 + \alpha} e_{bc} \, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\mu+\alpha} \frac{3}{2} V_m \cos\omega t \, d\omega t + \int_{\mu+\alpha}^{\alpha+60^\circ} \sqrt{3} V_m \sin(\omega t + 60^\circ) \, d\omega t\right]$$

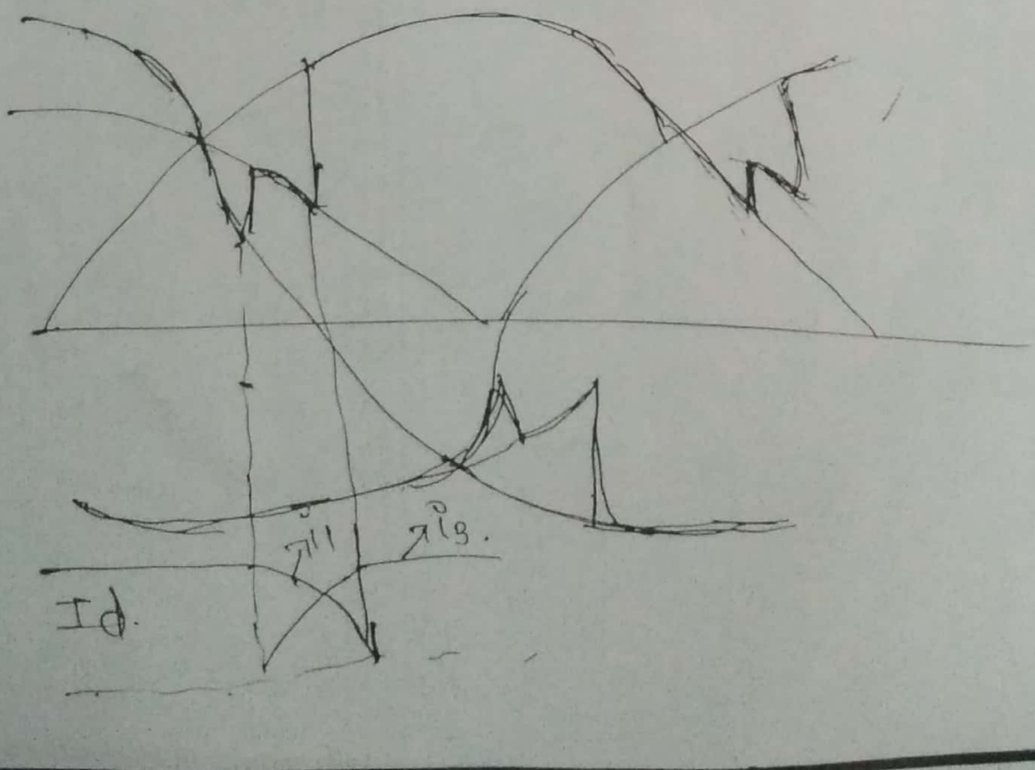
$$= \frac{3}{\pi}\left[\frac{3V_m}{2}\left(\sin(\alpha+\mu) - \sin\alpha\right) + \sqrt{3}V_m\left(\cos(\alpha+\mu+60^\circ) - \cos(\alpha+120^\circ)\right)\right]$$

$$= \frac{3}{\pi} V_m\left[\frac{3}{2}\sin(\alpha+\mu) - \frac{3}{2}\sin\alpha + \frac{\sqrt{3}}{2}\cos(\alpha+\mu) - \frac{3}{2}\sin(\alpha+\mu) + \frac{\sqrt{3}}{2}\cos\alpha + \frac{3}{2}\sin\alpha\right]$$

$$= \frac{3}{\pi} V_m\left[\frac{\sqrt{3}}{2}\cos(\alpha+\mu) + \frac{\sqrt{3}}{2}\cos\alpha\right]$$

$$\boxed{V_d = \frac{3\sqrt{3}}{2\pi} V_m\left[\cos\alpha + \cos(\alpha+\mu)\right]}$$

$$V_d = \frac{V_{do}}{2}\left[\cos\alpha + \cos(\alpha+\mu)\right] = V_{do}\cos\alpha - R_c I_c$$



Voltage equation using KVL, we get

$$e_a - L\frac{di_1}{dt} = e_b - L\frac{di_3}{dt}$$

$$L\frac{di_3}{dt} - L\frac{di_1}{dt} = e_b - e_a$$

$$= e_{ba}$$

$$i_1 + i_3 = I_d$$

$$\frac{di_1}{dt} = -\frac{di_3}{dt}$$

$$2L\frac{di_3}{dt} = e_{ba}$$

$$2L\frac{di_3}{dt} = \sqrt{3}\, V_m \sin\omega t$$

$$i_3 = \frac{-\sqrt{3}\, V_m}{2\omega L}\cos\omega t + A$$

$$\omega t = \alpha \;;\; i_3 = 0$$

$$A = \frac{\sqrt{3}\, V_m}{2\omega L}\cos\alpha$$

$$i_3 = \frac{-\sqrt{3}\, V_m}{2\omega L}\cos\omega t + \frac{\sqrt{3}\, V_m}{2\omega L}\cos\alpha$$

$$i_3 = \frac{\sqrt{3}\, V_m}{2\omega L}\left[\cos\alpha - \cos\omega t\right]$$

$$i_1 = I_d - i_3$$

Rectifier Operation

$$i_3 = \frac{\sqrt{3}\,E_m}{2\omega L}(\cos\alpha - \cos\omega t) \qquad \alpha \le \omega t \le \alpha + \mu$$

At $\omega t = \alpha + \mu$, $i_3 = I_d$

$$I_d = \frac{\sqrt{3}\,E_m}{2\omega L}\left[\cos\alpha - \cos(\alpha+\mu)\right]$$

$$V_d = \frac{V_{do}}{2}\left[\cos\alpha + \cos(\alpha+\mu)\right]$$

simplifying above equations

$$V_d = V_{do}\cos\alpha - \frac{3}{\pi}\omega L I_d$$

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

$X_c = \omega L$ is called commutation reactance.

$$\frac{I_d}{I_{s2}} = \cos\alpha - \cos(\alpha+\mu)$$

here $I_{s2} = \frac{\sqrt{3}\,E_m}{2\omega L}$

$$\cos(\alpha+\mu) = -\frac{I_d}{I_{s2}} + \cos\alpha$$

$$V_d = \frac{V_{do}}{2}\left[\cos\alpha - \frac{I_d}{I_{S2}} + \cos\alpha\right]$$

$$V_d = \frac{V_{do}}{2}\left[2\cos\alpha - \frac{I_d}{I_{S2}}\right]$$

$$= V_{do}\cos\alpha - \frac{I_d}{I_{S2}} \cdot \frac{V_{do}}{2}$$

$$= V_{do}\cos\alpha - \frac{I_d}{\frac{\sqrt{3}E_m}{2\omega L}} \cdot \frac{\frac{\sqrt{3}E_m}{\pi}}{2}$$

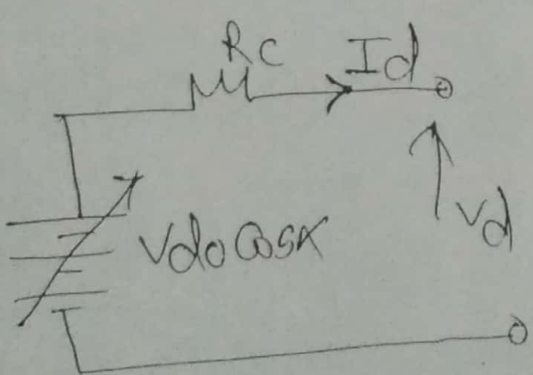
$$= V_{do}\cos\alpha - \frac{3}{\pi}\omega L \cdot I_d$$

$$R_c = \frac{3}{\pi}\omega L$$

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

R_c is called equivalent commutation resistance.

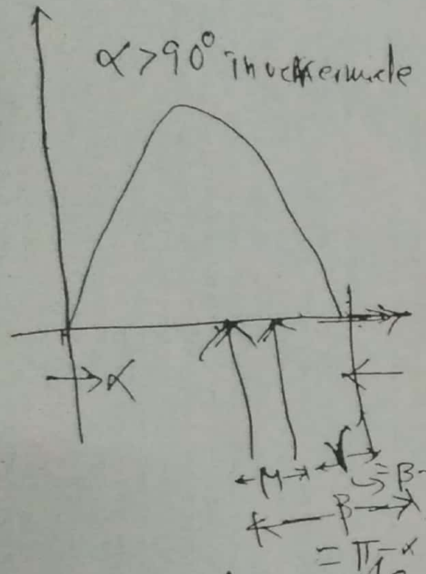
$X_c = \omega L$ is called commutation reactance



Equivalent circuit of rectifier.

Inverter Equations:-

$$V_{di} = -\frac{V_{doi}}{2}\left[\cos\alpha + \cos(\alpha+\mu)\right]$$



$$\alpha = \pi - \beta \quad ; \quad \gamma = \beta - \mu = \pi - \alpha - \mu$$

$$\therefore \alpha + \mu = \pi - \gamma$$

$$V_{di} = -\frac{V_{doi}}{2}\left[\cos(\pi-\beta) + \cos(\pi-\gamma)\right]$$

$$= \frac{V_{doi}}{2}\left[\cos\beta + \cos\gamma\right].$$

α = delay angle

β = advance angle

γ = extinction angle.

$$V_{di} = V_{doi}\cos\beta + R_{ci} I_d$$

$$V_{di} = V_{doi}\cos\gamma - R_{ci} I_d.$$

Inverter operation :-

$$V_{dr} = V_{dor}\cos\alpha - R_c I_d$$

$$V_{di} = -\left[V_{dor}\cos\alpha - R_c I_d\right]$$

$$= -\left[V_{doi}\cos(\pi-\beta) - R_c I_d\right]$$

$$\boxed{V_{di} = V_{doi}\cos\beta + R_c I_d}$$

$$V_{di} = \frac{V_{doi}}{2}\left[\cos\beta + \cos\gamma\right]$$

$$\frac{2V_{di}}{V_{doi}} = \cos\beta + \cos\gamma$$

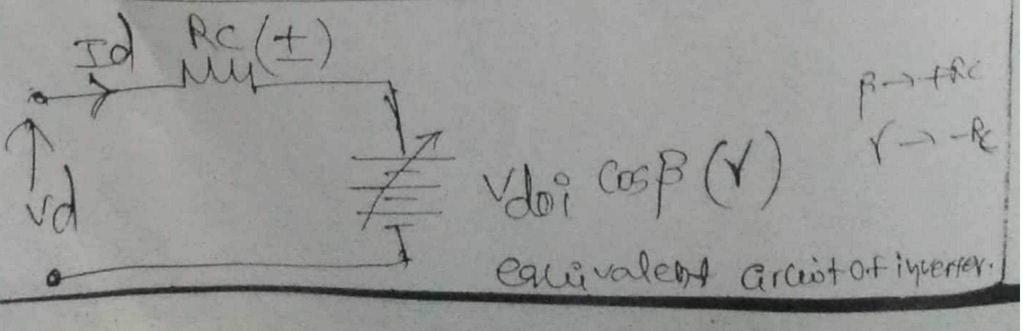
$$\cos\beta = \frac{2V_{di}}{V_{doi}} - \cos\gamma$$

$$V_{di} = V_{doi}\left[\frac{2V_{di}}{V_{doi}} - \cos\gamma\right] + R_c I_d$$

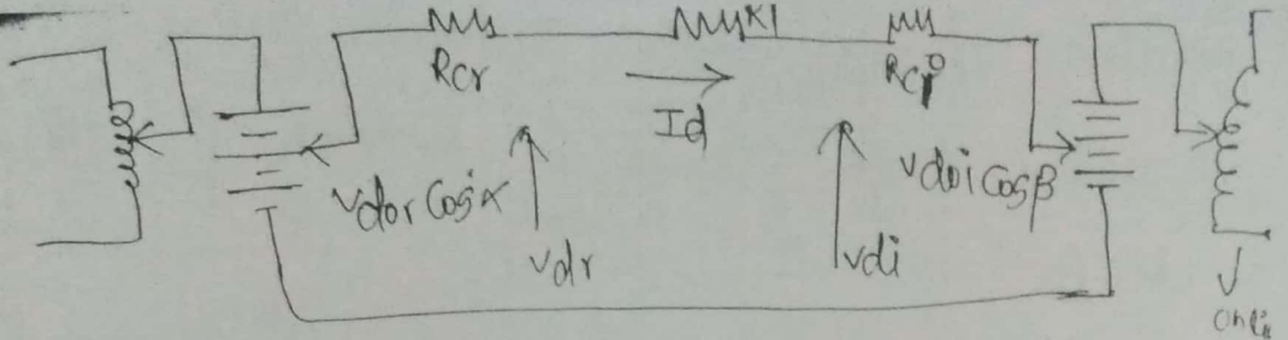
$$V_{di} = 2V_{di} - V_{doi}\cos\gamma + R_c I_d$$

$$-V_{di} = -V_{doi}\cos\gamma + R_c I_d$$

$$\boxed{V_{di} = V_{doi}\cos\gamma - R_c I_d}$$



equivalent circuit of inverter.



Rd → line resistance.

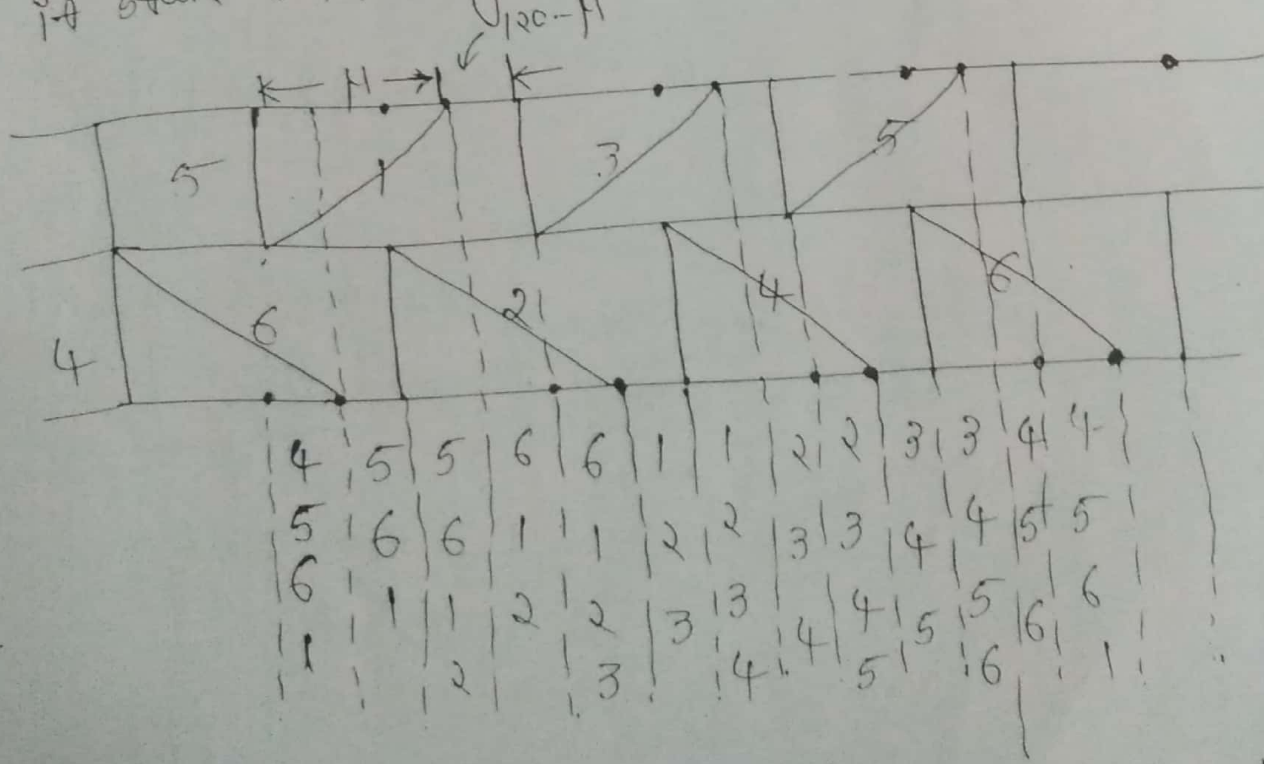
Equivalent circuit of HVDC Link.

3–4 valves Conduction Mode :- (μ > 60°).

⇒ Operation of bridge converter with overlap angle $60° \leq \mu \leq 120°$ is abnormal.

⇒ It is encountered only under overload, dc short circuit or low ac voltage.

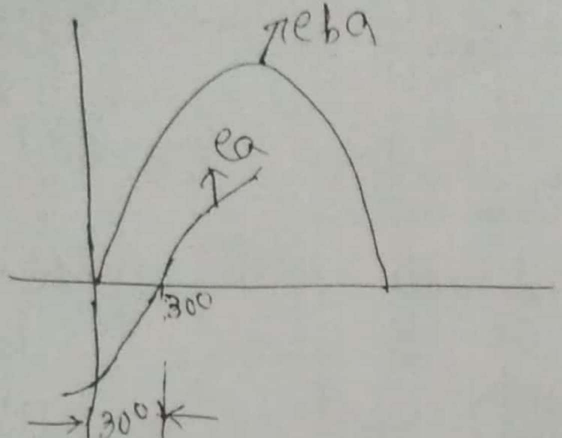
⇒ However, it is self clearing i.e after overlap time, it start conducting in 3 valves mode.

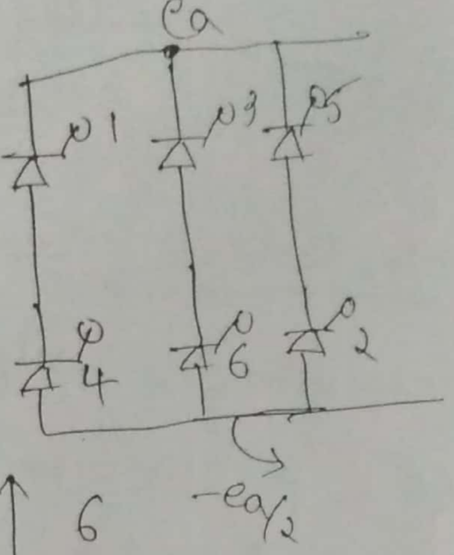


⇒ During the 4-valves conduction, there is dc short circuit and dc output voltage is zero.

⇒ Thus, during 3-valve conduction output is 1.5 e_c (?)

⇒ Delay angle cannot be less than 30°. It must be ($\alpha > 30°$). 30°



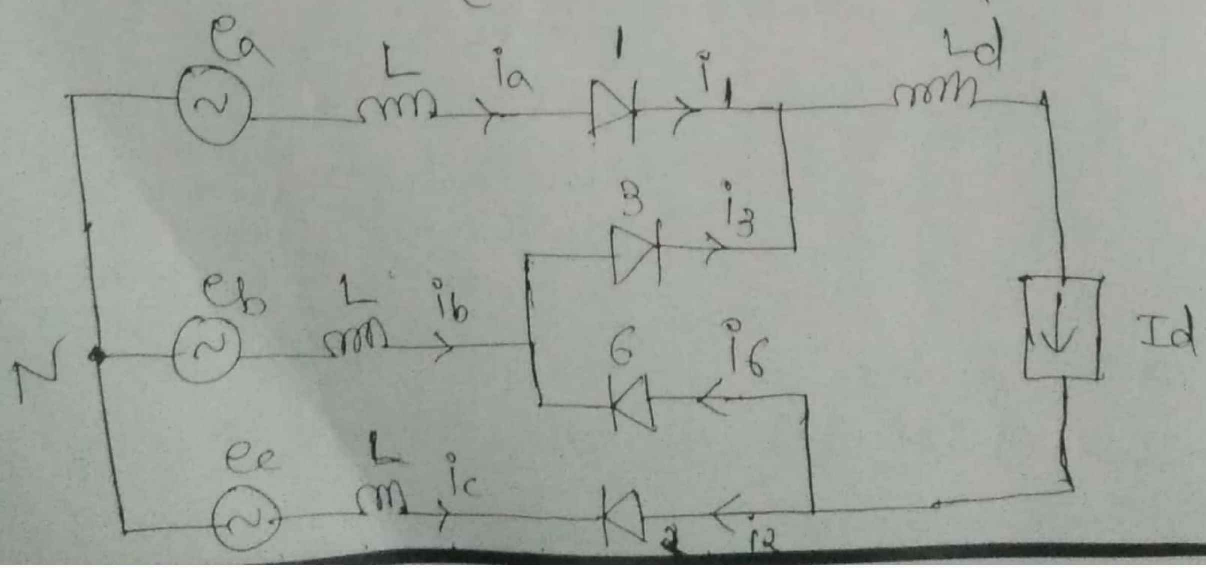


6 ↑ 6
1 | 1
2 ↑3 2
3

across valve 3 voltage = $-\frac{3}{2} e_a$ → Commutating voltage.

$\alpha \geq 30°$
$\mu \geq 60°$ } 3–4 valve conduction

$$V_d = \begin{cases} 0 \text{ (4 valve conduction)} & \alpha \leq \omega t \leq \alpha + \mu - 60° \\ -1.5 e_c \text{ (3 valve conduction)} & \alpha + \mu - 60° \leq \omega t \leq \alpha + 60° \end{cases}$$



$$V_d = \frac{3}{\pi}\left[0 + \int_{\alpha+\mu-60^\circ}^{\alpha+60^\circ} \left(-\frac{3e_c}{2}\right) d(\omega t)\right]$$

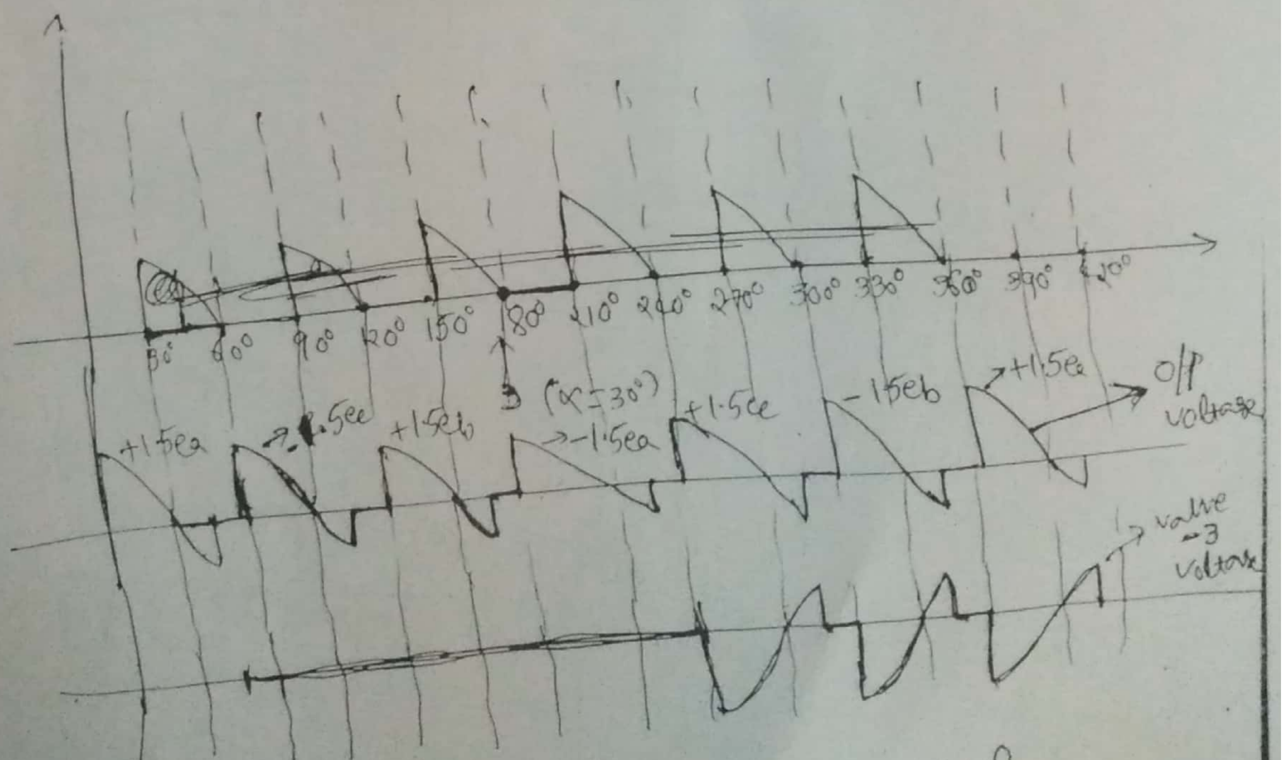
$$= \frac{3}{\pi}\left[\int_{\alpha+\mu-60^\circ}^{\alpha+60^\circ} \frac{3}{2} E_m \cos\omega t \, d\omega t\right]$$

$$= \frac{3}{\pi}\left[\frac{3E_m}{2} \sin\omega t\right]_{\alpha+\mu-60^\circ}^{\alpha+60^\circ}$$

$$= \frac{3}{\pi}\left[\frac{3E_m}{2} \cos(\omega t - 90^\circ)\right]_{\alpha+\mu-60^\circ}^{\alpha+60^\circ}$$

$$= \frac{9}{2\pi} E_m \left[\cos(\alpha-30) + \cos(\alpha+\mu+30)\right]$$

$$V_d = \frac{\sqrt{3}}{2} V_{do}\left[\cos(\alpha-30^\circ) + \cos(\alpha+\mu+30^\circ)\right]$$



Rectifier mode:–

$\alpha = 45^\circ$ 3 values → 45°

$\mu = 75^\circ$ 4 values → 15°

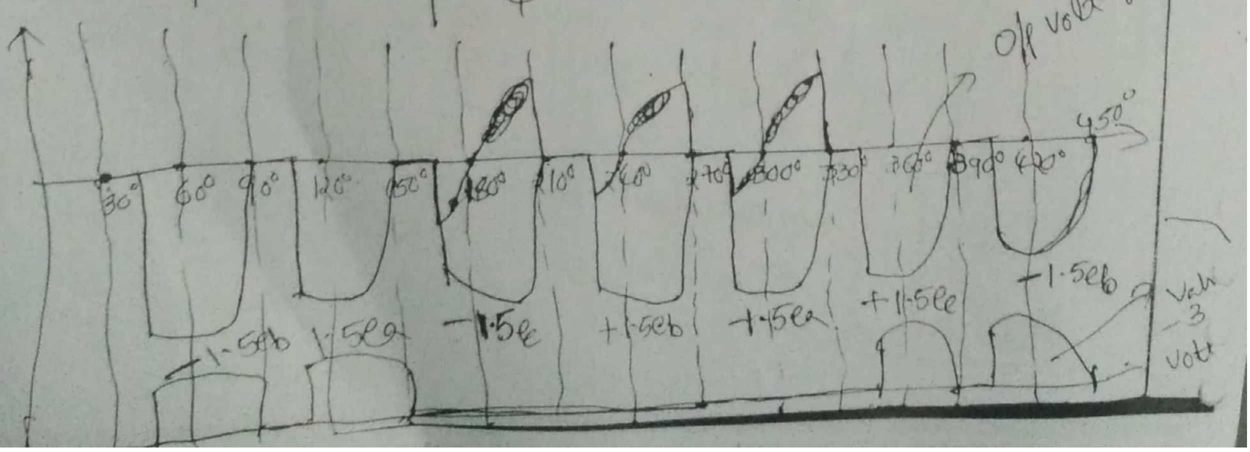
For valve-3

Conduction Valves	From	To	DC voltage	Valve voltage V(3)
6, 1, 2, 3	45°	60°	0	0
1, 2, 3	60°	105°	−1.5ec	0
1, 2, 3, 4	105°	120°	0	0
2, 3, 4	120°	165°	+1.5eb	0
2, 3, 4, 5	165°	180°	0	0
3, 4, 5	180°	225°	−1.5ea	0
3, 4, 5, 6	225°	240°	0	0
4, 5, 6	240°	285°	+1.5ec	−1.5ec
4, 5, 6, 1	285°	300°	0	0
5, 6, 1	300°	345°	−1.5eb	+1.5eb
5, 6, 1, 2	345°	360°	0	0
6, 1, 2	360°	45° (405°).	+1.5ea	−1.5ea

Inverter mode operation

$\alpha = 150°$ | 3 valves → 45°

$\mu = 75°$ | 4 valves → 15°



Conducting valves	From	To	DC voltage	Valve voltage
6 1 2 3	150°	165°	0	0
1 2 3	165°	210°	$-1.5e_c$	0
1 2 3 4	210°	225°	0	0
2 3 4	225°	270°	$+1.5e_b$	0
2 3 4 5	270°	285°	0	0
3 4 5	285°	330°	$-1.5e_a$	0
3 4 5 6	330°	345°	0	0
4 5 6	345°	30°	$+1.5e_c$	$-1.5e_e$
4 5 6 1	30°	45°	0	0
5 6 1	45°	90°	$-1.5e_b$	$+1.5e_b$
5 6 1 2	90°	105°	0	0
6 1 2	105°	150°	$+1.5e_a$	$-1.5e_a$

Valve conduction	duration	Current
6, 1, 2, 3	$\alpha \le \omega t \le \alpha+\mu-60°$	Current shared by valves 1 & 3
1, 2, 3	$\alpha+\mu-60° \le \omega t \le \alpha+60°$	"
1, 2, 3, 4	$\alpha+60° \le \omega t \le \alpha+\mu$	"
2, 3, 4	$\alpha+\mu \le \omega t \le \alpha+120°$	Valve 3 will carry current Id

When valves 6, 1, 2, 3 are conducting:-

Valve 3 voltage

$$e_a - L\frac{di_a}{dt} = e_b - L\frac{di_b}{dt}$$

$$e_a - L\frac{di_a}{dt} = e_c - L\frac{di_c}{dt}$$

$$2e_a - e_b - e_c = 2L\frac{di_a}{dt} - L\frac{di_b}{dt} - L\frac{di_c}{dt}$$

$$3e_a = 3L\frac{di_a}{dt}$$

$$\frac{di_a}{dt} = \frac{e_a}{L} = \frac{di_1}{dt} = \frac{E_m}{L}\sin(\omega t + 150^\circ) \quad = -\frac{di_3}{dt}$$

$$i_3 = \frac{E_m}{\omega L}\left[\cos(\omega t + 150^\circ) - \cos(\alpha + 150^\circ)\right]$$

$$= \frac{E_m}{\omega L}\left[-\cos(\omega t - 30^\circ) + \cos(\alpha - 30^\circ)\right]$$

$$I_3 \text{ (at } \omega t = \alpha + \mu - 60) = \frac{E_m}{\omega L}\left[-\cos(\alpha + \mu - 90^\circ) + \cos(\alpha - 30^\circ)\right]$$

$$i_1 + i_3 = I_d$$

$$\frac{di_1}{dt} + \frac{di_3}{dt} = 0$$

$$\frac{di_1}{dt} = -\frac{di_3}{dt}$$

when values 1, 2, 3 are conducting:—

$$\frac{di_3}{dt} = \frac{e_b - e_a}{2L} = \frac{\sqrt{3}E_m}{2L}\sin\omega t$$

$$i_3 = \frac{\sqrt{3}E_m}{2L}\int_{\delta - 60^\circ}^{\omega t}\sin\omega t \, d\omega t + I_3(\omega t = \delta - 60^\circ)$$

$$i_3 = \frac{\sqrt{3}E_m}{2\omega L}\left[-\cos\omega t + \cos(\delta - 60^\circ)\right] + I_3(\text{at } \delta - 60^\circ)$$

$$I_3(\text{at } \omega t = \alpha + 60^\circ) = \frac{\sqrt{3}E_m}{2\omega L}\left[\cos(\delta - 90) - \cos(\alpha + 60)\right]$$

$$+ \frac{E_m}{\omega L}\left[-\cos(\delta - 90) + \cos(\alpha - 30)\right]$$

$$= \frac{E_m}{\omega L}\left[\cos(\alpha - 30) + \frac{1}{2}\cos(\delta + 30) - \frac{\sqrt{3}}{2}\cos(\alpha + 60)\right]$$

When values 1, 2, 3, 4 are conducting (i_1 is not equal to e_a)

$$i_1 = i_a + i_4$$

$$e_a - L\frac{di_a}{dt} = e_b - L\frac{di_b}{dt}$$

$$e_b - L\frac{di_b}{dt} = e_c - L\frac{di_c}{dt}$$

$$2e_b - e_a - e_c = 2L\frac{di_b}{dt} - L\frac{di_a}{dt} - L\frac{di_c}{dt}$$

$$e_b = L\frac{di_b}{dt} = L\frac{di_3}{dt} = E_m\sin(\omega t + 30^\circ)$$

$$i_3 = \frac{E_m}{\omega L}\left[\cos(\alpha + 60 + 30^\circ) - \cos(\omega t + 30)\right] + I_{3(\text{at } \alpha + 60^\circ)}$$

At $\omega t = \delta\ (\alpha + \mu)$

$$I_d = I_3 = \frac{E_m}{2\omega L}\left[\cos(\alpha - 30) - \cos(\delta + 30)\right].$$

~~$V_d = \frac{V_{d0}}{2}(\cos\alpha + \cos\delta)$~~

~~$V_{d0} = \frac{3\sqrt{3}E_m}{\pi}$~~

$$V_d = \frac{\sqrt{3}}{2} V_{do} \left[\cos(\alpha - 30) + \cos(\delta + 30) \right]$$

$$\cos(\delta + 30) = \cos(\alpha - 30) - \frac{I_d}{I_{s3}}$$

$$V_d = \frac{\sqrt{3}}{2} V_{do} \left[\cos(\alpha - 30) + \cos(\alpha - 30) - \frac{I_d}{I_{s3}} \right]$$

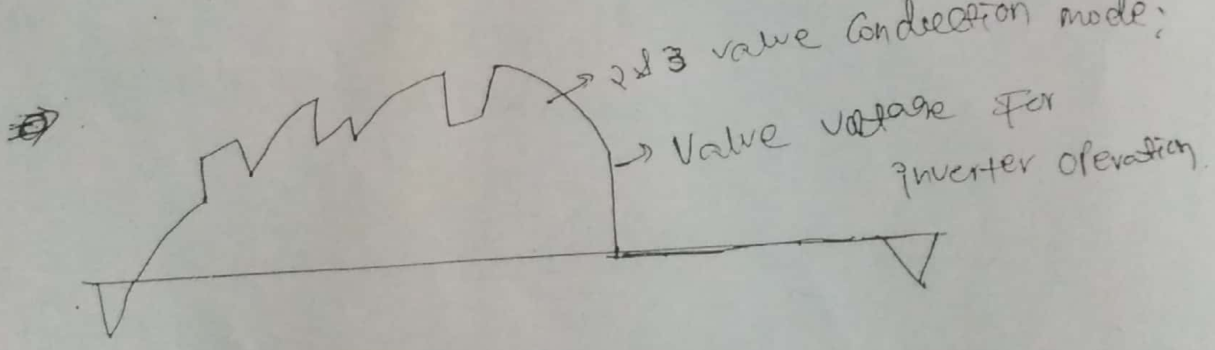
$$= \sqrt{3}\, V_{do} \cos(\alpha - 30) - \frac{\sqrt{3}}{2} \cdot I_d \frac{V_{do}}{I_{s3}}$$

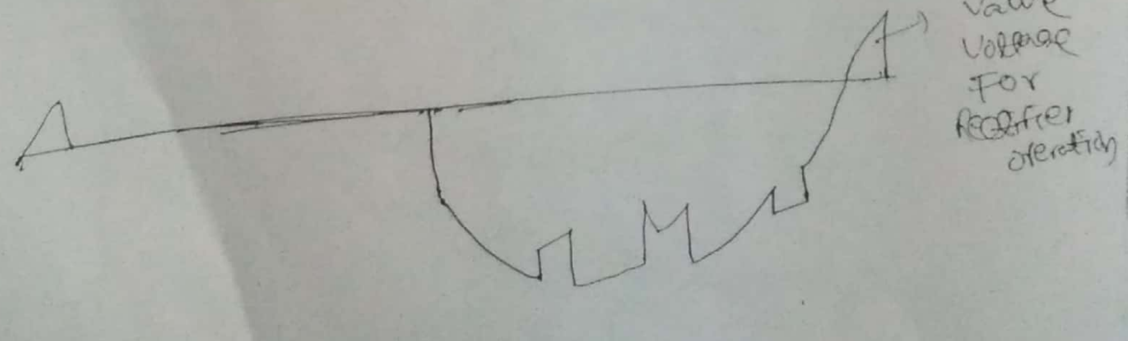
$$= \sqrt{3}\, V_{do} \cos(\alpha - 30) - \sqrt{3} \cdot I_d \frac{\frac{3\sqrt{3} E_m}{2\pi}}{E_m / 2\omega L}$$

$$V_d = \sqrt{3}\, V_{do} \cos(\alpha - 30) - 3 \cdot \frac{3\omega L}{\pi} \cdot I_d$$

$$R_c = \frac{3\omega L}{\pi}$$

$$V_d = \sqrt{3}\, V_{do} \cos(\alpha - 30) - 3 R_c I_d$$





⇒ Extinction advance angle is the time angle between the end of conduction and the reversal of the sign of the sinusoidal commutation voltage of the source.

Commutation margin angle :— is the time angle between the end of conduction and the reversal of the sign of the non-sinusoidal voltage across outgoing valve.

12- Pulse Bridge Converter :—

12-pulse is the best option.

⇒ Two six-pulse converter is connected with Y-Y transformer and second one with Y-Δ transformer.

⇒ One six-pulse converter is connected with Y-Y transfor-mer and second one with Y-Δ transformer.

⇒ This provides 30° phase shift and thus 12 pulse in one cycle.

⇒ It reduces harmonic current injection in the ac system and less harmonic in dc voltage.

⇒ For $\mu = 0$, there will always 4 valves in conduction

⇒ For $\mu > 0$, following modes are possible.

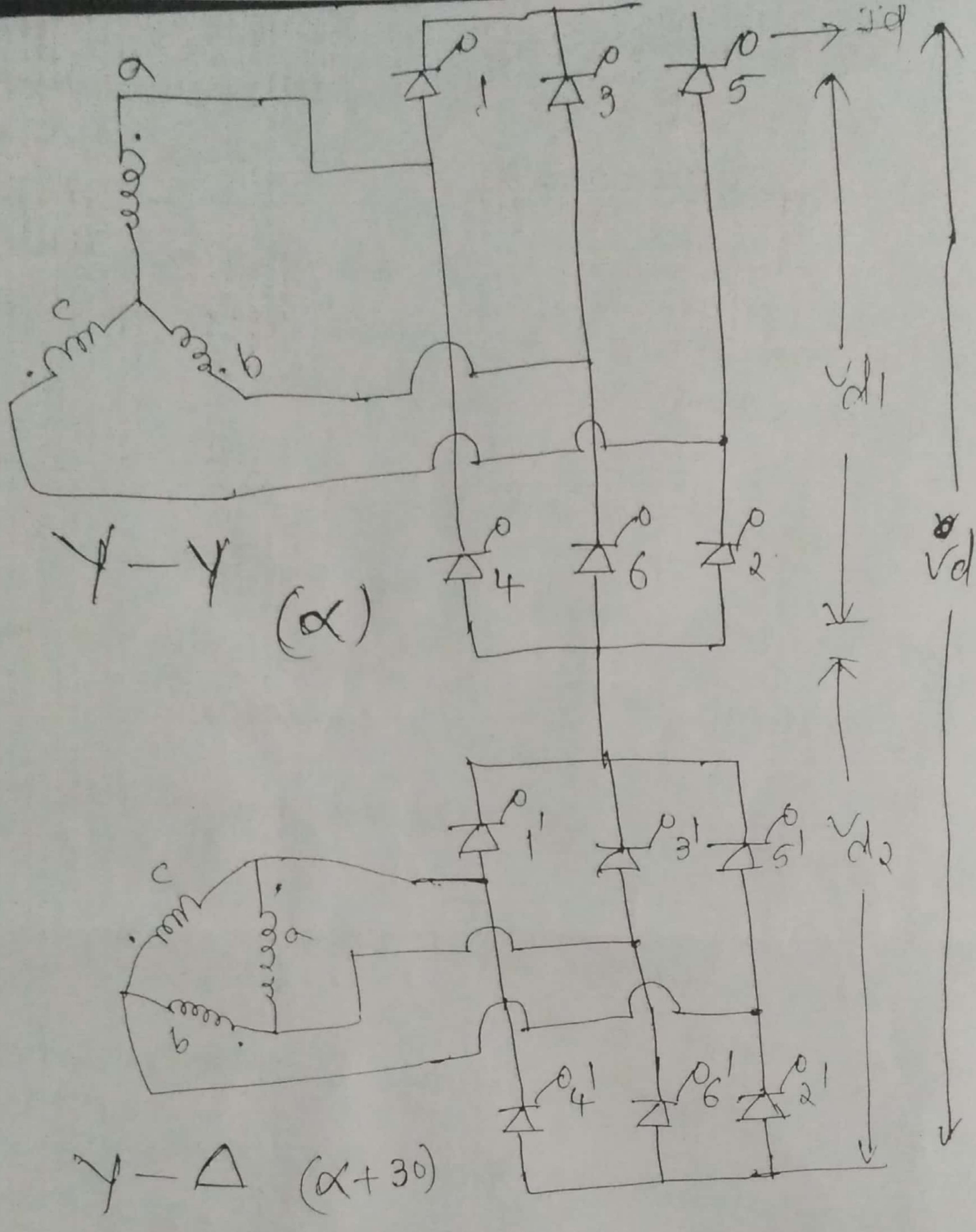
⇒ Mode-I (4/5 valves conduction) : $0 \le \mu \le 30°$

⇒ Mode-II (5/6 valves conduction) : $30° \le \mu \le 60°$.

⇒ Mode-III (6/7 valves conduction) : $60° \le \mu \le 90°$

⇒ Mode-IV (7/8 valves conduction) : $90° \le \mu \le 120°$

⇒ AC Current.



12 - Pulse Converter

$$V_{d_1}(t) = \sqrt{3}\, E_m \cos(\omega t - \pi/6) \quad (0 \le \omega t \le \pi/3)$$

with a 30° shift, the bottom brige's output unfiltered voltage is

$$V_{d_2}(t) = \sqrt{3}\, E_m \cos(\omega t - \pi/3) \quad (\pi/6 \le \omega t \le \pi/2)$$

The out put voltage $V_d(t) = V_{d_1} + V_{d_2}$

$$= \sqrt{3} E_m \left[\cos(\omega t - \pi/6) + \cos(\omega t - \pi/3) \right]$$

$$= 1.9319 \sqrt{3} E_m \cos(\omega t - \pi/4) \quad (\pi/6 \leq \omega t \leq \pi/3)$$

$$V_d = 1.9319 \sqrt{3} E_m \left\{ \left[\int_{\pi/6}^{\pi/3} \cos(\theta - \pi/4)\, d\theta \right] \Big/ \pi/6 \right\}$$

$$V_d = \frac{(6).(1.9319\sqrt{3})E_m}{\pi} \, 2\sin(\pi/12) = 3.3042 E_m$$

(Or)

$$V_d = 2 V_{d_1}$$

$$= 2 \left[\frac{3\sqrt{3}}{\pi} E_m \right]$$

$$V_d = 3.3042 E_m$$

$$E_m = \frac{1}{3.3042} V_d = 0.3026 V_d.$$

avg Current in a valve for a single bridge

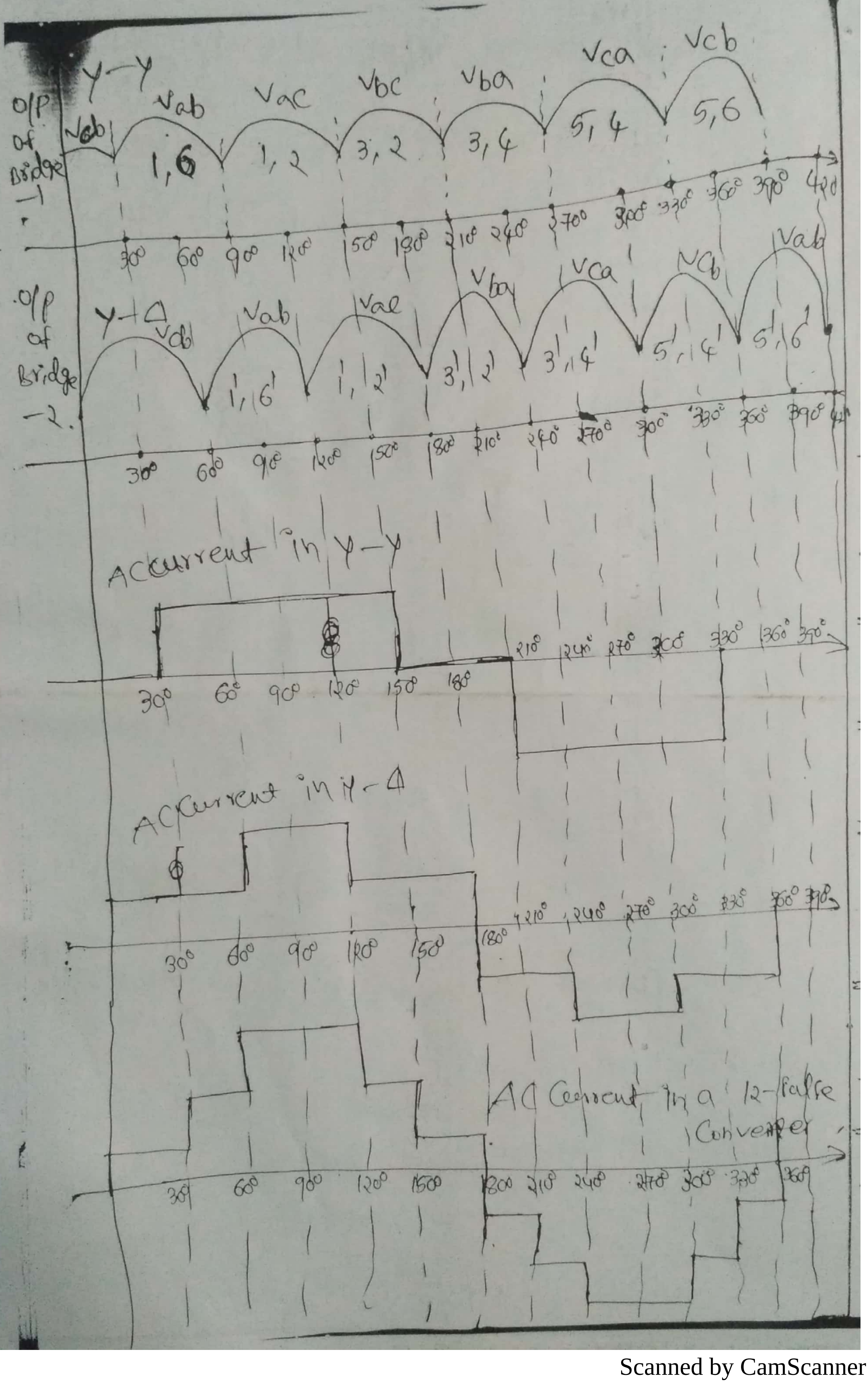
$$= \frac{I_d}{3}$$

$$= 0.333 I_d$$

Peak inverse voltage = PIV

$$= \frac{\pi}{3} \frac{(V_d)}{2}$$

$$PIV = 0.5236 V_d.$$



O/P of Bridge -1
Y-Y
Vcb
Vab
Vac
Vbc
Vba
Vca
Vcb
1,6
1,2
3,2
3,4
5,4
5,6
O/P of Bridge -2.
Y-Δ
Vcb
Vab
Vac
Vba
Vca
Vcb
Vab
1',6'
1',2'
3',2'
3',4'
5',4'
5',6'
AC current in Y-Y
AC current in Y-Δ
AC current in a 12-pulse converter

UNIT-III

Control - Characteristics

~~Differ~~ Desired Control Features:-

Control should have following features.

⇒ Control system should not be sensitive to normal variation in voltage and frequency of the ac supply system.

⇒ Control should be fast, reliable and easy (simple) to implement.

⇒ There should have continuous operating range from full rectification to full inversion.

⇒ Control should be such that it should require less reactive power.

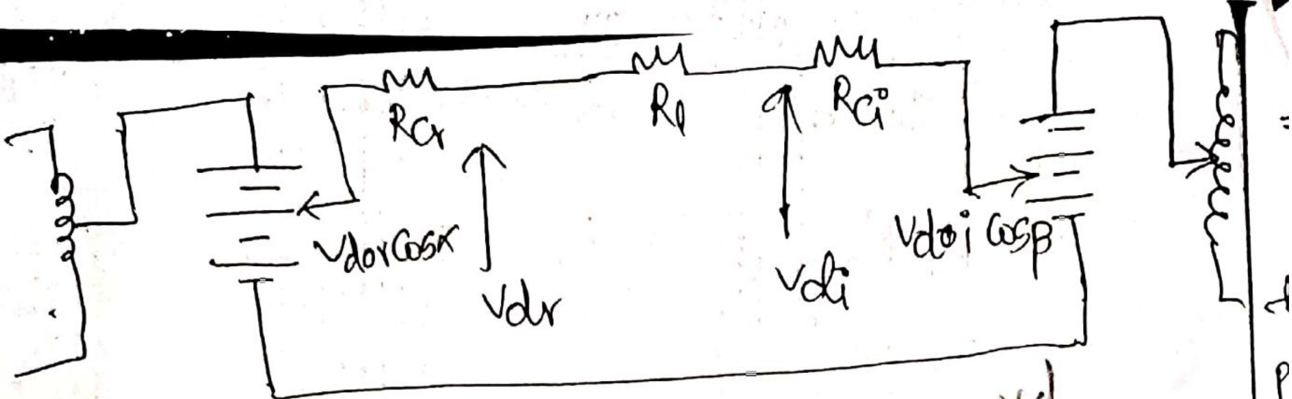
⇒ Under steady state conditions, the valve must be fired symmetrically.

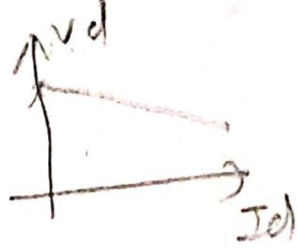
⇒ Control should be such that it must control the maximum current in the link, and limit the fluctuation of current.

⇒ Power should be controlled independently and smoothly which can be done by controlling the current and/or the voltage simultaneously in the link.

⇒ Control should be such that it can be used for protection of line and converter.

⇒ For maintaining safe commutation margin, γ is used as control variable instead of β.





$$V_{dr} = V_{dor}\cos\alpha - R_{cr} I_d$$

$$V_{di} = V_{doi}\cos\beta + R_{ci} I_d$$

$y = mx + c$

$$V_{di} = V_{doi}\cos\gamma - R_{ci} I_d$$

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

⇒ A change of current and therefore power transfer can be achieved by altering any one of the four possible parameters —

(a) The control angle of the rectifier α

(b) The control angle of the inverter β or γ

(c) The rectifier - transformer secondary winding voltage by the tap-changer

(d) The inverter - transformer secondary winding voltage by the tap-changer

⇒ The cases (c) and (d) can be effected by employing tap-changing of the converter transformer to change the AC voltage.

⇒ The increase of power in the link is achived by reducing α_r which improves the power factor, at the rectifier for higher loadings and minimizes the reactive power consumption.

⇒ The inverter can now be operated at minimum γ, there by minimizing the reactive power consumption at the inverter also.

⇒ The operation at minimum extinction angle at the inverter and current control at the rectifier results in better voltage regulation than the operation with minimum delay angle at the rectifier and current control at the inverter

⇒ The currents during line faults are automatically limited with rectifier station in current control.

⇒ while there is a need to maintain a minimum extinction angle of the inverter to avoid commutation failure, it is economical to operate the inverter at constant extinction angle (CEA).

⇒ However, the main drawback of CEA control is the negative resistance characteristic of the converter which makes it difficult to operate stably when the AC system is weak

⇒ under normal conditions, the rectifier operates at constant current (CC) control and inverter at the CEA control.

⇒ under conditions of reduced AC voltage at the rectifier, it is necessary to shift the current control to the inverter to avoid run down of the DC link when the rectifier control hits the minimum limit. This implies that current controller must also be provided at the inverter in addition to the CEA controllers.

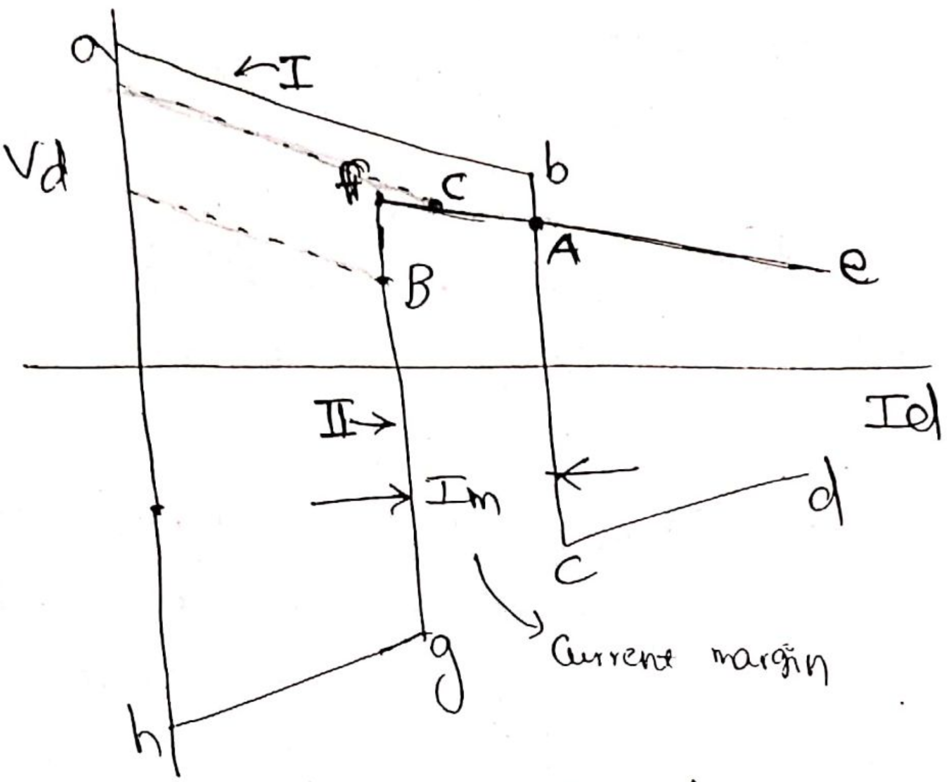
⇒ To avoid the clash of two current controllers, the current reference at the inverter is kept below that at the rectifier by an amount called the "current margin". this is typically about 10% of the rated current.

⇒ The power reversal in the link can take place by the reversal of the DC voltage. this is done easily by increasing the delay angle at the station initially operating as the rectifier, while reducing the delay angle at the station initially operating as the inverter.

⇒ The on-load tap changer control at the inverter is used mainly to maintain a constant DC voltage.

Converter Control Characteristics:—

1). Basic characteristics:—



DC voltage at the station to II versus DC Current. each station characteristic has three Parts as given below:

Station I	Station II	Type
ab	hg	minimum α
bc	gf	Constant Current
cd	fe	minimum γ

⇒ The intersection of the two characteristics (Point A) determines the mode of Operation — station I Operating as rectifier with constant Control and station II operating at constant (minimum) extinction angle.

There can be three modes of operation of the link. These are defined below.

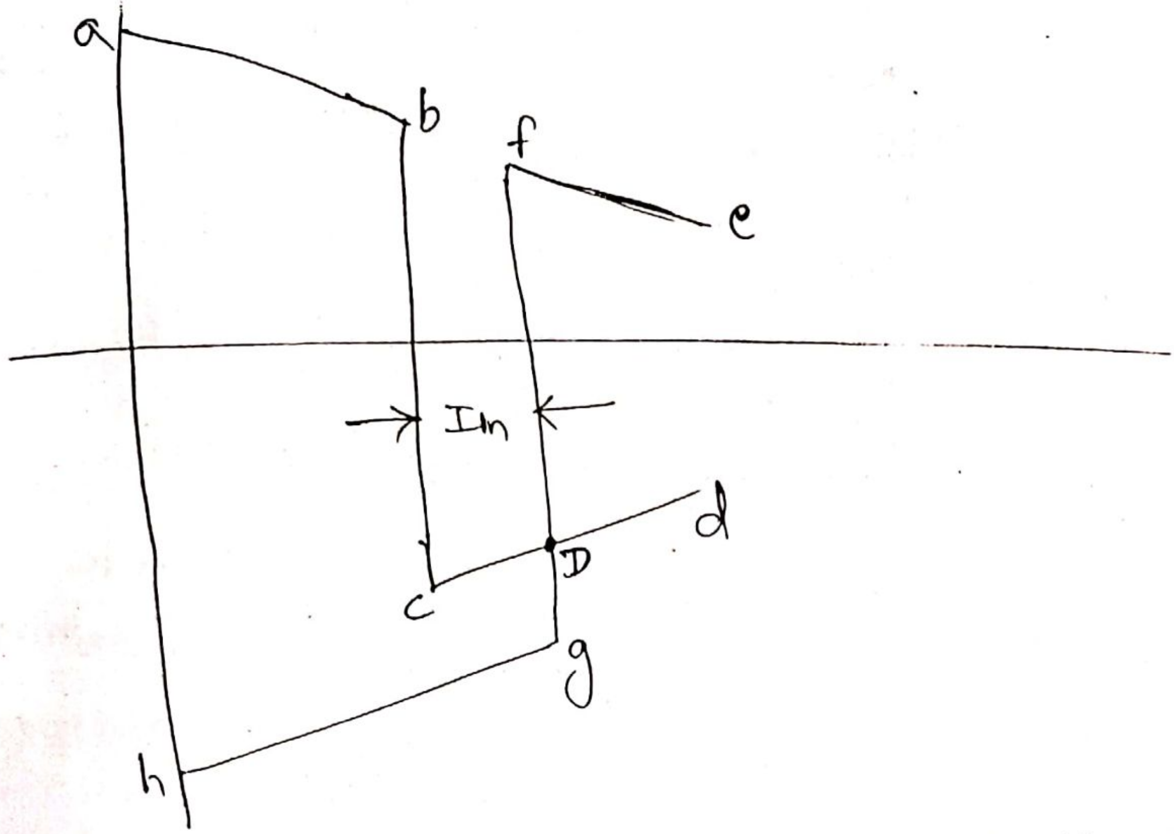
1. CC at rectifier and CEA at inverter. (operating A) which is the normal mode of operation.
2. With slight dip in the AC voltage, the point of intersection drifts to C which implies minimum α at rectifier and minimum γ at the inverter.
3. With lower AC voltage at the rectifier, the mode of operation shifts to point B which implies CC at the inverter with minimum α at the rectifier.

⇒ The characteristic ab has, generally, more negative slope than characteristic fe for similar values of Rcr and Rci. This is because of the fact that the slope of ab is due to the combined resistance (Rl + Rcr). while the slope of fe is due to Rci.

<u>Power reversal control characteristics:</u> —

⇒ below fig shows the control characteristics for negative current margin Im.
⇒ The operating point shifts now to 'D' which implies power reversal with station I (now acting as inverter) operating with minimum CEA control while station

-II operating with CC Control.



Modification of the Control Characteristics:—

⇒ The previous discussion has outlined the need to restrict the control region the first quadrant of the Vd - Id plane to avoid unwanted reversal of power.

Mode stabilization :—

⇒ The slope of ab and fe are nearly equal which can lead to poor definition of the intersection of point "c".

⇒ Further, if the slope of fe exceeds that of ab (see below fig ⓐ), there will be three possible operating points A, A' and A''.

⇒ This implies instability of the control which will result in hunting between different modes of operation

fig ⓐ : Illustration of 3-point instability.

⇒ To eliminate the above problem, the inverter characteristics are modified and given a positive slope when the current is between I_{d1} and I_{d2} (See below fig ⓑ).

⇒ Alternate solution is to modify the inverter control to maintain a constant DC voltage with back-up control of minimum CEA (See below fig ⓒ)

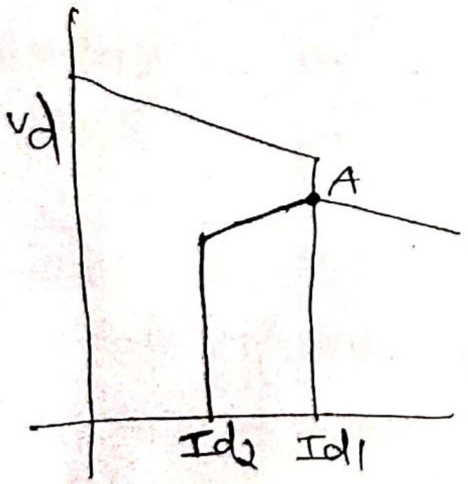


fig ⓑ

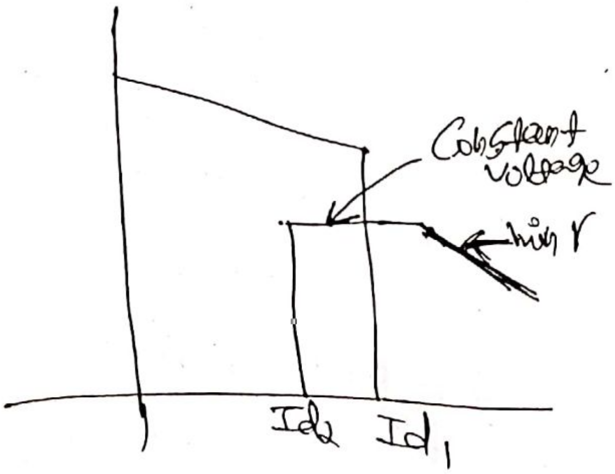
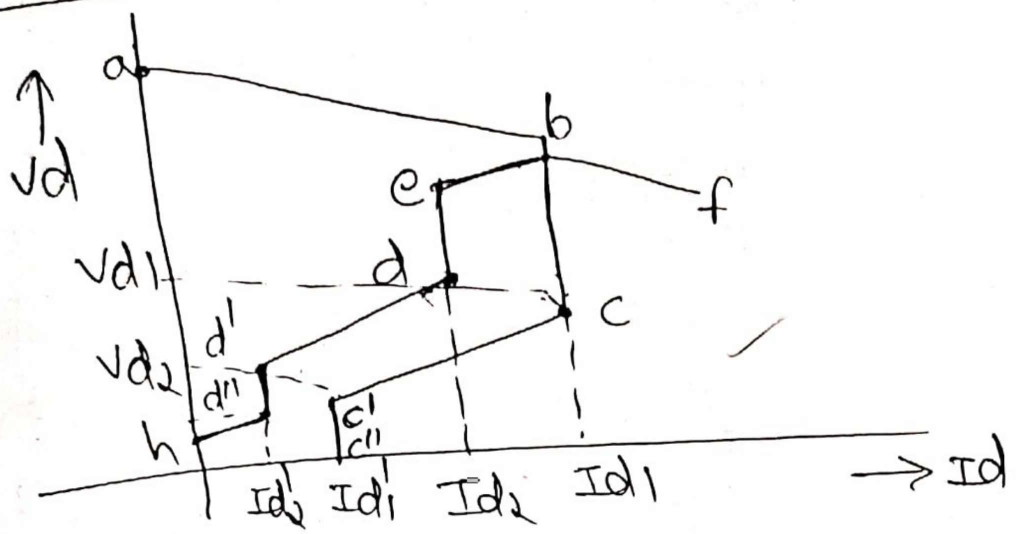


fig ⓒ

Scanned by CamScanner

Control characteristics including voltage dependent current order limit (VDCOL) :-



⇒ The low DC voltage in the link is mainly due to the faults in the AC system on the rectifier or inverter side.

⇒ If the low voltage is due to faults on the rectifier side AC system, the inverter has to operate at very low power factor causing excessive consumption of reactive power, which is also undesirable.

⇒ Thus, it becomes useful to modify the control characteristics to include voltage dependent current limits. This is shown in above fig.

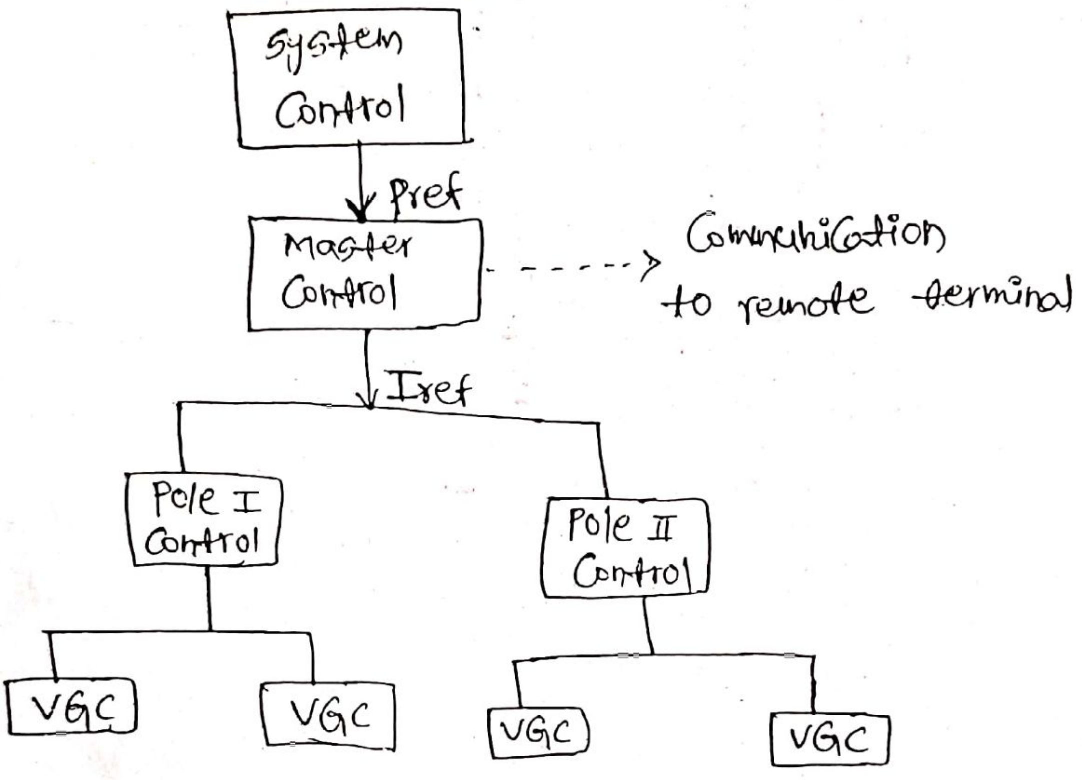
⇒ Current error characteristics to stabilize the mode when operating with DC current between I_{d1} and I_{d2}.

⇒ The characteristic cc' and c'c'' show the limitation of current due to the reduction in voltage.

⇒ The DC current is reduced from I_{d1} to I'_{d1} linearly and maintained at I'_{d1} below the voltage V_{d2}.

⇒ the inverter characteristic also follows the rectifier characteristic to maintain the current margin except for hd". which is due to the lower limit imposed on the delay angle of the inverter.

System Control Hierarchy :—



VGC → valve group control.

Hierarchical Control structure for a DC link

⇒ The control functions required for the HVDC link are performed using the hierarchical control structure shown in above fig.

⇒ The master controller for a bipole is located at one of the terminals and is provided with the power order (Pref) from the system controller (from energy control centre).

⇒ It also has other information such as AC voltage at the converter bus, DC voltage, etc.

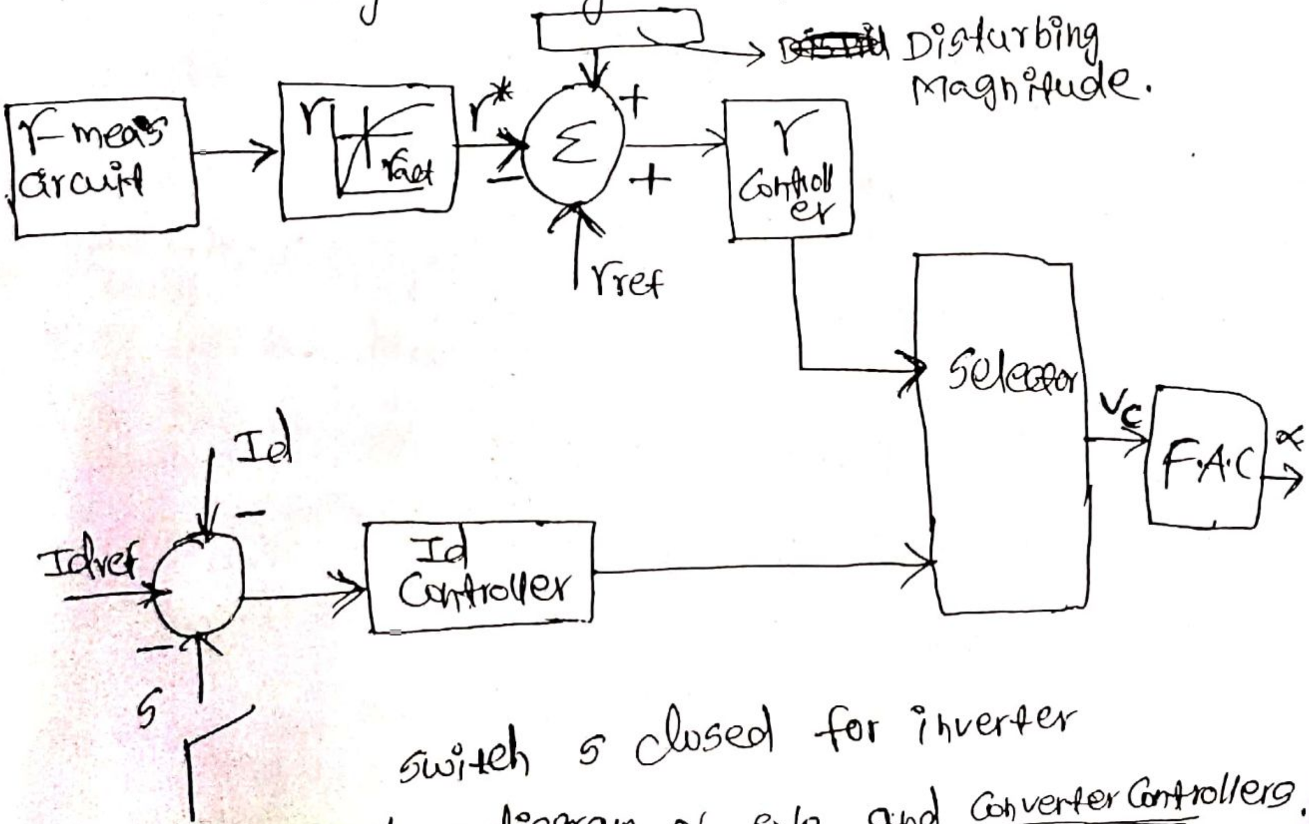
⇒ The master controller transmits the current order (I_{ref}) to the pole control units which in turn provide a firing angle order to the individual valve groups (converters).

⇒ The valve group or converter control also oversees valve monitoring and firing logic through the optical interface.

⇒ It also includes bypass pair selection logic, commutation failure protection, tap changer control, converter start/stop sequences, margin switching and valve protection circuits.

⇒ The pole control also incorporates pole protection, DC line protection and optional converter paralleling and deparalleling sequences.

⇒ The master controller which oversees the complete bipole includes the functions of frequency control, power modulation, AC voltage and reactive power control and torsional frequency damping control.



switch S closed for inverter

Block diagram of pole and converter controllers.

⇒ The block diagram of the pole and converter controls is shown in above fig: this shows the basic control functions.

⇒ The current or extinction angle controller generates a control singal V_C which is related to the firing angle required.

⇒ the firing angle controller generates gate pulses in response to the control signal V_C.

⇒ The selector picks the smaller of the α determined by the current and CEA controllers.

Firing Angle Control:—

⇒ The operation of CC and CEA controllers is closely related to the gate pulse of valves.

⇒ Two types of firing controls:

1) individual phase control (IPC): used in past
2) equidistance pulse control (EPC)

Individual phase control:—

⇒ Firing instance is determined individually for each valve i.e phase position of each control pulses is determined separately for each valve and related to commutation voltage (zero crossing).

⇒ Six parallel delay circuit is required.

⊙ This is classified into two types

i) Cosine control → constant α control
ii) Linear control, → Inverse cosine control

Advantage of IPC :-

⇒ DC Output voltage is higher.

Disadvantages :-

⇒ due to fault, distortion etc, zero crossing will shift and this may result in uncharacteristic harmonics.

⇒ may cause harmonic instability (weak ac system) at frequencies where filter impedance and system impedance are in parallel.

⇒ more filters are required and damping resistance is required to damped out harmonic oscillations.

Equidistance Pulse Control (EPC) :-

⇒ No synchronization of control pulses with applied ac voltage and used in modern HVDC

⇒ It produces pulses at equal intervals of $1/f_0 P$.

⇒ There are three methods of EPC

i) Pulse frequency Control (PFC)

ii) Pulse phase Control (PPC)

iii) Pulse period Control

⇒ This method gives low dc output voltage but successful in weak ac system.

⇒ EPC scheme also results in higher negative damping contribution to torsional oscillations.

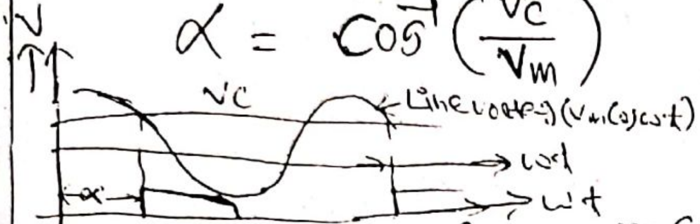
Cosine Control:-

⇒ There are several version of this method.

⇒ Pulse are generated at the crossing of control voltage V_c and ac line voltage.

$$\alpha = \cos^{-1}\left(\frac{V_c}{V_m}\right) \quad ; \quad V_d = V_{do}\cos\alpha$$

$$V_d = K V_c$$



⇒ This control system results in a linear transfer characteristics.

⇒ The output voltage is independent on change in input ac voltage.

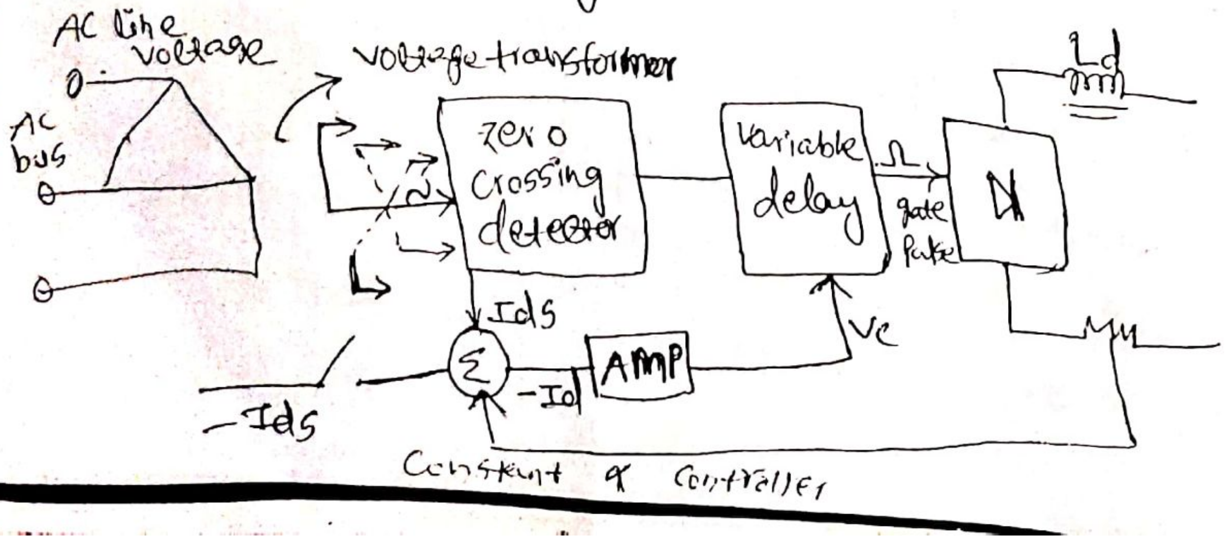
⇒ However, near alpha zero, it is very sensitive to V_c and leads to high inaccuracy.

Linear Control:-

⇒ Pulse are generated at the crossing of control voltage V_c and ac line voltage.

$$\alpha = K_1 V_c \quad ; \quad V_d = V_{do}\cos(K_1 V_c)$$

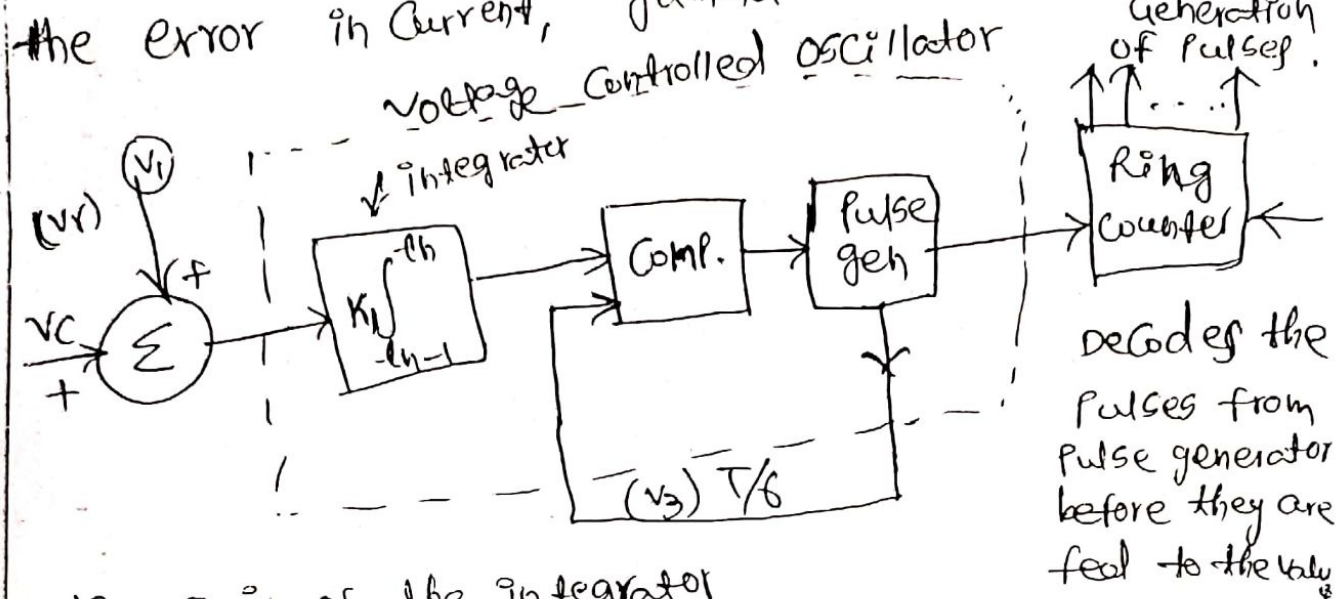
⇒ This makes linear transfer characteristics non-linear. But accuracy is of $\pm 1^\circ$.



ii) Pulse frequency Control (PFC):—

Voltage Control Oscillator (VCO)

⇒ The frequency of voltage Control oscillator (VCO) is determined by the Control voltage V_c related to the error in Current, gamma or voltage.

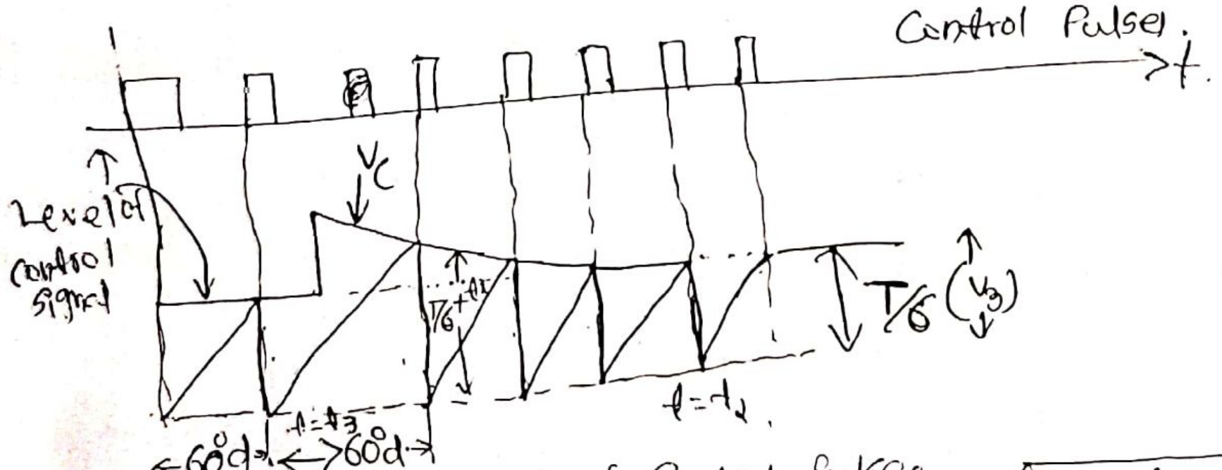


K_1 = gain of the integrator

V_1 = Bias voltage

V_C = Control voltage.

Block diagram of a PFC system



Generation of Control pulses.

to Ti base frequency

$$K_1 \int_{-t_{n-1}}^{-t_n} (V_c + V_1)\, dt = V_3$$

(or) $$K_1 (V_c + V_1) = \frac{V_3}{t_n - t_{n-1}} = V_3 f_{fo}$$

⇒ At steady state, $v_c = 0$, and thus

$$K_1 = \frac{V_3 \, Pf_0}{V_1}$$

⇒ V_1 is required?

⇒ frequency change is not taken care of, Hence with V_3 reset, f_0 is also be reset.

⇒ Ainsworth suggested frequency correction control as

$$K_1 \int_{t_{n-1}}^{t_n} v_1 \, dt = V_3 + v_c$$

(Or)

$$K_1 = \frac{V_3 \, Pf_0}{V_1}$$

⇒ PFC has better stability but problem of harmonics in control as it is integrated.

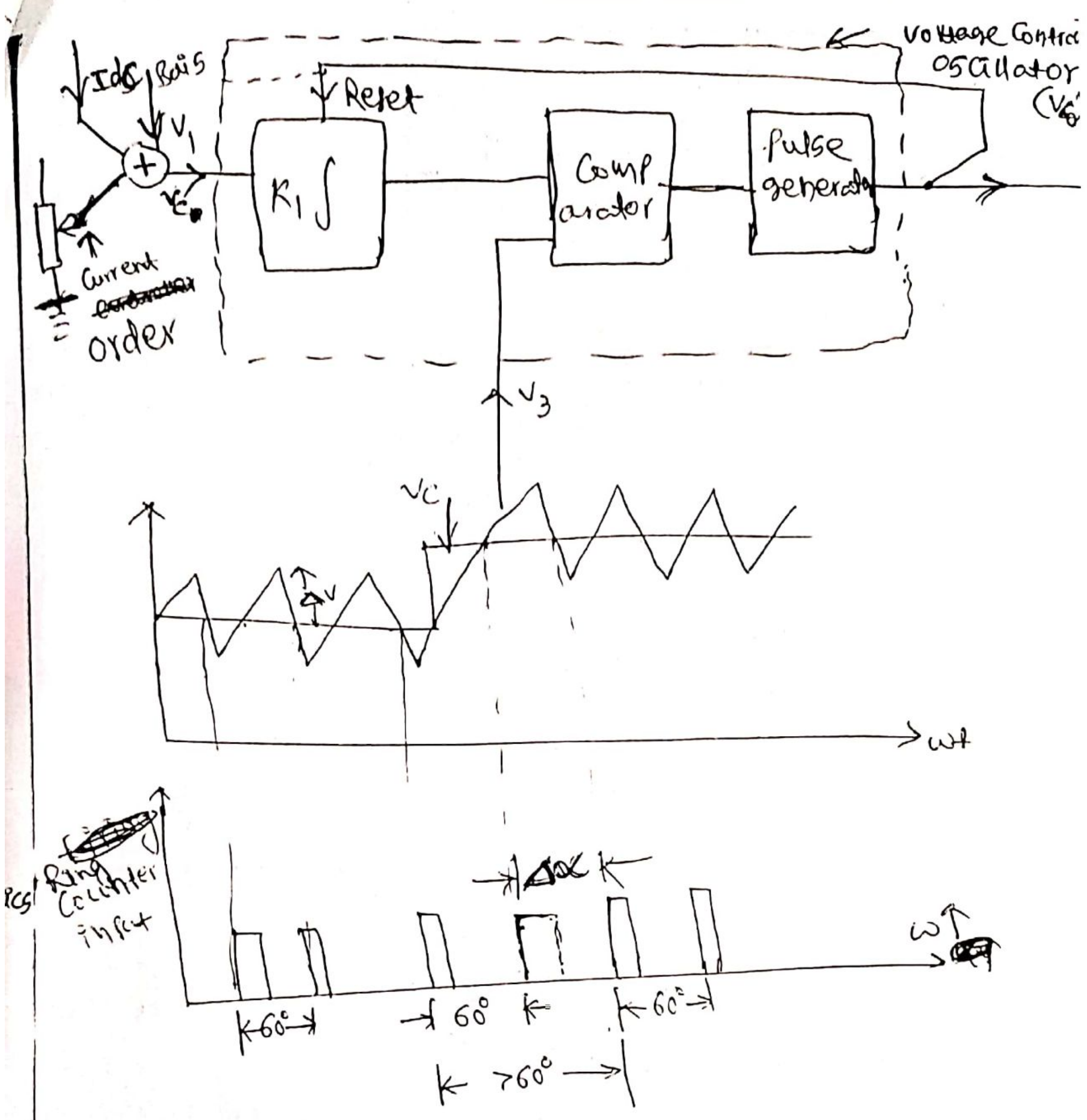
Pulse Phase Control (PPC) :—

⇒ A train of pulses are generated proportional to the control voltage v_c.

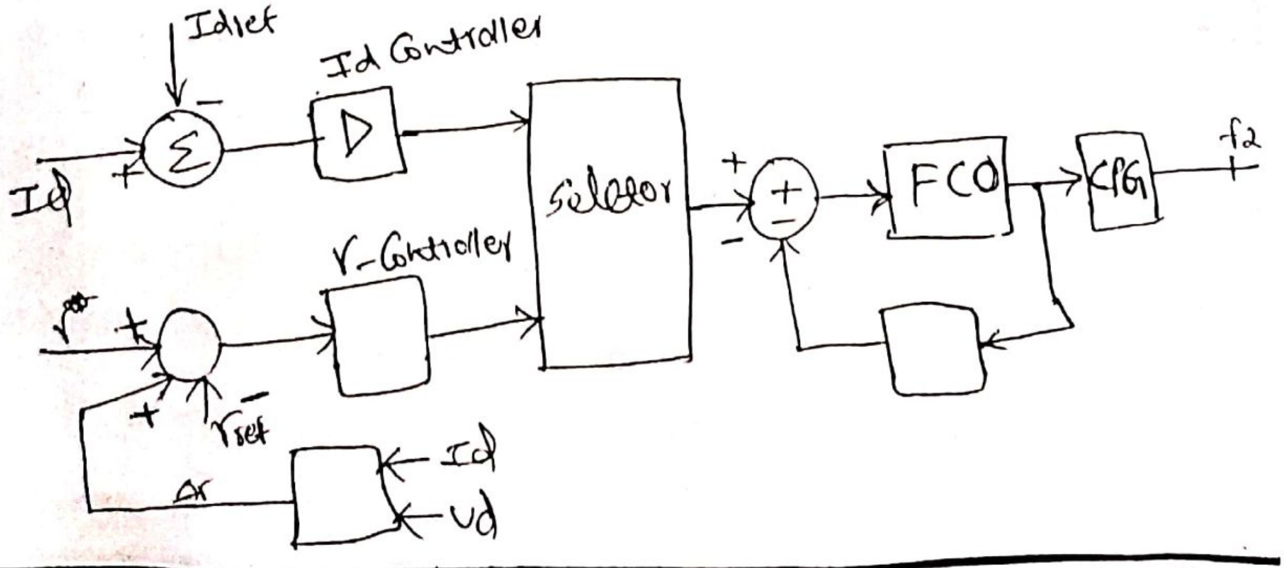
⇒ Response of this system is fast as it does not have integrator characteristic

⇒ The charging and discharging of capacitor is maintained between $\pm \Delta V$.

$$\int_{t_{n-1}}^{t_n} K_1 v_1 \, dt = v_{cn} - V_{c(n-1)} + V_3$$

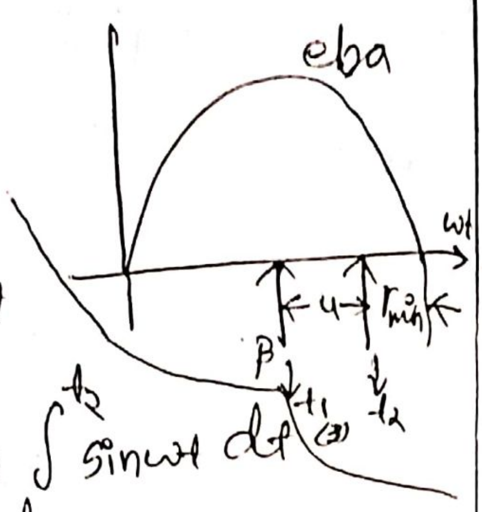


Current and CEA Control:



CEA Control :-

⇒ Knowing commutation voltage and γ_{min}, one can find β.



$$2L\frac{di_3}{dt} = e_b - e_a$$

$$= \sqrt{3}\, E_m \sin\omega t$$

$$2L\int_0^{I_d} di_3 = \sqrt{3}\, E_m \int_{t_1}^{t_2} \sin\omega t \, dt$$

here $t_1 = \alpha/\omega$; $t_2 = \frac{\pi - \gamma_{min}}{\omega}$

$$2L\, I_d = -\frac{\sqrt{3}\, E_m}{\omega}\left[\cos\omega t\right]_{\alpha/\omega}^{(\pi-\gamma_{min})/\omega}$$

$$-\cos\alpha = \cos\gamma_{min} - \frac{2\omega L}{\sqrt{3}\, E_m} I_d = \cos\beta$$

⇒ β depends on ω, L, I_d, E_m and these are measured continuously.

⇒ For precise control, I_d is replaced by I_d'

$$I_d' = I_d + \Delta I_d .$$

⇒ ΔI_d is to take care of change of I_d during the interval μ.

Transition of CEA to CC :-

⇒ In the event of sudden system disturbance due to inverter end ac voltage rise or dip in dc voltage, the dc link current decreases, if current amplifier of rectifier saturated, the firing pulse of inverter

92

we(7) explained

UNIT - IV

Harmonic Analysis and Filter design

Harmonic Analysis:-

⇒ characteristic harmonic

$h = np$ (dc side, voltage harmonic)

$h = np \pm 1$ (ac side, current harmonic)

DC

⇒ Non-characteristic harmonics are other than this

⇒ Assumptions involved in harmonic analysis

→ AC supply is 3-phase balanced.

→ DC Current is constant (ripple free)

→ valves are ignited at equal intervals of 1/6 of cycle.

→ Commutation inductances are equal in all three phases.

⇒ AC voltage and DC current has no harmonics.

⇒ Some Observations:-

⇒ The alternating voltage has no harmonics except fundamental.

⇒ The direct current has no harmonics.

⇒ overlap angle is same for every commutation;

⇒ Ripples in DC voltage has a period of 1/6 of that AC voltage.

⇒ Hence the harmonics of direct voltage are of order 6 and its multiples 12, 18, ... etc.

⇒ AC Current of three phases have the same wave shape but are displaced by $120°$.

⇒ $F(\theta + 180°) = F(\theta)$, NO even harmonics in AC Current.

⇒ No triple harmonic present in AC Current.

⇒ phase difference of h^{th} harmonic is h times that For the fundamental Component.

sequence	h
zero	0, 3, 6, 9, 12, ... 3n
+ve	1, 4, 7, 10, 13 ...... 3n+1
−ve	2, 5, 8, 11, 14 .... 3n−1

⇒ Fourier series

$$F(\theta) = \frac{A_0}{2} + \sum_{h=1}^{\infty} (A_h \cos h\theta + B_h \sin h\theta)$$

where

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

$$A_h = \frac{1}{\pi} \int_0^{2\pi} F(\theta) \cos h\theta\, d\theta;$$

$$B_h = \frac{1}{\pi} \int_0^{2\pi} F(\theta) \sin h\theta\, d\theta.$$

Avg value ← $A_0 = 0$

$A_h = ?$

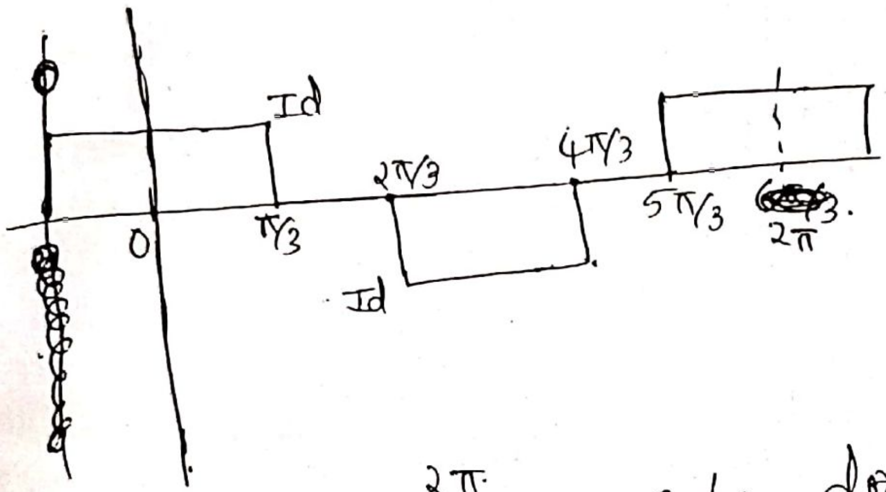
$B_h = ?$

Scanned by CamScanner

⇒ Cosine or sin can be removed by choosing the appropriate axis.

i) $F(\theta) = -F(-\theta)$ → sine comp

ii) $F(\theta) = F(-\theta)$ — cos comp



$$I_h = \frac{I_{h0}\left[A^2+B^2-2AB\cos(2\alpha+\mu)\right]^{1/2}}{\cos\alpha - \cos(\alpha+\mu)}$$

where

$$A = \frac{\sin(h+1)\,\mu/2}{h+1}, \quad B = \frac{\sin(h-1)\,\mu/2}{h-1}$$

DC voltage harmonics

$$V_h = V_{d0}\left[C^2+D^2-2CD\cos(2\alpha+\mu)\right]^{1/2}/\sqrt{2}$$

where

$$C = \frac{\cos(h+1)\,\mu/2}{h+1}, \quad D = \frac{\cos(h-1)\,\mu/2}{h-1}$$

with overlap angle formula

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

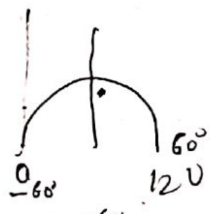
$$= \frac{1}{\pi}\left[\int_0^{\pi/3} I_d \cos h\theta \, d\theta + \int_{\pi/3}^{2\pi/3} 0 + \int_{2\pi/3}^{4\pi/3} -I_d \cos h\theta \, d\theta + \int_{4\pi/3}^{5\pi/3} 0 + \int_{5\pi/3}^{2\pi} I_d \cos h\theta \, d\theta\right]$$

$$A_h = \frac{I_d}{\pi h}\left[\sin\frac{h\pi}{3} - \sin\frac{4\pi h}{3} + \sin\frac{2\pi h}{3} - \sin\frac{5\pi h}{3}\right]$$

$$A_1 = \frac{I_d}{\pi}\left[\frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2}\right]$$

$$A_1 = \frac{2\sqrt{3}}{\pi} I_d = I_{1m}$$

$$I_{1rms} = \frac{I_{1m}}{\sqrt{2}} = \frac{\sqrt{6}}{\pi} I_d.$$



$\int_{-60}^{120\,60} (\ )$ Sin & cos

$$A_2 = \frac{I_d}{2\pi}\left[\frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2} + \frac{\sqrt{3}}{2}\right]$$

$$A_2 = 0.$$

$$A_3 = 0$$

$$A_4 = 0$$

$$A_5 = \frac{I_d}{\pi}\left[-\frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2} - \frac{\sqrt{3}}{2}\right]$$

$$= \frac{-2\sqrt{3}}{5\pi} I_d = \frac{-I_{1m}}{5}$$

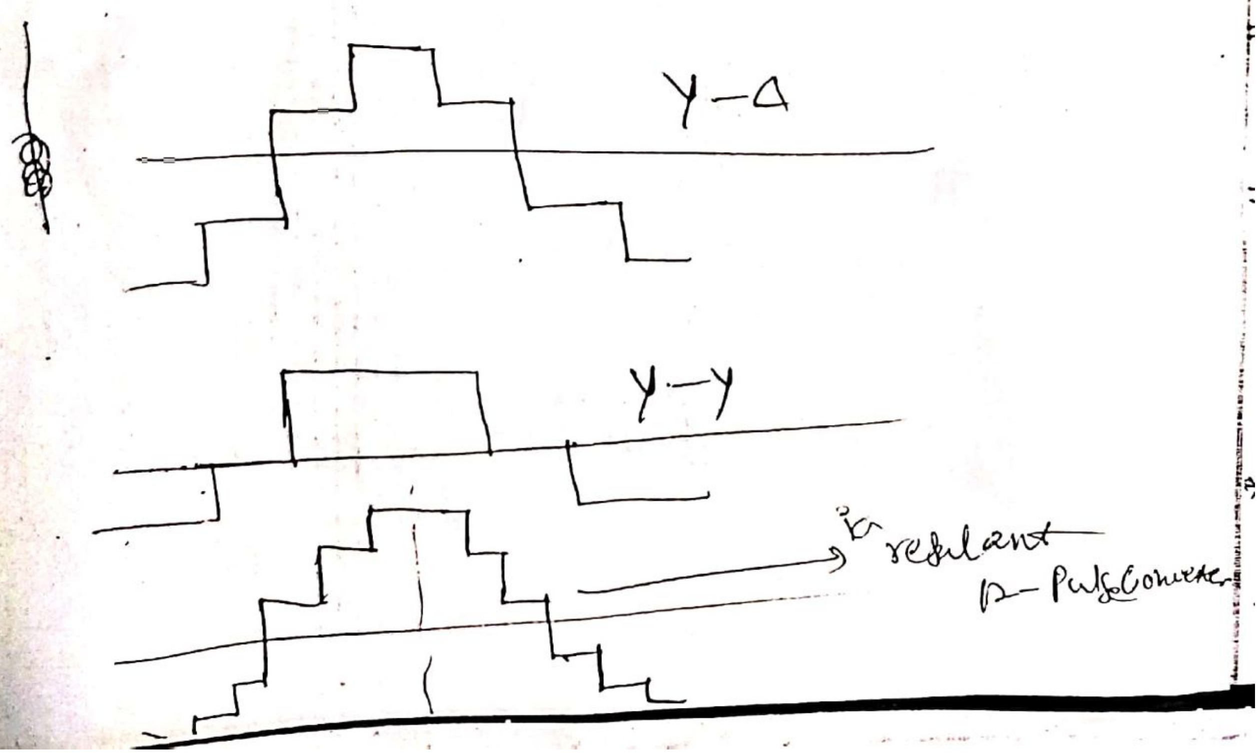
For Y-Y Connection:-

$$i_a = \frac{2\sqrt{3} I_d}{\pi}\left[\cos\theta - \frac{1}{5}\cos 5\theta + \frac{1}{7}\cos 7\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta - \cdots\right]$$

For star-delta Connection

$$i_a = \frac{2\sqrt{3} I_d}{\pi}\left[\cos\theta + \frac{1}{5}\cos 5\theta - \frac{1}{7}\cos 7\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta + \cdots\right]$$

12-Pulse Converter:-



$$i_a = \frac{2\sqrt{3} I_d}{\pi} \left[\cos\theta - \frac{1}{11}\cos 11\theta + \frac{1}{13}\cos 13\theta - \frac{1}{23}\cos 23\theta + \frac{1}{25}\cos 25\theta - \cdots \right]$$

=> The effect of overlap decreases the amplitude of harmonics and introduces uncharacteristic harmonics.

Uncharacteristic harmonics:-

=> Converter produces harmonics of all orders and some dc component on the valve winding of transformers.

=> Harmonics other than $np \pm 1$ are known as uncharacteristic harmonics. There are of low magnitude.

Causes:-

=> Normally valves are not fired at equal intervals due to unbalance of 3-phase supply system.

=> Even balance circuit with jitter in electronic circuitry produces uncharacteristic harmonics.

=> Controllers actions (specially CEA controller).

=> Interaction of characteristic harmonics and fundamental current in non-linear element of power system.

=> Saturation of transformers.

Effects of Harmonics:-

=> Improper operation of converter and sometimes inaccuracy or instability of CC control.

⇒ shift of zero-crossing
⇒ Telephone interference
⇒ Extra losses and heating in the system,
⇒ over-voltage due to resonance.
⇒ Interference with the ripple control system.

Definitions of wave Distortion or Ripple:-

⇒ Total RMS harmonics

→ Alternating Current

$$H_1 = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1}$$

$$= \frac{\sqrt{I^2 - I_1^2}}{I_1}$$

→ Direct Current

$$H_2 = \frac{\sqrt{\sum_{h=1}^{\infty} I_h^2}}{I_d} = \frac{\sqrt{I^2 - I_d^2}}{I_d}$$

where I = effective (rms) Current

I_1 = rms fundamental Current

I_h = rms harmonic Current of order h

⇒ Deviation from sine wave

→ Alternating Current

$$H_3 = \frac{|i - i_1|_{max}}{I_{1m}}$$

→ Direct Current

$$H_4 = \frac{|i - I_d|_{max}}{I_d}.$$

⇒ peak to peak value of Ripple

$$H_5 = \frac{i_{max} - i_{min}}{I_d}$$

⇒ maximum Theoretical Deviation From a sine wave

$$H_6 = \frac{\sum_{h=2}^{\infty} I_h}{I_1}$$

Characteristic variation of harmonic current with variation of α & μ :-

⇒ As μ increases, the magnitude of harmonics decreases, but higher order harmonics decreases more rapidly than low order.

⇒ The rate of reduction of harmonics increases as μ increases up to a certain limit.

⇒ Each harmonic decreases to minimum at an angle $\mu = 2\pi/h$ and then rises slightly ~~thereafter~~ there after.

⇒ when μ is held constant, the change in the various values of alpha(α) is small.

⇒ For a given current when α is increased μ is decreased, the harmonics tend to increase and reached highest at $\mu = 0$.

Harmonic filters:—

Purpose:—

⇒ To reduce the harmonic voltage & current in the ac power network

⇒ To provide some reactive power support.

Types:—

⇒ Based on Locations

→ AC side

- Primary side (never connected to valve side)
- Tertiary winding (low voltage and thus cost is less but cost of tertiary winding and high impedance of winding).

→ DC side

- DC reactors are used.

⇒ Based on Connection

→ series type

→ shunt type.

Comparison:—

⇒ Shunt filters are cheap.

⇒ series filters carry full current and must be insulated for full voltage to ground.

⇒ shunt filters carry small amount of current plus some fundamental amount of current.

⇒ shunt filters supply reactive power at fundamental freq-uency. where as series filters consume it.

⇒ shunt filters could be delta or star types. Norm-ally star type filters are used series filters are phase filters.

⇒ Based on sharpness of tuning

⇒ Tuned filters (limited for one or two frequencies)

- high quality factor
- only one inductor is subjected to full line impulse voltage.
- power loss at fundamental frequency is consi-derably reduced.

⇒ Damped filters (low Q filters) or high pass filters

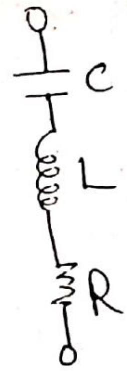
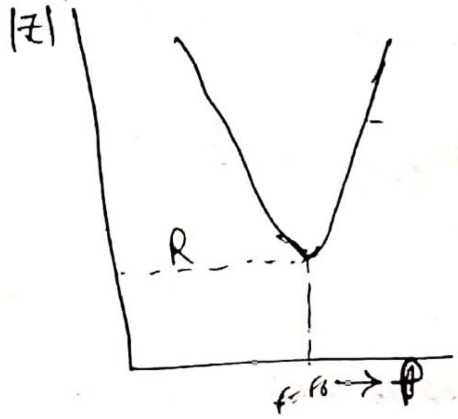
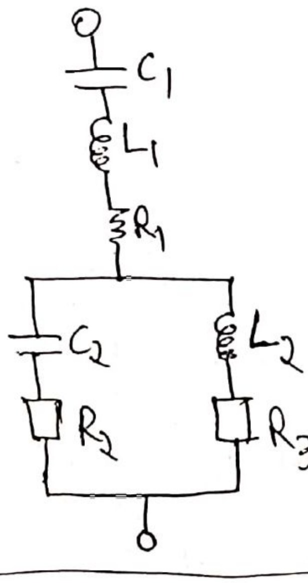
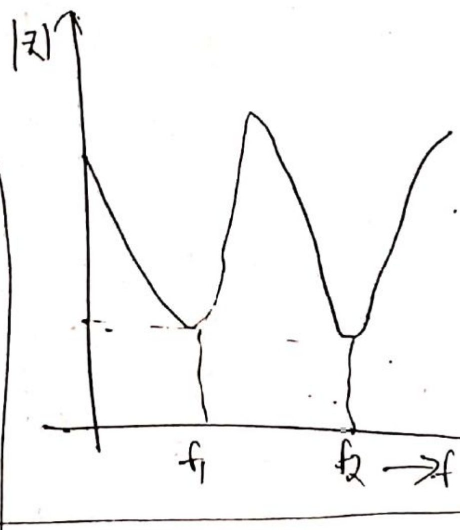
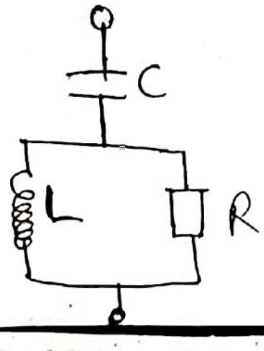
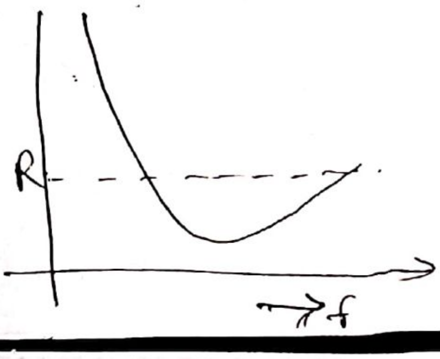
- Low Quality factor
- No sharp tuning is required
- Tolerate large steady state frequency variat-ions.
- Reduce transient voltage due to high resistance.
- C type of filters can be used to reduce the loss.

→ Rating of filters

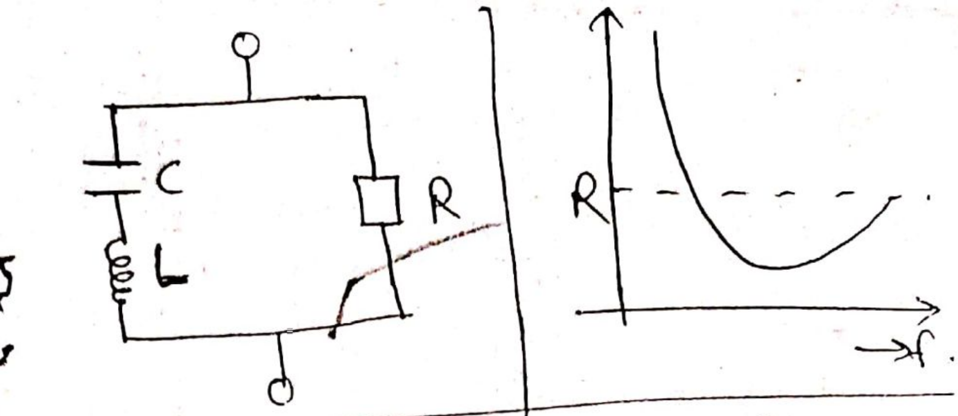
→ Highest power frequency ac voltage.

→ Higher effective frequency deviation

→ Highest harmonic contents.

Type	Circuit	|Z| vs frequency
Single tuned		
Double tuned		
second order high pass		

C type



⇒ size of filter is defined as the reactive power that the filter applies at fundamental frequency.

Design of Tuned Filter :-

⇒ selection of size

⇒ sharpness of tuning, Q-factor of inductor.

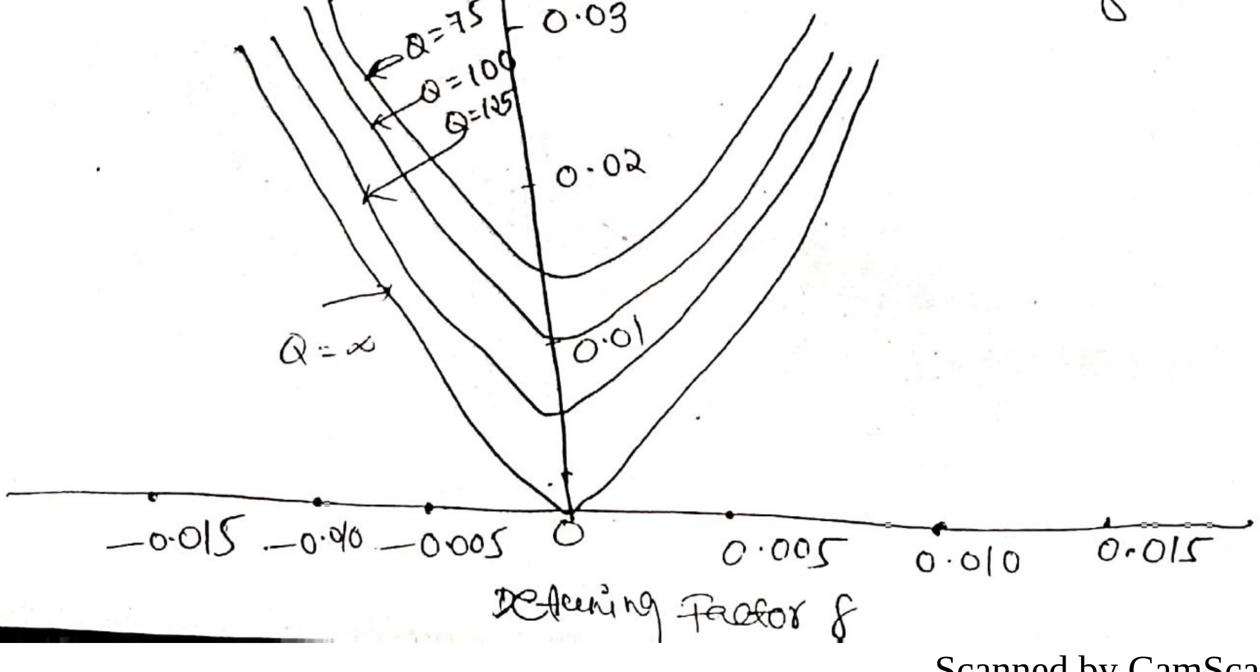
→ power frequency may change and thus causing the harmonic frequency to change.

→ Due to change in L and C (ageing and heating).

$$\delta = \frac{\Delta f}{f_n} + \frac{1}{2}\left(\frac{\Delta L}{L_n} + \frac{\Delta C}{C_n}\right)$$

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

$\delta = \frac{\omega - \omega_n}{\omega_n}$



$$\omega_n = \frac{1}{\sqrt{LC}} \; ; \quad Z_f = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

$$\delta = \frac{\omega - \omega_n}{\omega_n}$$

$$\omega = \omega_n (1+\delta)$$

$$X_0 = \omega_n L = \frac{1}{\omega_n C}$$

$$X_0^2 = \omega_n L \times \frac{1}{\omega_n C} = \frac{L}{C}$$

$$X_0 = \sqrt{\frac{L}{C}}$$

$$Z_f = R + j\left(\omega L - 1/\omega C\right)$$

$$= R\left[1 + j\left(\frac{\omega L}{R} - \frac{1}{\omega R C}\right)\right]$$

$$= R\left[1 + j Q\left(\frac{\omega}{\omega_n} - \frac{\omega_n}{\omega}\right)\right]$$

$$Z_f = R\left[1 + j Q\left((1+\delta) - \frac{1}{(1+\delta)}\right)\right]$$

$$Z_f = R\left[1 + j Q \delta \left(\frac{2+\delta}{1+\delta}\right)\right]$$

if $\delta << 1$

$$Z_f \cong R\left[1 + j 2 Q \delta\right]$$

$$Z_f = X_0 K \qquad X_0 = QR$$

here $K = \left[\frac{1}{Q} + j\,\delta\frac{(2+\delta)}{(1+\delta)}\right]$

$Q \to \infty$

$$|K| = \left[0 + j\,\delta\frac{(2+\delta)}{1+\delta}\right]$$

Double-tuned Filters

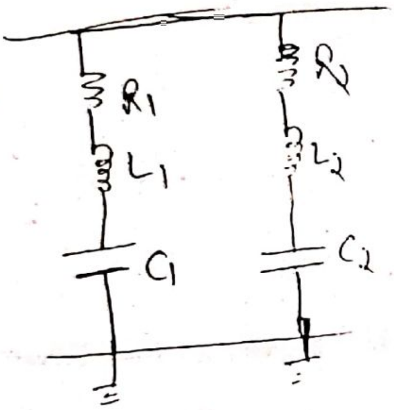
⇒ Two single tuned Filters connected in Parallel

⇒ one single double tuned Filter

⇒ **Advantages**

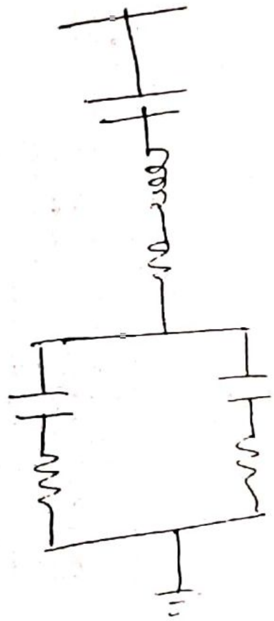
⇒ Power loss at Fundamental frequency is less

⇒ one inductor is subjected to the full impulse voltage

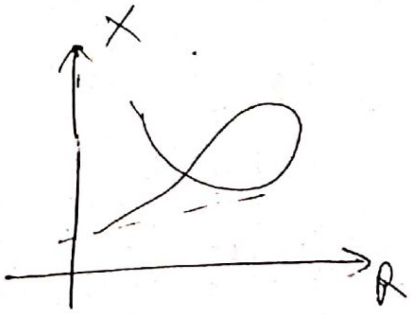


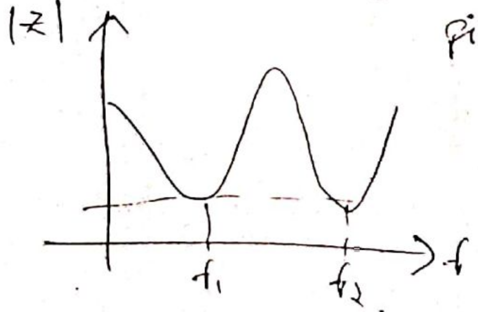
two single tuned Filters connected in parallel

⊕



one single double tuned filter.



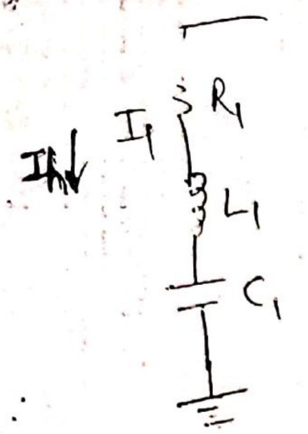


$$\delta = \frac{\omega - \omega_n}{\omega_n} = \frac{\omega}{\omega_n} - 1$$

$$\omega_n = 1/\sqrt{LC}$$

$$= \omega\sqrt{LC} - 1$$

$$\Delta\delta = \frac{\Delta\omega}{\omega} + \frac{1}{2}\left(\frac{\Delta C}{C} + \frac{\Delta L}{L}\right)$$



$$Q = I_1^2 (X_L - X_C)$$

$$= I_1^2 \left(\omega_1 L - \frac{1}{\omega_1 C}\right)$$

$$= I_1^2 \omega_1 L \left(1 - \frac{1}{\omega_1^2 LC}\right)$$

$$Q = I_1^2 \omega_1 L \left(1 - \frac{\omega_h^2}{\omega_1^2}\right)$$

$$Q = I_1^2 \omega_1 L \left[1 - h^2\right]$$

$$[\because \omega_n = h\omega_1]$$

⇒ filter cost is 5-10% of terminal equipment.

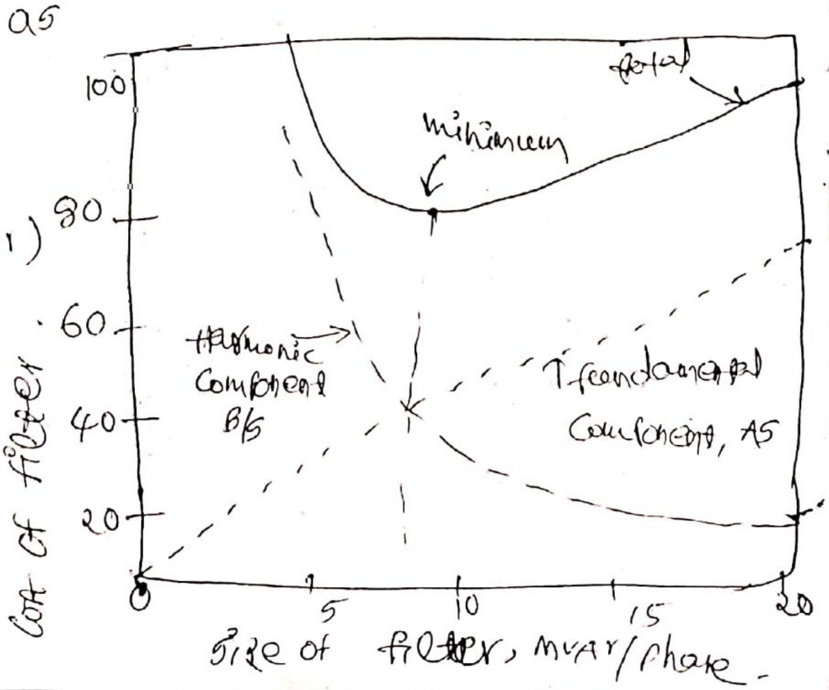
⇒ These filters are used to lower order harmonics i.e for 6 pulse converter 5th and 7th harmonics. For 12 pulse converter 11th and 13th Harmonics.

<u>Minimum Cost Tuned Filter</u> :-

⇒ The cost of filter tuned for a particular harmonic varies with size as

$$K = AS + B/S$$

where S = size (MVAr)



⇒ Filter capacitor is subjected to current and voltage of two frequency. (f and hf)

⇒ Rating of capacitor in MVAR must be largest sum of fundamental - frequency reactive power plus harmonic reactive power for which it is tuned.

⇒ The cost of capacitor is directly proportional to its rating.

⇒ The size of capacitor, by definition, is the reactive power of the capacitor at fundamental frequency only

⇒ Fundamental frequency source is essentially a constant voltage source and harmonic source is constant current source.

⇒ Rating of capacitor

$$Q_r C = V_1^2 \omega_1 C + \frac{I_{hf}^2}{h\omega_1 C} = S + \frac{V_1^2 I_{hf}^2}{hS}$$

⇒ Rating of inductor will be

$$Q_r L = \frac{S}{h^2} + \frac{V_1^2 I_{hf}^2}{hS}$$

$Q_{rL} = I_1^2 \omega_1 L + I_{hf}^2 h\omega_1 L$

$\omega_n^2 = \frac{1}{LC} \Rightarrow L = \frac{1}{h^2\omega_1^2 C}$

⇒ Neglecting the cost of resistor, the total cost of filter is $K = Q_{rC} U_C + Q_{rL} U_L$

where U_C and U_L are the unit cost of capacitor and inductor, respectively.

$$K = S\left(U_C + \frac{U_L}{h^2}\right) + \frac{V_1^2 I_{hf}^2}{hS}(U_C + U_L)$$

$$K = AS + B/S$$

Size of minimum cost filter will be obtained by

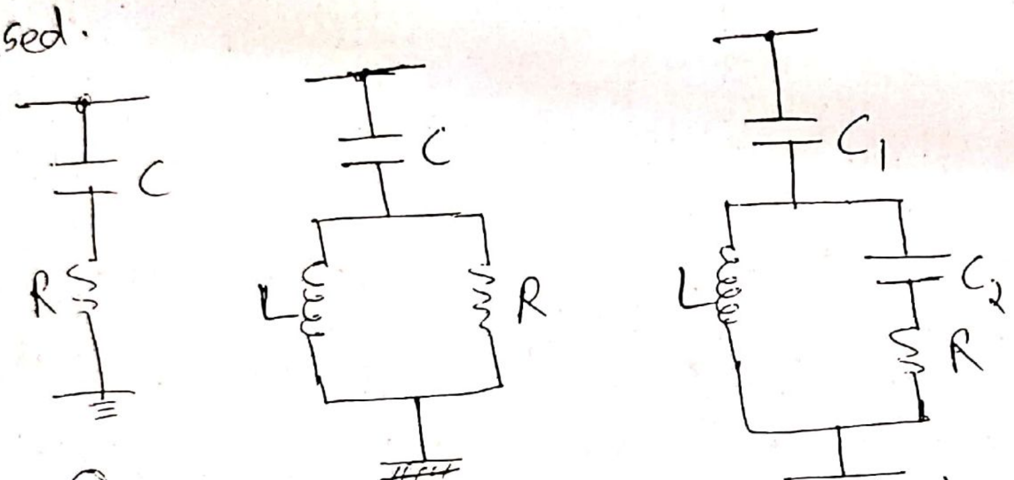
$$\frac{\partial K}{\partial S} = 0 = A - B/S^2$$

Thus, $S = \sqrt{\frac{B}{A}}$

$$K_{min} = 2\sqrt{AB}$$

Design of high pass Filter :-

⇒ First order Filter is very lossy due to large Capacitor. second and third order are generally used.

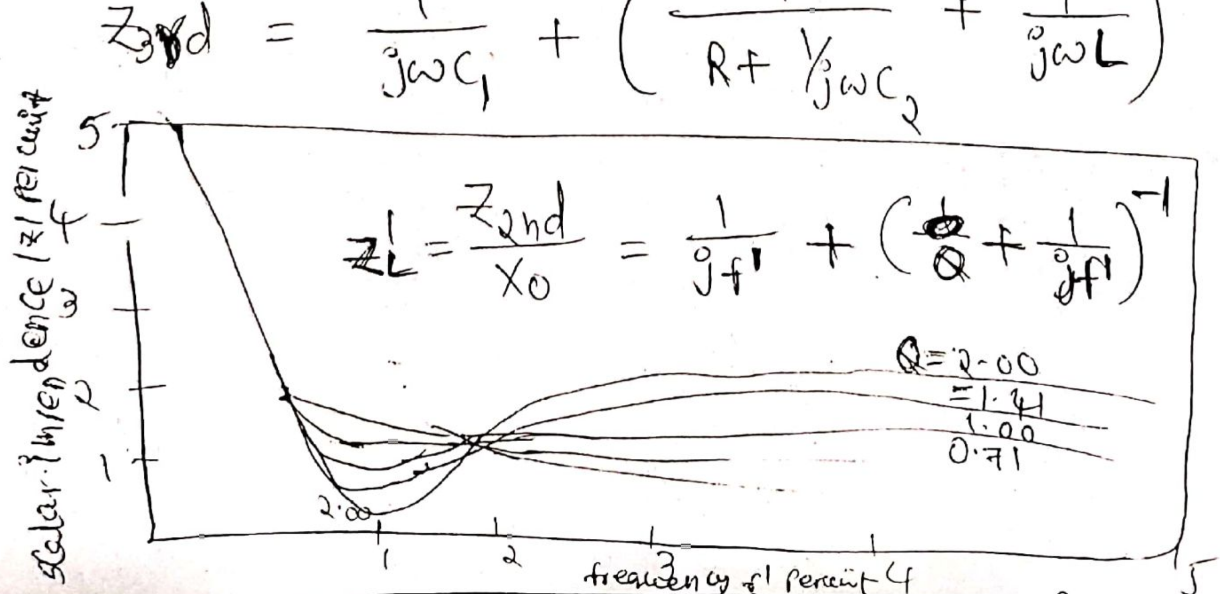


ⓐ 1st order ⓑ 2nd order ⓒ 3rd order.

$$Z_{2nd} = \frac{1}{j\omega C} + \left(\frac{1}{R} + \frac{1}{j\omega L}\right)^{-1}$$

$$Z_{3rd} = \frac{1}{j\omega C_1} + \left(\frac{1}{R + 1/j\omega C_2} + \frac{1}{j\omega L}\right)^{-1}$$

$$Z_L' = \frac{Z_{2nd}}{X_0} = \frac{1}{jf'} + \left(\frac{1}{Q} + \frac{1}{jf'}\right)^{-1}$$



$$\omega_n = \frac{1}{\sqrt{LC}} \;;\; X_0 = \sqrt{\frac{L}{C}} \;;\; Q = \frac{X_0}{R}$$

$$z' = \frac{Z}{X_0} \;;\; f' = \frac{f}{f_n} = \frac{\omega}{\omega_n}$$

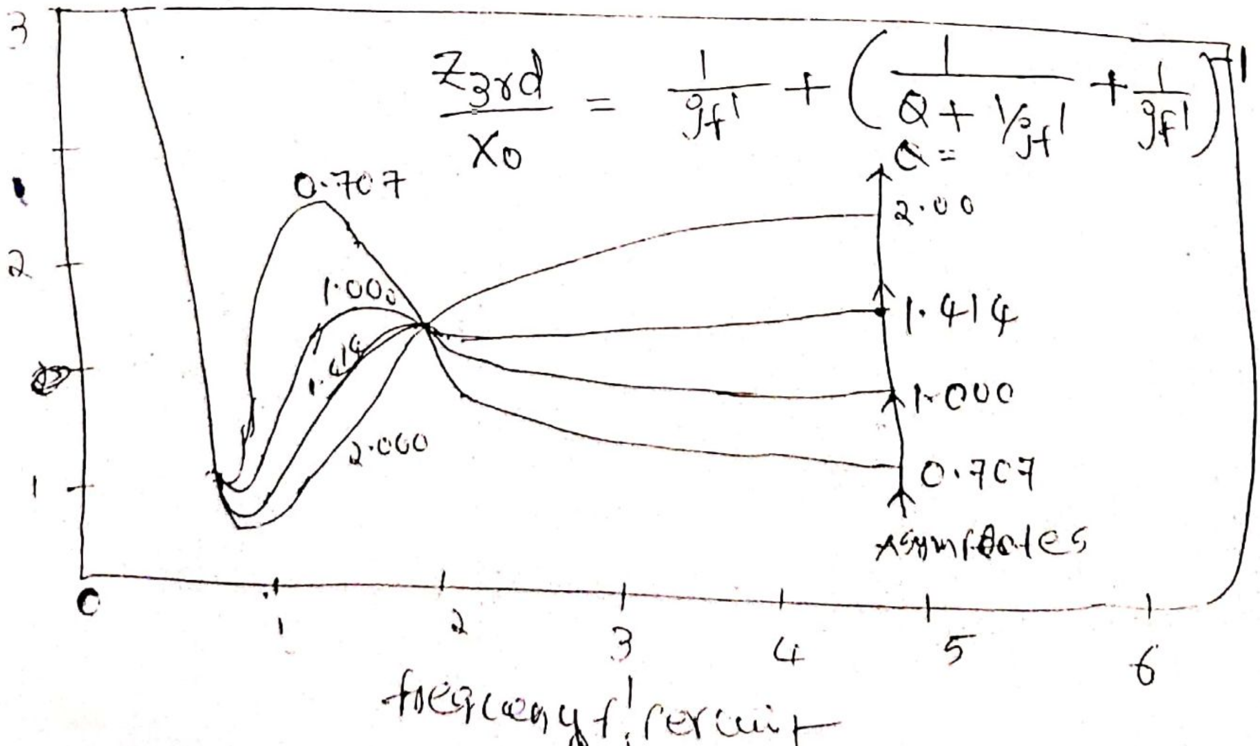
$$Z_{nd} = \frac{1}{j\omega C} + \left(\frac{1}{R} + \frac{1}{j\omega L}\right)^{-1}$$

$$= X_0\left(\frac{1}{j\omega X_0 C} + \left(\frac{X_0}{R} + \frac{X_0}{j\omega L}\right)^{-1}\right)$$

$$= X_0\left(\frac{1}{j\omega/\omega_n} + \left(Q + \frac{1}{j\omega/\omega_n}\right)^{-1}\right)$$

$$= X_0\left[\frac{1}{jf'} + \left(Q + \frac{1}{jf'}\right)^{-1}\right]$$

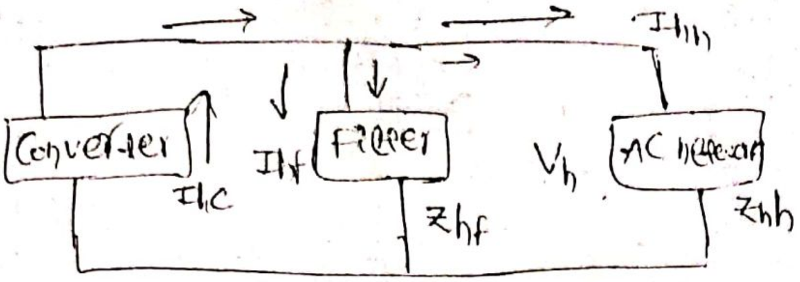
$$\frac{Z_{nd}}{X_0} = \frac{1}{jf'} + \left(Q + \frac{1}{jf'}\right)^{-1}$$



$$\frac{Z_{3rd}}{X_0} = \frac{1}{jf'} + \left(\frac{1}{Q + 1/jf'} + \frac{1}{jf'}\right)^{-1}$$

Effect of Network impedance on Filtering :-

⇒ Converter generates constant current harmonics on ac side and constant voltage harmonics on dc side.



$$V_h = \frac{Z_{nh} Z_{nf}}{Z_{nh} + Z_{nf}} I_{hc} = \frac{I_{hc}}{Y_{nh} + Y_{hf}}$$

Z_{hf} = impedance of filter to harmonic of order h.

Z_{nh} = Impedance of network to harmonic of order h.

when $Z_{hn} = 0$, (un realistic)

when Z_{hn} = infinite (∞), ideal case

when network and filter are in parallel reasonance ⇒ Resulting impedance will be high.

$$Z_{hn} >> Z_{hf}$$

Scanned by CamScanner

UNIT – IV

Converter Fault & Protection

Nature and types of Faults.

⇒ AC network faults at rectifier end

⇒ AC line faults at inverter end

⇒ DC Line / Cable fault

⇒ Converters station faults.

Type of fault	Occurrence	fault Current	Protection
Converter and internal faults	Rare	10 pu	Valves are rated for small duration of fault occurrence.
DC Line faults	frequent	2 to 3 pu	Force retardation of firing angle
Commutation Failure	very frequent	1.5 to 2.5 pu	Single – self clearing Multiple – beta Control and VDCOL

⇒ According to the origin of the malfunction, Converter faults can be divided into three broad groups:

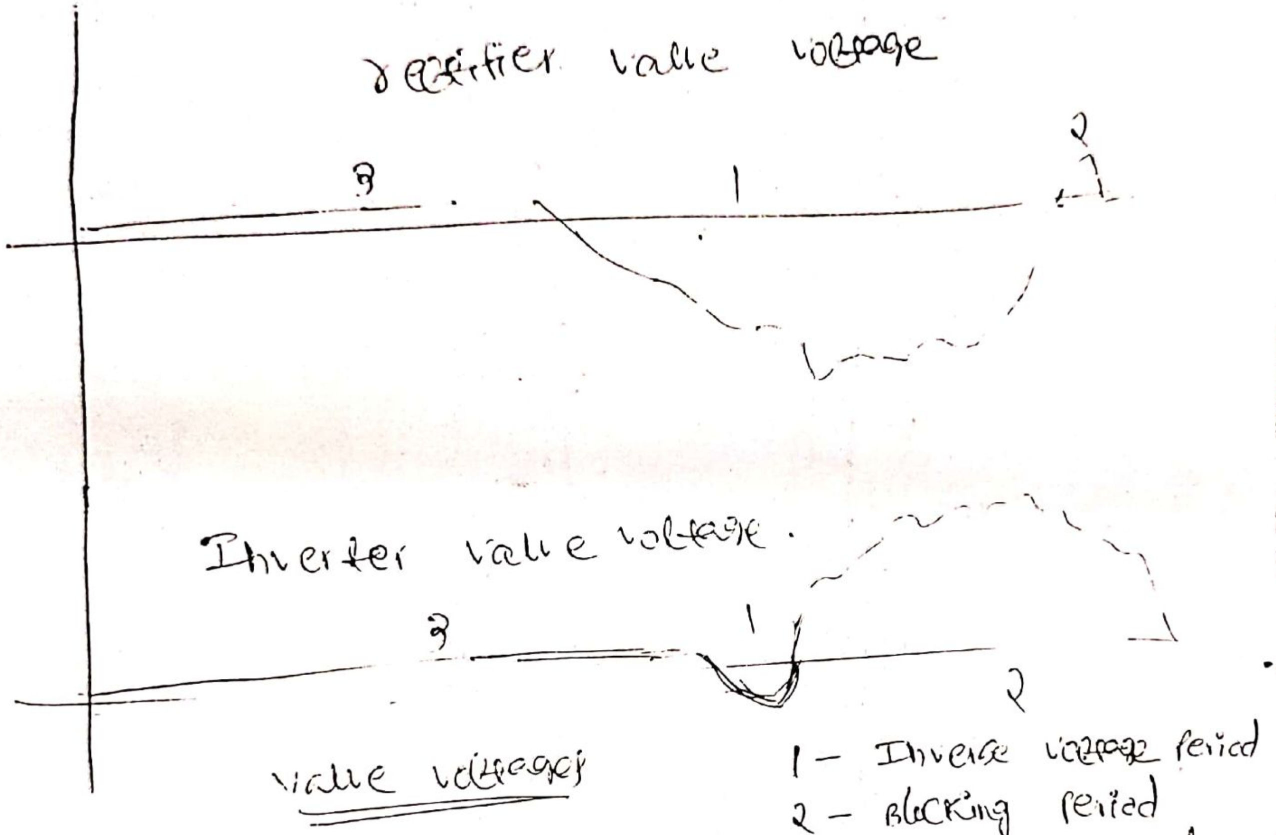
⇒ Faults due to malfunction of valves and Controllers.

- Arc backs (or back fire) in mercury valves only.
- Arc through (or fire through or short through)
- Quenching (arc quenching or arc chopping)

- Misfire

⇒ Commutation failure in inverters (or break through) i.e failure to complete commutation before commutating emf reverse.

⇒ short circuit within converter stations.



Arc Back:—

⇒ This mal-operation, which is conduction in the inverse voltage period of valves, occurs mainly in the rectifiers because inverse voltage period in rectifiers are much more than that of inverters.

⇒ It is most common and serve malfunction in mercury valve rectifier and random in nature.

⇒ on average, it is one or two arc back per —valve/month. modern thyristors do not suffer from arc backs.

⇒ Factors increases the arc back are

1) High PIV.

2) High voltage jump, especially of the jump at arc extinction.

3) High rate of change of current at end of conduction.

4) over current.

5). Impurity of anode and grid.

6). High rate of size of inverse voltage.

⇒ Factors 1 and 2 can be reduced by having low voltage whereas having low current can reduce factors 3 and 4

⇒ these reduce power handling/valve and increase the cost of converter

⇒ Factors 2 and 3 can be improved by using small (α, β, γ, δ) but they are larger for control operation (momentary)

⇒ Factor 6 is minimized by use of RC damper in parallel to each valve. However factor 3 can be improved with high H.

⇒ This malfunction of valves results into line-to-line short circuit and sometimes 3-phase short circuit. It also generates some harmonics.

Arc Through :-

⇒ This is also known as fire through or short through.

⇒ It occurs during blocking period of valve that is when the voltage across the valves is positive. Since the positive voltage across valve is more during the inverter operation, the chance of this malfunction is also more in inverters.

than rectifiers.

⇒ It is similar to commutation failure. This malfunction is due to mainly.

→ failure of negative grid pulse.

→ Early occurrence of positive grid pulse.

→ sufficient high positive transient over voltage on grid or anode.

⇒ The main problems with arc through are that

→ It reduces delay angle (α)

→ It introduces DC component into transformer current.

→ It changes harmonic components.

⇒ Short circuit occurs once/cycles until arc through is removed or bridge is bypassed.

Misfire:—

⇒ As its name, it is a failure of valve to ignite during a scheduled conducting period whereas arc through is the failure to block a valve during a scheduled non conducting period.

⇒ this can occur either in rectifier or in inverter but it is more severe when occurs in inverters.

⇒ It may be either due to negative gate pulse or positive anode to cathode voltage or fault in valves.

⇒ The effect of misfire in inverter is similar to commutation failure and arc through.

⇒ Let values 6 and 1 are conducting and valve 2 fails to ignite. values 6 and 1 will continue to conduct and there after value 3 will conduct and DC short circuit occurs for smaller durations.

⇒ There is a small jump of voltage at beginning of short circuit and large jump at end of short circuit.

Arc Quenching :-

⇒ It is a permature extinction of valve in normal conduction period. This malfunction has the same effect as misfire (almost) and causes short circuit on DC terminal. [This is present in mercury valves because of ionizati

Commutation Failure :-

⇒ This Fault, which is more common in inverter, is the result of a failure of the incoming valve, due to insufficent extinction time, to take over the direct current before the commutating voltage reverse its polarity.

⇒ there after, the direct currents shifted back from the incoming valve to the outgoing valve.

⇒ It is not due to mal-function of valve but due to AC or DC condition outside bridge. It is due to increased DC current, low AC voltage (due to AC short circuit), late ignition or combination of these.

⇒ Nearly all inverter valve fault lead to results simila to Commutation failure.

⇒ The failure of two sucessive Commutations in the same Cycle is Called double commutation failure.

⇒ Let us take example that values 1 and 2 are Conducting and now valve 3 has to be ignited and to take the complete Current of valve 1 which is in the upper limb of converter.

⇒ If Current in incoming valve 3 is diminishes to zero after Conduction, the Current in valve 1 will Continue to Carry full link Current.

⇒ Firing of valve 4 (next in sequence) will result in short Circuit of the bridge, as both valve of same arm will Conduct.

⇒ If the Commutation Form valve 2 to valve 4 is sucessful, only valve 1 and 4 will Conduct.

⇒ Firing of valve 5 (in sequence) will be ~~........~~ unsuccessful, ~~only ....~~ as voltage across it is negative and valves 1 and 4 will still Continue.

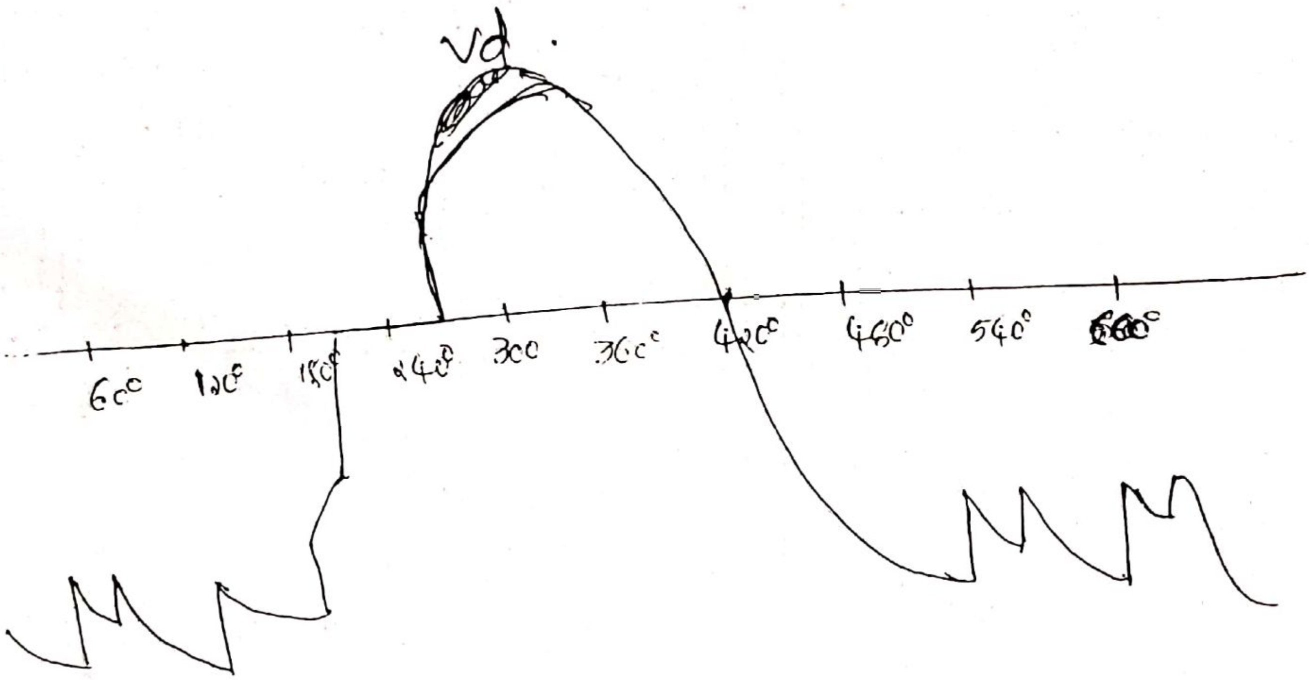
⇒ Now valve 6 will be fired and if Commutation from valve 4 to 6 is successful, valves 6 and 1 will Conduct which is normal pattern of conduction.

⇒ Thus a single Commutation failure is self-clearing.

⇒ The double Commutation failure is more severe and should be averted which depends on the Current Control of link and the magnitude of AC voltage.

⇒ If unsuccessful commutation from 1 to 3 and back -.
completed before 4 fires and if the condition that first failure persists a second failure may occur in the commutation from 2 to 4 causing DC current back to 2

⇒ Now 1 and 2 will be conducting.



⇒ After occurance of commutation failure, the succeeding commutation is carried by CEA control and is usually successful.

⇒ If caused by low AC voltage, the reappearance on normal voltage helps preventing the further failures.

⇒ In the event of commutation failure persists, the bridge in which it occurs should be bypassed or blocked.

Scanned by CamScanner

Protections:—

⇒ Desirable characteristics of protection

→ selective
→ discriminative.
→ Reliable
→ speed
→ Backup

⇒ protection of AC systems

→ over-voltage protection (using o/h wires, protective gaps, LA)
↳ lightning arrestors.

→ over-current protection (using CB, fuses, relays, current limiting reactors).

⇒ Protection of HVDC systems:

→ over-voltage protection (similar to ac system with some differences).

→ over-current protection (using control of valves)

→ Damper circuits.

→ DC reactors.

⇒ Over-voltages in a converter station:

→ Due to distrubance originating on the AC side

→ Due to distrubance originating on the DC side.

→ Due to the internal faults in the converter.

⇒ Type of external over-voltages in AC side:

→ switching over-voltages (wave-front time > 100ms) due to initiation and clearing of faults.

→ Temporary over-voltages (lasting few seconds) due to load rejection in weak AC system.

→ steep front over-voltages (0·3–3·0 ms) due to lighting strokes.

Disturbances in DC side:

-) Disturbances in DC side:

→ steep front surges due to lightning strokes (external)

→ switching surges due to ground fault on the pole producing the over-voltage on the un-faulted pole.

⇒ over-voltages can also arise from current and voltage oscillations caused by sudden jumps in converter voltage due to converter faults and commutation failures.

⇒ switching of DC filters and parallel connection of poles.

⇒ switching surges originating from an AC system, transmitted to the DC side. series connection of valve groups multiplies the over-voltage by the number of groups.

⇒ sudden loss of load on a rectifier

⇒ increased overshoot of DC voltage of bridge at the end of each commutation due to short overlap.

=) Disturbances due to internal Converter faults :

-> Due to energization of DC Lines

-> Due to stray capacitances and inductances

-> Due to Converter faults

=) Means for reducing the over - voltages

-> Lightning arresters or surge diverters are us

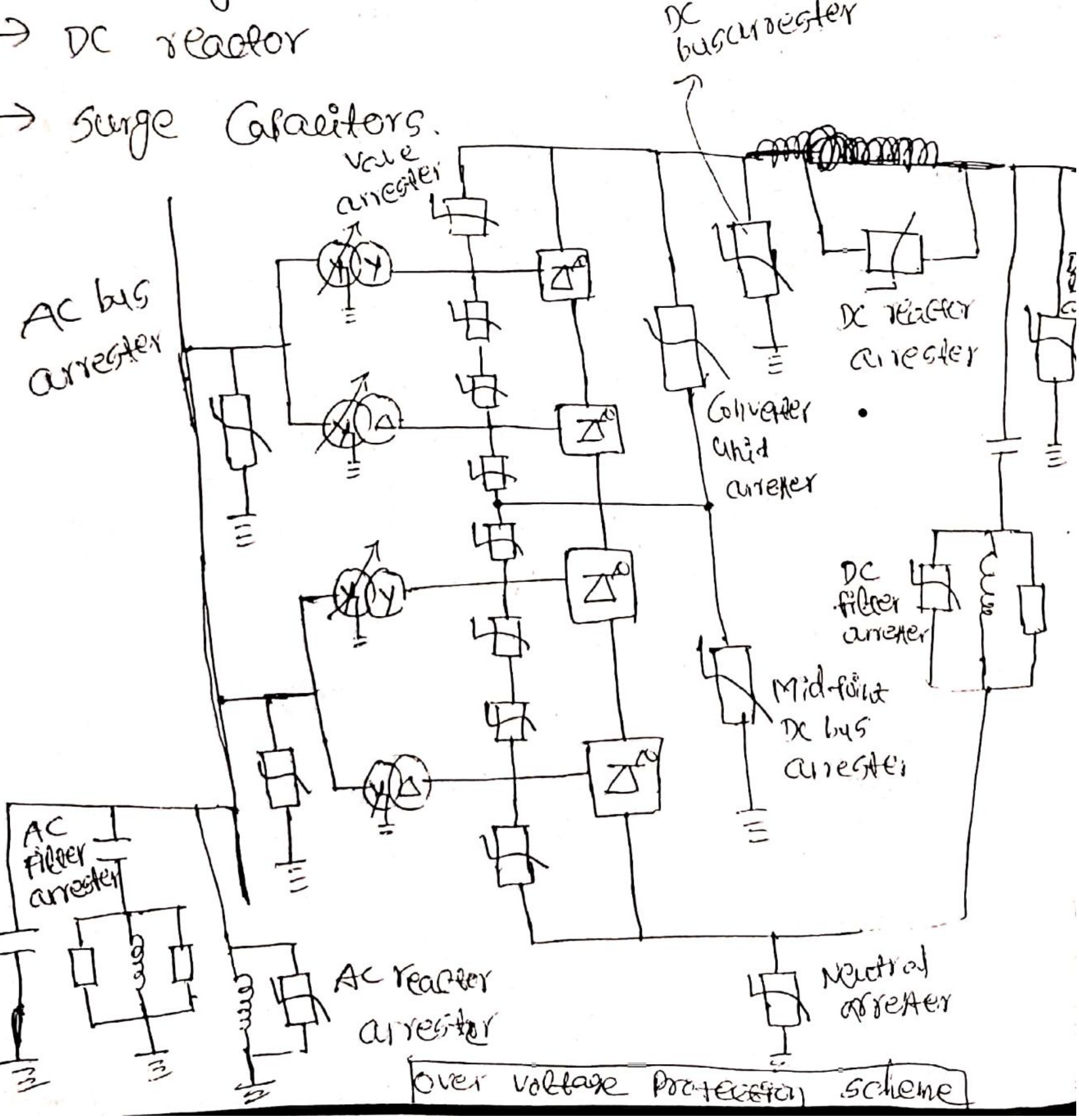
-> plain gap and shield of O/H lines.

-> Converter Control system

-> Damping circuit

-> DC reactor

-> Surge Capacitors.



Over voltage protection scheme

DC Line arresters :-

→ The current through arrester does not have natural zero to aid in resealing the arrester against sustained dc voltage.

→ voltage is buffered by the huge lumped inductance (through smoothing reactor and transformers)

→ special LA are built for DC

⇒ protection against over-current

→ main Features of converter protection is that it is possible to clear faults by fast controller action(<20ms)

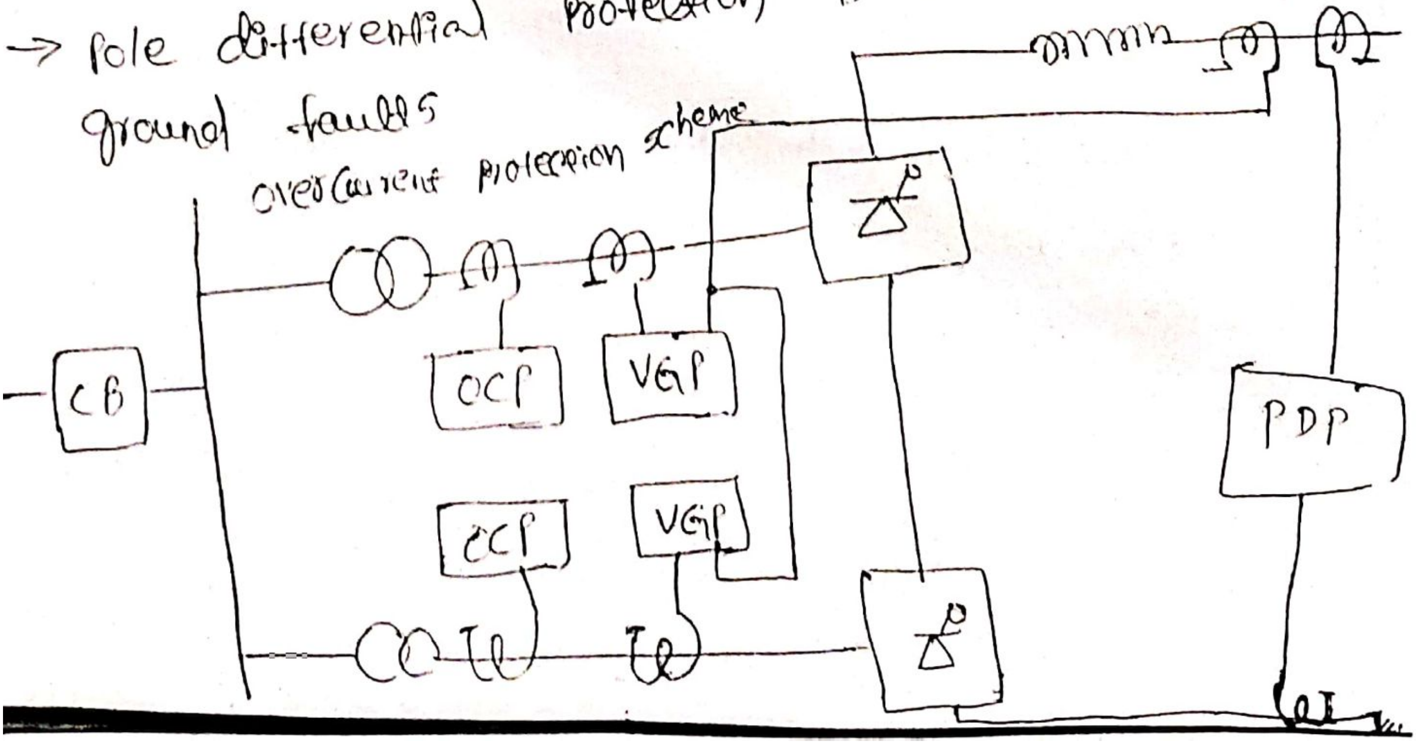
→ Differential protection is because of its selectivity and fast detection.

→ over-current protection is used as backup.

→ The level of over-current required to trip must be set higher than that of the valve group differential protection.

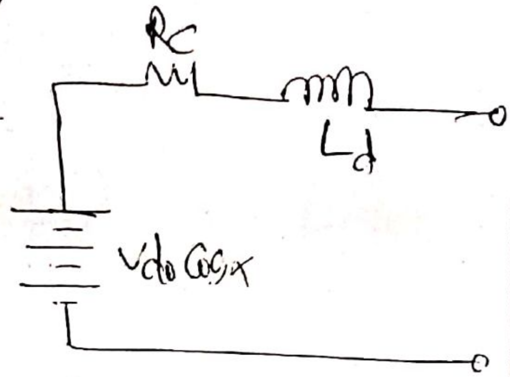
→ Pole differential protection is used to detect ground faults

overcurrent protection scheme



OCP → over current protection
VGP → valve group protection
PDP → pole differential protection
CB → circuit breaker.

DC Reactors :- (0.4 to 1.0 H)



⇒ It limits di/dt rise to prevent commutation failure in inverter of one bridge when dc voltage of one bridge collapses.

⇒ It reduces the incidence of commutation failure in inverter during AC dip.

⇒ It reduces the harmonic voltage and current in dc link

→ It reduces the current ripples.

⇒ It limits crest of short circuit current in the DC Line

⇒ Calculation on inductance value for sufficiently limiting the rise of direct current after collapse of direct voltage.

⇒ Assumptions :

⇒ DC voltage is constant at its initial value

⇒ AC voltage at inverter remains constant.

⇒ Tap Changer does not move

⇒ Initial Current was I_{dn}

⇒ Collapse of voltage of voltage with the beginning of Commutation:

⇒ Normal advance angle is Calculated

$$I_{dn} = I_{S2}(\cos\gamma_n - \cos\beta_n) \quad \text{where } I_{S2} =$$

⇒ At β, $I_{d\beta_n} = I_{dn}$

⇒ At γ_m, $I_{d\gamma_m} = I_{dn} + \Delta I_d$

$$L_d = \frac{\Delta V_d \, \Delta t}{\Delta I_d} \quad \text{where } \Delta t = \frac{\beta_n - \gamma_m}{2\pi f} \text{ (mini)}$$

$$= \frac{\beta_n^0 - \gamma_m^0}{360 \times f}$$

$$\Delta I_d = 2 I_{S2}(\cos\gamma_m - \cos\beta_n) - 2 I_{dn}$$

Damper Circuits :-

⇒ Voltage oscillations and valve dampers

→ To avoid frequent arc-back (Conduction in negative valve voltage)

→ To limit the rate of rise of inverse voltage

→ To reduce peak inverse voltage

→ To avoid the breaking down on inverse voltage exceeding the rated value.

⇒ Rate of rise of inverse voltage is infinite but in reality it is not so due to stray Capacitance across the valves.

⇒ Along with the transformer inductance, it causes an oscillation of voltage (10 – 20 KHz) and overshoot of 100%.

⇒ Rate of rise of inverse voltage is infinite but in reality it is not so due to stray capacitance across the valves.

⇒ Along with the transformer inductance, it causes an oscillation of voltage (10 – 20 KHz) and overshoot of 100%

⇒ Satisfactory rate of rise voltage can be obtained by connecting a capacitor across each valve (1 – 2 KHz).

⇒ overshoot can be reduced by connecting a resistor in series with each capacitor

⇒ RC dampers serve the additional purpose of improving the

ASSIGNMENT-I

Academic **Y**ear : **2022-23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **Dr J. SRIDEVI** Designation: **PROFESSOR**.

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

This Assignment corresponds to Unit No. / Lesson ………………**I**……………

1) Draw the schematic diagram of HVDC Systems and explain each part of the system.
2) How to plan for HVDC Transmission?
3) What is the function of smoothing reactor?
4) Explain Different Types of HVDC Links.

ASSIGNMENT-II

Academic **Y**ear : **2022-23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **Dr J. SRIDEVI** Designation: **PROFESSOR**

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

This Assignment corresponds to Unit No. / Lesson ………………**II**……………

1. What is the effect of source inductance on HVDC System?
2. Explain 6 pulse converters with neat waveforms of HVDC Systems.
3. Explain 6 pulse converters with overlap angle of HVDC Systems.

ASSIGNMENT-III

Academic **Y**ear : **2022-23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **Dr J. SRIDEVI** Designation: **PROFESSOR**

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

This Assignment corresponds to Unit No. / Lesson ………………**III**……………

1. Draw and discuss equivalent circuit of dc link with inverter in Gamma Control Mode.
2. Explain the operation of CEA control technique with a neat diagram.
3. Explain with a neat diagram, the combined control characteristics of Rectifier and Inverter.

ASSIGNMENT-IV

Academic **Y**ear : **2022-23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **Dr J. SRIDEVI** Designation: **PROFESSOR**

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

This Assignment corresponds to Unit No. / Lesson ………………**IV**……………

1. List out the problems associated with the injection of harmonics both on AC and DC side of HVDC link.
2. Give the detailed description of various types of filter circuits' configurations along with impedance characteristics.
3. Discuss the analysis of Double Tuned Filter with neat diagrams.

ASSIGNMENT-V

Academic **Y**ear : **2022-23** Semester : **II**

Name of the Program: **B.Tech - EEE** Year: **III** Section: **A**

Course/Subject: **HVDC TRANSMISSION** Course Code: **GR20A3094**

Name of the Faculty: **Dr J. SRIDEVI** Designation: **PROFESSOR**

Department: **ELECTRICAL AND ELECTRONICS ENGINEERING**

This Assignment corresponds to Unit No. / Lesson ………………**V**……………

1. What are the types of Faults?
2. How much is the resistance value of electrode in uniform earth and non-uniform earth?
3. What are the reasons for DC and AC system faults?

Assignment - 1

1) List out any two merits of AC and DC transmission.

A) * AC transmission:

→ AC circuit breakers are cheap than DC circuit breakers.

→ The repairing and maintenance of AC substation is easy and inexpensive than DC substation.

* DC Transmission:

→ There is no concept of skin effect in DC transmission. Therefore, small cross sectional area conductor required.

→ There are no inductance and surges. Due to absence of inductance, there are very low voltage drop in DC transmission lines.

2) What are the different types of DC link?

A) There are three different types of DC links. They are

1) Monopolar link
2) Bipolar link
3) Homopolar link.

3) List some of the advantages and disadvantages of HVDC transmission.

A) Advantages:-

1) Cost of transmission is less, since only two conductors are used for transmission.

2) Due to high voltage transmission, for the same power current is less. So I^2R loss is very less.

Disadvantages:

1) High cost converting and inverting equipments are required for HVDC transmission. So it is uneconomical for low power supply over short distances.

2) Converters control is quite complex.

4) What are the types of power losses in thyristor?

A) Different losses that occur are

1) Forward conduction losses during conduction of the thyristor

2) Loss due to leakage current during forward and reverse blocking

3) power loss at gate or Gate triggering loss

4) Switching losses at turn-on and turn-off

5) Define Reliability

A) This is a factor specifying the performance of HVDC systems during recordable faults on the associated AC systems. The transient reliability can be defined as the ratio of

$$= \frac{\text{No. of times HVDC systems performed as designed}}{\text{No. of recordable AC faults.}}$$

6) Define - Energy Availability.

A). The availability of a given system is defined as the maximum useful work that can be obtained in a process in which the system comes to equilibrium with the surroundings or attains the dead state.

7) List out any two applications of DC transmission.

A) → connecting remote generation.

→ interconnecting grids.

8). What are the factors to be considered for planning HVDC transmission ?

A) The factors to be considered for planning HVDC transmission are:-

1) cost
2) technical performance
3) reliability.

9) What are the advantages of LTT over ETT ?

A) In applications with high voltages and series connection the LTT offers advantages because less electronics operati-ng on high potential are required. This reduces the costs and improves the reliability of the system.

10) Distinguish between AC and DC Transmission.

A) The AC transmission line transmits the alternating current over a long distance, whereas the DC transmission line is used for transmitting the DC over the long distance. The AC transmission line uses three conductors for long power transmission and DC transmission line uses two conductors for power transmission

11) What is meant by MOS controlled thyristor?

A) An MOS controlled thyriston is a voltage controlled fully controllable thyristor. It was invented by V.A.K Temple. A thyriston with only one MOSFET in its equivalent circuit which can be only turned on is called a MOS-gated thyriston

12) List any two HVDC projects in India.

A) 1) Rihand - Dadri

2) Ballia - Bhiwadi

16 Mark Questions:-

1) Explain in detail the economic choice of voltage level selected in DC transmission system.

A) ⇒ The cost of a transmission line includes the investment and operational costs.

⇒ The investment includes cost of right of way (ROW) transmission towers, conductors, insulators, and terminal equipment.

⇒ The operational cost include mainly the cost of losses.

⇒ Lines designed with the same insulation level, a DC line can carry as much power with two conductors as an AC line with 3 conductors of the same size.

⇒ For a given power level, DC lines requires less row, smaller and cheaper towers and reduced conductor and insulator costs.

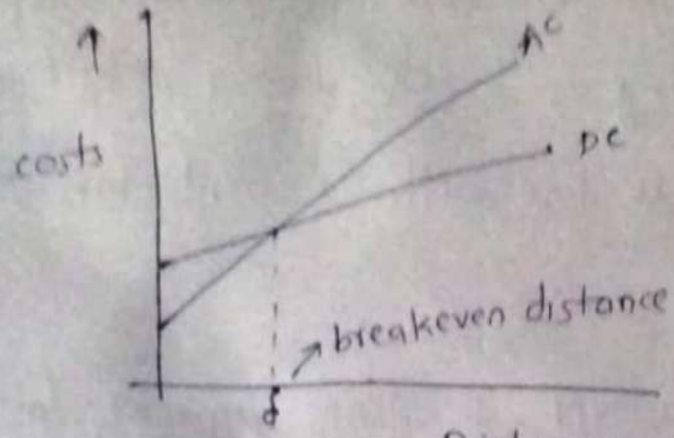
⇒ The power losses are also reduced with DC as there are only two conductors.

⇒ The absence of skin effect with DC is also beneficial in reducing power losses marginally.

⇒ The dielectric losses in case of power cables is also very less for DC transmission.

⇒ The corona effect tends to be less significant on DC conductors than for AC and this also leads to the choice of economic size of conductors with DC transmission

⇒ DC lines donot require compensation but the terminal equipment costs are increased due to the presence of converters and filters



⇒ If the transmission distance is shorter than the breakeven distance, ac transmission is cheaper than DC

⇒ If the transmission distance is longer than the breakeven distance dc transmission is cheaper than AC.

⇒ The breakeven distances can vary from 500 to 800km in overhead lines depending on the per unit line costs.

2) Explain in detail the technological development in control and protection for better performance & reliability of dc transmission system.

A) <u>Modern trends in DC Transmission:</u>

⇒ The ~~continuo~~ continuing technological developments in the areas of power semiconductor devices, digital electronics, adaptive control, DC protection equipment have increased the pace of application of DC transmission.

Scanned by CamScanner

→ The major contribution of these developments is to reduce the cost of converter stations while improving the reliability and performance.

1) power semiconductors and valves:-

⇒ The cost of the converters can come down if the number of devices to be connected in series and parallel can be brought down

⇒ The power rating of thyristors is increased by better cooling methods.

⇒ As forced commutated converters operating at high voltages are uneconomic

⇒ The development of devices that can be ~~formed~~ turned off by application of a gate signal would be desirable.

⇒ Gate turn off (GTO) thyristors are already available at 2500V and 2000A. However, the main disadvantage of GTO's is the large gate current needed to turn them OFF.

⇒ MOS(metal oxide semiconductor) controlled thyristor or MCT appears to be a promising technology.

⇒ In this device, a very large line current can be switched off by a small gate current.

⇒ The turn off time of MCT is also less than one third that of GTO's.

2) converter control:-

⇒ The development of micro computer based converten control equipment has now made it possible to design systems with completely redundant converter control with automatic transfer between ton-systems in the case of a malfunction

⇒ Not only is the forced outage rate of control equipment reduced but it is also possible to perform scheduled preventive maintenance on the stand-by system when the converter is in operation

⇒ The micro computer based control also has the flexibility to try adaptive control algorithms or even the use of expert systems for fault diagnosis and protection

3) DC breakers:-

→ with the development and testing of prototype DC breakers it will be possible to go in for tapping an existing DC link on the development of new MTDC systems.

⇒ The DC breaker ratings are not likely to exceed the full load ratings as the control intervention is expected to limit the fault current.

⇒ The possibility of decentralized control necessitated by communication failure, the coordination of control and protection are some of the issues currently being studied

4) Conversion of existing DC lines:-

⇒ The constraints on row are forcing some utilities to look into the option of converting existing AC circuits, to DC in order to increase the power transfer limit. The could be some operational problems due to electromagnetic induction from AC circuits operating in the same row

⇒ An experimental project of converting a single circuit of a double circuit 220KV line is currently under commissioning stage in india.

5) operation with weak AC systems:-

⇒ The strength of AC systems connected to the terminal of the DC link is measured in terms of short circuit ratio (SCR) which is defined as

$$SCR = \frac{\text{short circuit level at the converter bus}}{\text{Rated DC power}}$$

⇒ If SCR is less than 3, the AC system is said to be weak.

3) Explain in detail the applications of DC transmission systems.

A) The main areas of application based on the economics and technical performances are

1. long distance bulk power transmission
2. The under ground or submarine cables
3. Asynchronous connection of AC system with different frequencies

4. control and stabilize the power system with power flow control.

5. Based on the interconnection three types of HVDC links are possible.

6. HVDC transmission system where bulk power is transmitted from the one point to another point over long distance.

7. Back to back DC link where rectification and inversion is carried out in the same converter station with very small or no DC lines.

8. This is basically used to control the power and stabilize the system. It is also used sometimes to connect two different frequencies systems

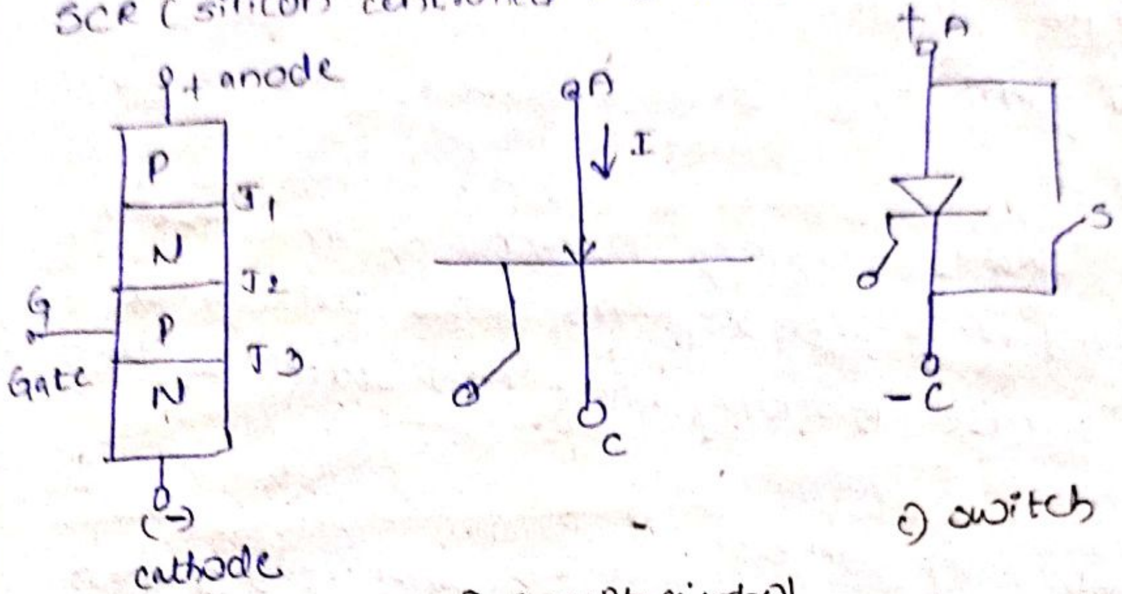
9. Parallel connection of AC and DC links where both AC and DC lines run parallel. It is mainly used to modulate the power of AC line.

10. Due to its fast control DC line can improve the transient stability of the system.

UNIT - II

Thyristor and their characteristics:

SCR (silicon controlled rectifier):-



a) Representation b) circuit symbol c) switch

→ SCR is a type of thyristor

→ A thyristor is a three terminal, four layer semi conductor device.

→ The terminal connect to end P region is called anode, the terminal connected to end N region is called cathode and the terminal connected to P region adjacent to cathode is called gate.

→ static VI characteristics of SCR is three nodes. They are

1) Reverse Blocking
2) forward Blocking
3) forward conduction.

Reverse Blocking: The SCR is said to be reverse blocking when the cathode is made positive with respect to cathode

→ Then J_1 and J_3 are reverse biased while J_2 is forward biased

→ A small reverse leakage current of the order of few hundred micro-amperes flows through it. This is reverse blocking mode (OFF state) of the SCR

Forward Blocking mode:

→ A thyristor is said to be forward biased when the anode is +ve w.r.t cathode

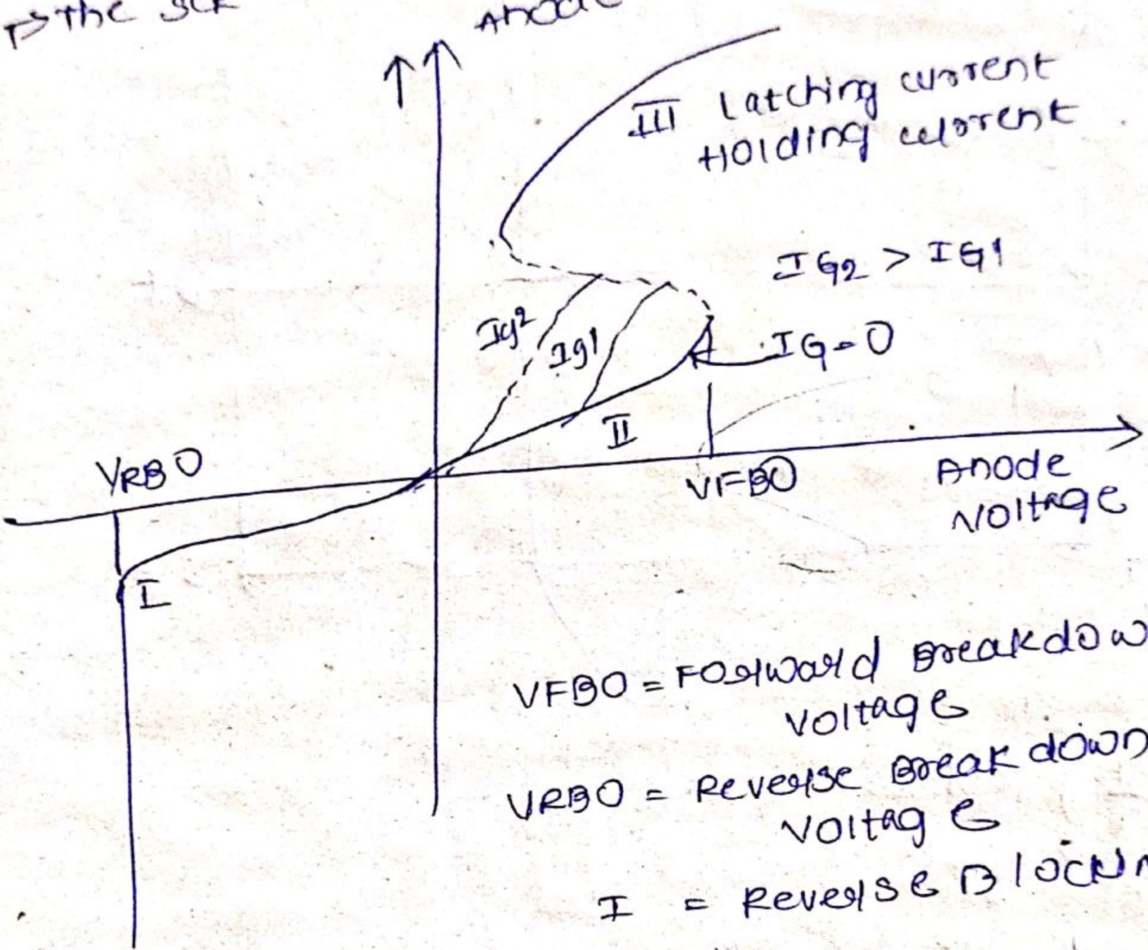
→ J_1 and J_3 are forward biased while J_2 is reverse biased

→ The reverse bias on J_2 limits the forward current to the value of forward leakage current in order of milli amps. This forward blocking mode of the SCR.

3) Forward conduction Mode: When the SCR is forward biased, it comes to an on state only when the gate trigger pulse is given it acts as a closed switch.

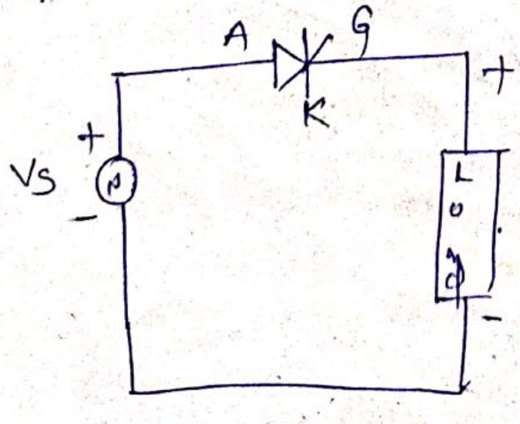
→ with forward bias voltage, a thyristor can be made to come to a conducting state (ON state) using any one of the four techniques mentioned below:

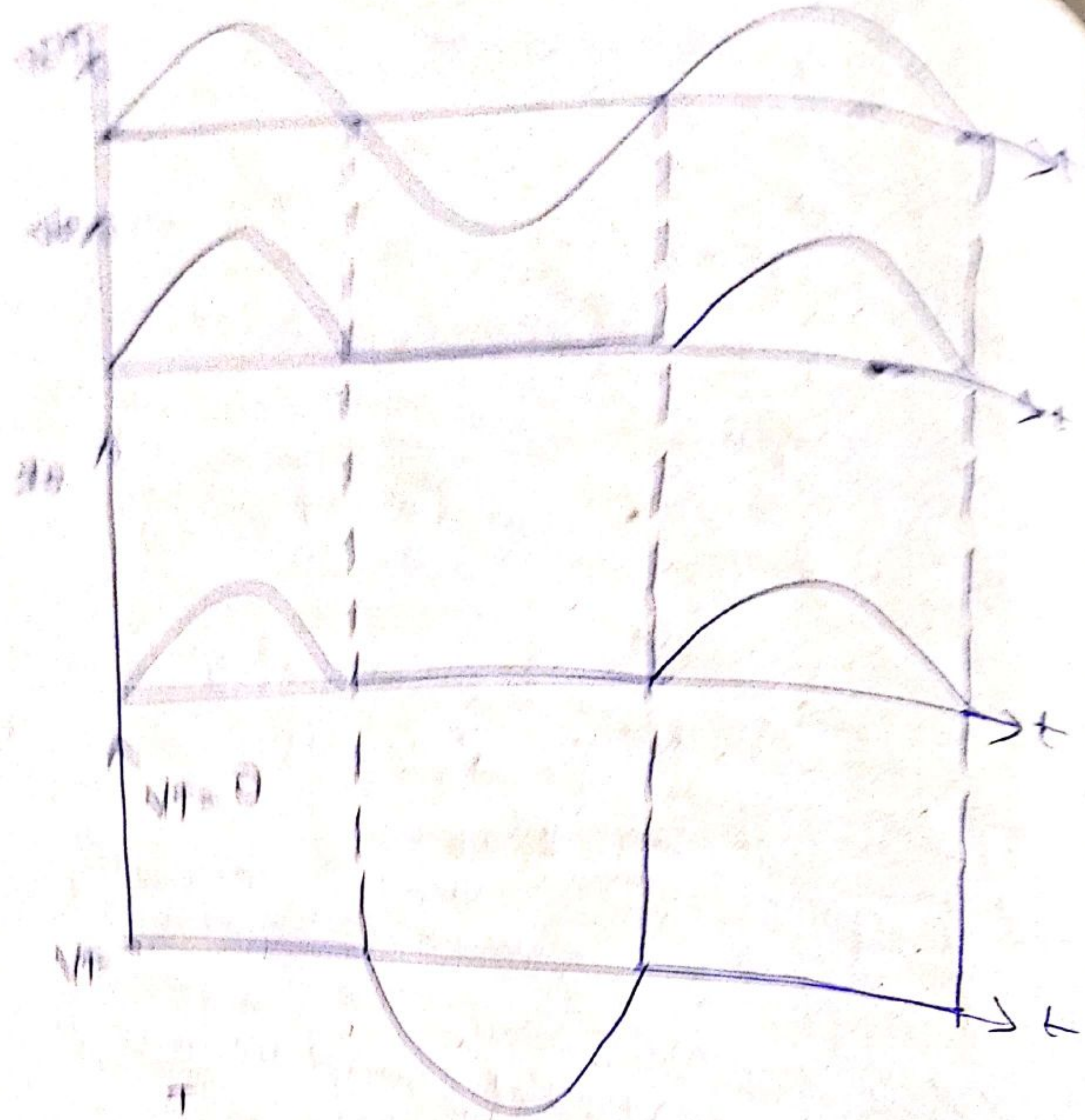
a) exceeding forward break over voltage
b) gate current (or) gate triggering
c) exceeding $\frac{dv}{dt}$ rating of the SCR
d) irradiation at the gate-cathode junction
⇒ The SCR is a unidirectional controlled switch



VFBO = Forward Breakdown voltage
VRBO = Reverse Break down voltage
I = Reverse Blocking
II = Forward blocking
III = Forward conduction

1-φ Half wave rectifier:





$$V_0 = \frac{1}{T}\int_0^T V(t)\, dt$$

$$= \frac{1}{2\pi}\int_0^{2\pi} V_m \sin\omega t\, dt$$

$$= \frac{V_m}{2\pi}\left[-\cos t\right]_0^{2\pi}$$

$$= \frac{V_m}{2\pi}\left[-\cos 2\pi + \cos 0^\circ\right]$$

$$= \frac{V_m}{2\pi}$$

Unit - 3 - Assignment - 3.

1) What is commutating resistance?

High contact resistance between commutator segments and brushes, achieved by using carbon brushes, adds resistance to the circuit of the commutating coil thereby reducing the tc-constant (L/R) of the current transient ($i_c(t)$), helping it to change faster the desired direction. Carbon brushes are invariably used in dc machines. They also help reduce commutator wear and are themselves easily replaceable.

2) Obtain a relation between firing angle and power factor angle in a three phase bridge rectifier?

The ac power supplied to the converter is given by

$$P_{AC} = \sqrt{3} E_{LL} I_1 \cos\phi$$

The DC power must match AC power, ignoring the losses in the converter, thus we get

$$P_{AC} = P_{DC} = V_d \cdot I_d = \sqrt{3} E_{LL} I_1 \cdot \cos\phi$$

Substitute the value of V_d and I_1

$$V_{do} \cos\alpha \cdot I_d = \sqrt{3} E_{LL} \cdot \frac{\sqrt{6} I_d}{\pi} \cos\phi$$

$$V_{do} \cos\alpha = \frac{\sqrt{3}\sqrt{6}}{\pi} \frac{\sqrt{6} I_d}{\pi} \cos\phi$$

$$V_{do} \cos\alpha = \frac{\sqrt{3}\sqrt{6}}{\pi} E_{LL} \cos\phi$$

$$V_{do} \cos\alpha = 1.35 E_{LL} \cos\phi$$

$$\boxed{\cos\alpha = \cos\phi}$$

→ The reactive power requirements are increased as alpha is decreased from zero
→ when alpha is 90 degree the power factor is zero and only reactive power consumes.

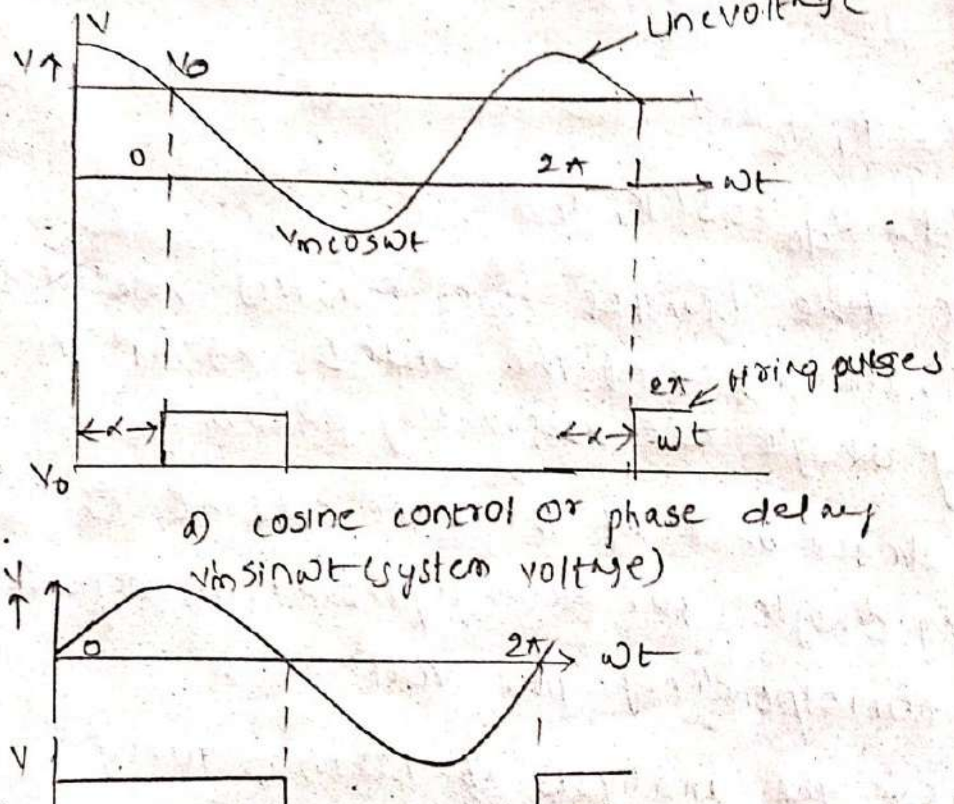
Unit-4 Assignment-4

1. compare cosine control of phase delay and linear control phase delay?

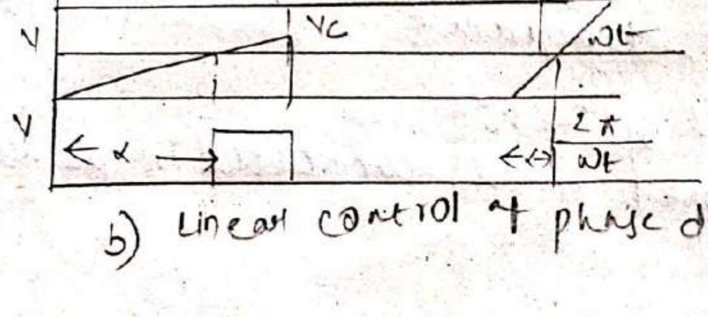
cosine control of phase delay:-

→ There are several versions of this method. In this scheme, a control voltage common (V_0) to all delay circuits generates pulses at the crossing point of the control voltage and the appropriate AC line voltage. This is illustrated in Fig 4.15(A). The phase delay angle α is given by α.

$$\alpha = \cos^{-1}(V_c/V_m)$$



a) cosine control or phase delay



b) Linear control of phase delay

the output voltage of the converter is given by

$V_d = V_{d0} \cos\alpha$

$= \frac{V_{d0}}{V_m} \cdot V_c = K V_c$

therefore, the cosine control system results in a linear transfer characteristic.

Linear control of phase delay:-

In this scheme, a control voltage (V_c) common to all delay circuits, generates pulses at equal time delays from zero crossing of AC voltages. this is illustrated in Fig 7.15(b). The firing angle is proportional to the control voltage.

$\alpha = K_1 V_c$

$V_d = V_{d0} \cos(K_1 V_c)$

this make the transfer characteristics nonlinear. However, accuracies of the order of $\pm 1°$ in the firing angle are normally possible.

A major drawback of the IPC scheme is that firing angle for each thyristor is dependent on the corresponding line voltage.

2. Discuss the analysis of double tuned filter with neat diagram.

Ans:- Double tuned filters:-

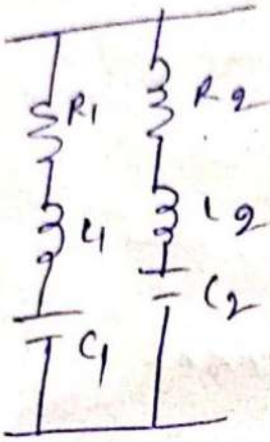
→ two single tuned filters connected in parallel

Scanned by CamScanner

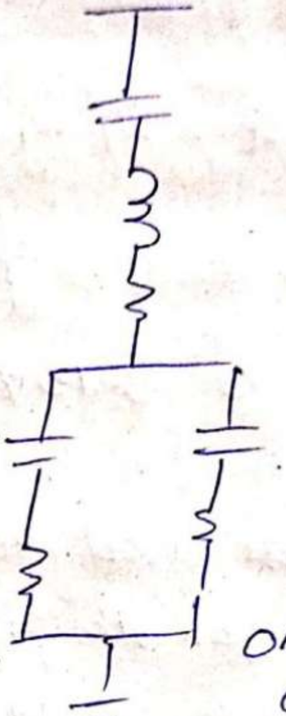
Advantages:-

1) power loss at fundamental frequency is less

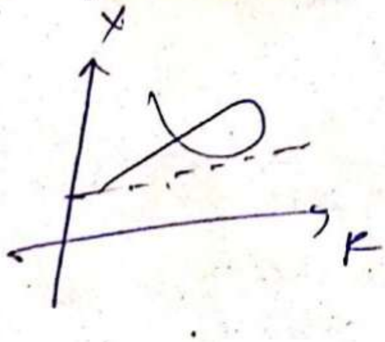
2) one inductor is subjected to the full inside voltage.

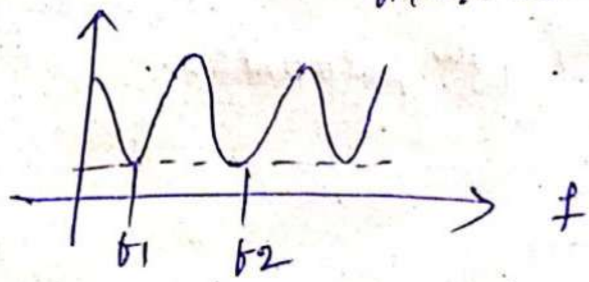


two single-tuned filters connected in parallel.



one single double tuned filter



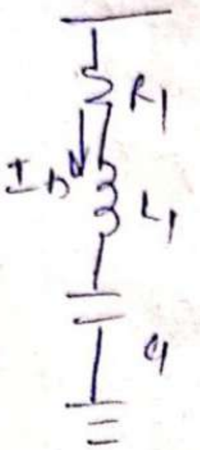


$$\delta = \frac{\omega - \omega_n}{\omega_n} = \frac{\omega}{\omega_n} - 1$$

$$\omega_n = 1/\sqrt{LC}$$

$$= \omega\sqrt{LC} - 1$$

$$\Delta f = \frac{\Delta f}{f} + \frac{1}{2}\left[\frac{\Delta C}{C} + \frac{\Delta L}{L}\right]$$



$$Q = I_1^2 (X_L - X_C)$$

$$= I_1^2 \left(\omega_1 L - \frac{1}{\omega_1 C}\right)$$

$$= I_1^2 \omega_1 L \left(1 - \frac{1}{\omega_1^2 LC}\right)$$

$$Q = I_1^2 \omega_1 L \left(1 - \frac{\omega_n^2}{\omega_1^2}\right)$$

$$Q = I_1^2 \omega_1 L \left[1 - h^2\right]$$

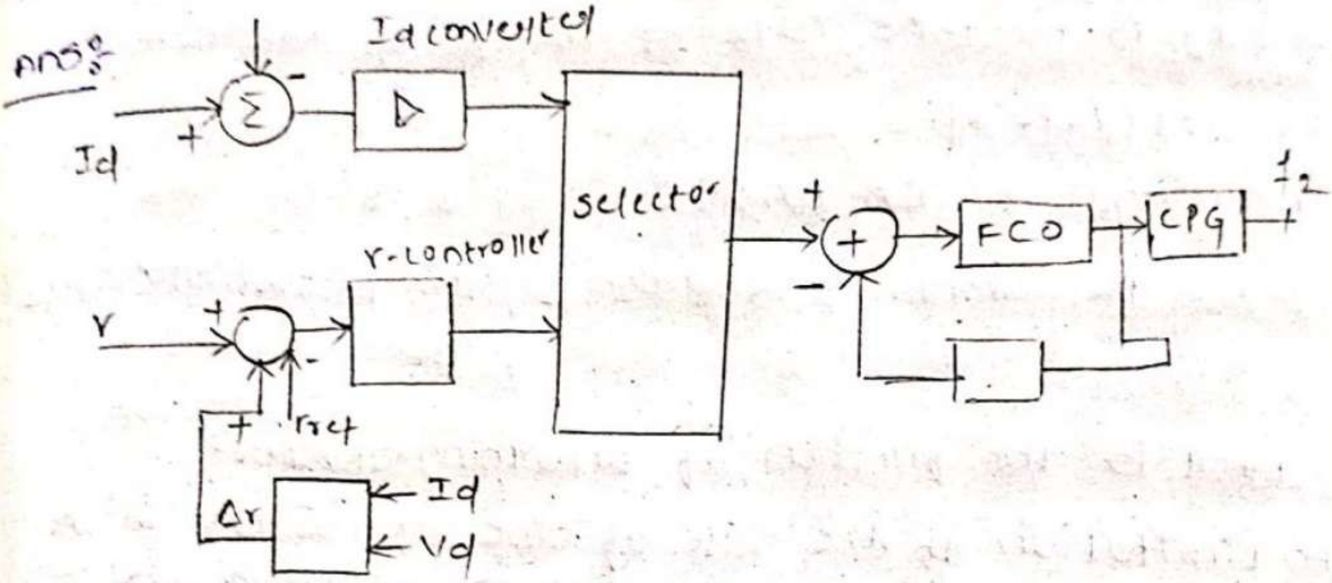
$$\therefore \left[\omega_n = h\omega_1\right]$$

⇒ filters cost is 5-10% of terminal equipment.

⇒ These filters are used to lower order harmonics i.e., for 6th pulse converter 5th and 7th harmonics for 12 pulse converter 11th and 13th harmonics.

1. Explain the operation of CEA control technique with a neat diagram?

Ans:

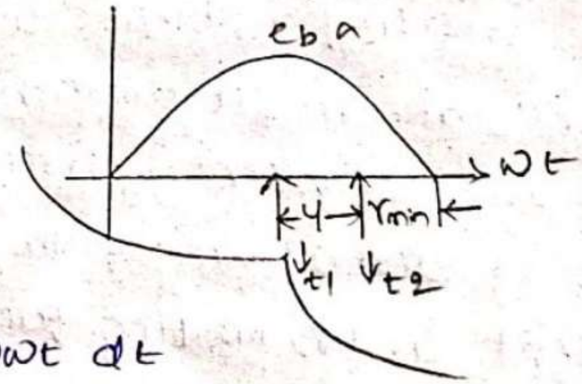


CEA control:

⇒ Knowing commutation voltage and γ_{min}, one can find β.

$$2L\frac{di_3}{dt} = e_b - e_a$$

$$= \sqrt{3}\, e_m \sin\omega t$$



$$2L\int_0^{I_d} di_3 = \sqrt{3}\, e_m \int_{t_1}^{t_2} \sin\omega t \, dt$$

here $t_1 = \alpha/\omega$; $t_2 = \frac{\pi - \gamma_{min}}{\omega}$

$$2LI_d = -\frac{\sqrt{3}E_m}{\omega}\left[\cos\omega t\right]_{\alpha/\omega}^{(\pi-\gamma_{min})/\omega}$$

$$-\cos\alpha = \cos\gamma_{min} - \frac{2\omega L}{\sqrt{3}E_m} I_d = \cos\beta$$

→ β depends on ω, L, Id, Em and these are measured continously

..for precise control, I_d is replaced by I_d'

$$I_d' = I_d + \Delta I_d$$

⇒ ΔI_d is to take care of change of I_d during the interval μ.

Transition of CEA to CC :-

⇒ In the event of sudden system disturbance due

2. What is the function of smoothing reactor?

A) Limitation of the rate of rise of current in the event of dc-dc side faults, i.e., line-to-ground faults or commutation failures of the inverter station, in combination with dead time and regulating speed of the rectified current control, results in a limitation of peak short-circuit current. Since dc current causes an equivalent current on the ac-side, the degree of disturbance of the ac network is directly dependent on this limiting function. For the inverter which has suffered a commutation failure, the limitation of the rate of current rise is critical for recovery of operation. The lower the current slope in the dc circuit, the greater the chance for the next commutation, which is due after 30° to be successfully. On the other hand the fast response of HVDC system prefers a low inductive dc circuit, which means a moderate smoothing reactor size. therefore a trade off of all dynamic aspects shall be considered in the selection of reactor size.

→ the limitation of the direct current ripples has already has been discussed in chapter "DC Harmonic filters" as being important w.r.t. frequency transfer between asynchronous networks (non-harmonic oscillations) and the avoidance of current discontinuities in the light load range. the smoothing reactor plays a key role in this process, though the leakage inductances of the converter transformer are also involved.

3. What are the types of fault?

Most of the short circuit type faults that occur in HVDC systems are from AC source through DC link to the other AC system and may be summarised as.

→ AC networks faults like line-to-ground or line-to-line short circuits. converter transformer or AC bus faults or short circuits in filter and other equipment. these may be temporary and if so, they are cleared by tripping the AC side breakers. the system suffers power loss till the faults are cleared and supply is restored.

→ AC line faults on the inverter side; For this type of faults, commutation failure occurs in general but power is restored in a very short time clearing the faults.

iii) DC line or cable faults. the pole to ground or line to ground fault is the usual fault, but rarely pole-to-pole short circuit can also occur. The fault is cleared by turning the rectifier in to an inverter, so that fault energy is dissipated in a short time of 80 to 100ms. sometimes faults due to a lightning stroke can cause a temporary short circuit. such faults are cleared in about 200ms and the system is restored.

→ DC cable damages and short circuits are rare. They occur where an underground cable link is used between the sending end and receiving end. In such cases the rectifier is blocked. the stored energy is pumped back to the AC system and the power is disconnected till the fault is isolated and cleared.

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(Autonomous)
Department of Electrical and Electronics Engineering

Academic Year: **2022-23**	**MID Exam – I (Descriptive)**	Date:__
Year:**III**	**Subject Name: HVDC Transmission**	Duration:**90 min**
Semester:**II**	**Subject Code:**	Max Marks: **15**

Note: Answer any ALL questions. All questions carry equal marks.

Q.No	Questions	Marks	CO	BL	PI
	Answer ALL questions. All questions carry equal marks **3 * 5 = 15 Marks**				
1.	**(a)** Explain the various apparatus required for HVDC station and explain the purpose of each.	**[5M]**	**CO1**	**BL3**	**1.1.2**
	OR		**OR**		
2.	**(a)** Compare the HVDC transmission HVAC transmission with reference to following factors: i) Economics ii) Reliability	**[5M]**	**CO1**	**BL3**	**1.3.1**
3.	**(a)** Explain the 6-pulse Greatz Circuit and derive the expressions for average DC voltage with delay angle (α=30°).	**[5M]**	**CO2**	**BL3**	**1.1.2**
	OR				
4.	**(a)** Obtain an expression of Vd and draw an equivalent circuit diagram of a 3-phase bridge thyristor converter when it is working as a Inverter. Assume the converter is grid controlled and having overlap angle less than 60°.	**[5M]**	**CO2**	**BL3**	**1.1.2**
5.	**(a)** What are the applications of HVDC transmission?	**[5M]**	**CO1**	**BL2**	**1.3.1**
	OR				
6.	**(a)** Explain briefly about different types of HVDC links.	**[5M]**	**CO1**	**BL2**	**1.1.2**

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(Autonomous)
Department of Electrical and Electronics Engineering

Academic Year: **2022-23**
Year:**III**
Semester:**II**

MID Exam – I (Objective)
Subject Name: HVDC Transmission
Subject Code:

Date:
Duration: **10 min**
Max Marks:**5M**

Roll No:

Note: Answer ALL questions. All questions carry equal marks.

Answer all Objective Questions. All questions carry equal marks

Q.No	Questions	Option	CO	BL	PI
1	HVDC systems are mainly used with large power rating for A. interconnection of two systems with different frequencies B. bulk power transmission over long distances C. underwater cable transmission D. for connecting non conventional power	[ ]	CO1	BL1	1.3.1
2	Which factor is consider in HVDC planning A. cost B. technical performance C. reliability D. all of the above	[ ]	CO1	BL1	1.3.1
3	In the following Corona effect is more in A. DC conductor B. AC conductor C. Both D. None	[ ]	CO1	BL1	1.3.1
4	A 12-pulse converter consists of A. two 6-pulse converters in series B. two 6-pulse converters in parallel C. a or b D. a and b	[ ]	CO2	BL1	1.3.1
5	The break-even distance is the distance beyond which ___________transmission is economical A. DC B. AC C. Both D. None	[ ]	CO1	BL1	1.3.1
6	Modern HVDC systems are ____________pulse converters A. 6 B. 24 C. 12 D. 3	[ ]	CO2	BL1	1.3.1
7	A bipolar system has ____________ conductors and polarities of each conductor is ____________ A. 2, Opposite	[ ]	CO2	BL2	1.3.1

	B. 2, Same C. 1, Opposite D. 1, Same				
8	Graetz circuit output voltage wave form frequency is equal to ____________times of supply frequency A. 3 B. 1 C. 2 D. 6	**[ ]**	**CO2**	**BL2**	**1.3.1**
9	Q, R and S are represented as respectively number of commutation groups, number of parallel valves, number of series valves then pulse number is equal to __________ A. Q*R*S B. Q+R+S C. (Q*R)+S D. Q+(R*S)	**[ ]**	**CO2**	**BL2**	**1.3.1**
10	In 12-pulse connections, transformers are connected A. Both Star/Star B. Both Delta/Delta C. Both Star/Delta D. One Star/Star and Other Star/Delta	**[ ]**	**CO2**	**BL1**	**1.3.1**

BL – Bloom's Taxonomy Levels
CO – Course Outcomes
PI – Performance Indicator Code3

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(Autonomous)
Department of Electrical and Electronics Engineering

Academic Year: **2022-23** Year:**III** Semester:**II**	**MID Exam – II (Descriptive)** **Subject Name : HVDC Transmission** **Subject Code: GR20A3094**	Date:**14.06.2023** Duration:**90 min** Max Marks: **15**

Note: Answer any ALL questions. All questions carry equal marks.

Answer ALL questions. All questions carry equal marks 3 * 5 = 15 Marks					
Q.No	**Questions**	**Marks**	**CO**	**BL**	**PI**
1.	Explain about Individual Phase Control scheme for firing angle control employed in a converter.	**[5M]**	**CO3**	**BL3**	**3.1.5**
OR			**OR**		
2.	Explain the operation of CEA control technique with a neat diagram.	**[5M]**	**CO3**	**BL4**	**3.1.5**
3.	What do you understand by “characteristic harmonics” in HVDC system? Using Fourier analysis, obtain an expression for nth harmonic voltage on the DC side of the converter system.	**[5M]**	**CO4**	**BL4**	**3.2.1**
OR					
4.	Give the detailed description of various types of filter circuits’ configurations along with impedance characteristics	**[5M]**	**CO4**	**BL3**	**3.2.1**
5.	Broadly classify the HVDC faults and explain all possible converter faults with their causes and effects on its operation	**[5M]**	**CO5**	**BL3**	**3.2.1**
OR					
6.	What are the different types of over voltages due to disturbances on AC system side? Explain them in detail.	**[5M]**	**CO5**	**BL4**	**3.2.1**

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(Autonomous)
Department of Electrical and Electronics Engineering

Academic Year: **2022-23**
Year:**III**
Semester:**II**

MID Exam – I (Objective)
Subject Name : HVDC Transmission
Subject Code: GR20A3094

Date: **14.06.2023**
Duration: **10 min**
Max Marks:**5M**

Roll No:

Note: Answer ALL questions. All questions carry equal marks.

Answer all Objective Questions. All questions carry equal marks

Q.No	Questions	Option	CO	BL	PI
1	Characteristic of a converter is the relation between A. DC output voltage and Id B. DC power and Id C. Alpha and Id D. AC voltage and Id	[ ]	CO3	BL1	3.1.5
2	If pulse number p, and k is an integer, current harmonics generated on the AC side is/are A. pk+1 B. pk-1 C. Both A&B D. pk	[ ]	CO3	BL1	3.1.5
3	High pass filter have ___________ quality factor. A. High B. Low C. Any one D. None	[ ]	CO4	BL1	3.1.5
4	Converter transformer act as a source of generation of harmonics because of A. Magnetising current B. Nonlinear nature of B-H curve of iron core C. Magnetostiction D. None of the above	[ ]	CO4	BL2	3.1.5
5	Arc back occurs mainly in the _________ mode of operation. A. Inverter B. Rectifier C. Both D. None	[ ]	CO4	BL2	3.1.5
6	Firing angle control in modern HV converters is/are A. IPC B. EPC C. IPC or EPC D. None	[ ]	CO3	BL1	3.1.5
7	A rectifier station is set at a current level of 900A and inverter station at 800A. The current margin is A. -100A B. 50A C. -50A D. 100A	[ ]	CO3	BL2	3.1.5
8	The resistivity of average land surface is of the order(ohm-meter) A. 1 to 1000 B. 50 to 200 C. 1000 D. 1000 to 10,000	[ ]	CO5	BL1	3.1.5
9	Fault current level is highest in the following types of faults A. Converter internal fault B. DC Line fault C. Commutation failure D. Lightning stroke on lines	[ ]	CO5	BL2	3.1.5
10	Which of the following fault is self-clearing A. DC line Fault B. Multiple Commutation failure C. Single Commutation failure D. Arc back and Arc through	[ ]	CO5	BL1	3.1.5

BL – Bloom's Taxonomy Levels
CO – Course Outcomes
PI – Performance Indicator Code3

CODE: GR20A3094	GR 20	SET - 1

III B.Tech II Semester Regular Examinations, June/July 2023

HVDC TRANSMISSION SYSTEMS

(Electrical and Electronics Engineering)

Time: 3 hours Max Marks: 70

Instructions:

1. Question paper comprises of **Part-A** and **Part-B**
2. **Part-A** (for 20 marks) must be answered at one place in the answer book.
3. **Part-B** (for 50 marks) consists of **five questions with internal choice,** answer all questions.
4. CO means Course Outcomes. BL means Blooms Taxonomy Levels.

PART – A

(Answer ALL questions. All questions carry equal marks)

10 * 2 = 20 Marks

1. a.	What are the applications of HVDC transmission?	[2]	CO1	BL1
b.	Where was the first HVDC scheme in India established?	[2]	CO1	BL2
c.	State the main reason for using 12-pulse converters in modern converters.	[2]	CO2	BL1
d.	In 12-pulse connections, what is the type of transformers connections (in star or delta) are preferred.	[2]	CO2	BL2
e.	Write the factors that affects Power transfer in DC line.	[2]	CO3	BL1
f.	A rectifier station is set at a current level of 900A and inverter station at 800A, find the current margin.	[2]	CO3	BL2
g.	State the reason for Converter transformer to act as a source of generation of harmonics?	[2]	CO4	BL1
h.	In a 12-pulse bridge, if one transformer Y–Y has turns ratio 1:1, what is the turns ratio of the other transformer Y–Δ?	[2]	CO4	BL2
i.	What is the range of resistivity of average land surface in (Ω-m)?	[2]	CO5	BL1
j.	List the different types of faults and their occurrence.	[2]	CO5	BL2

PART – B

(Answer ALL questions. All questions carry equal marks)

5 * 10 = 50 Marks

2.	(a) State the advantages of HVDC transmission over EHVAC transmission for bulk power transmission. (b) Explain in detail "Break even distance" for HVDC Transmission Systems.	[10]	CO1	BL3

OR

3.	(a) What are the advantages and disadvantages of homopolar HVDC links over other types of links? (b) Explain in detail, the economic choice of voltage level selected in DC transmission system.	[10]	CO1	BL3
4.	(a) List some of the assumptions made to develop the equivalent circuit of a converter. (b) Write an expression for current ratio of an HVDC link. Also compute its value for a bipolar DC line of ± 400 kV, transmitting a power of 1000MW, when power factor on the AC side voltage of the converter transformer is = 0.9, assuming that the insulation levels are the same. Also compute current on the AC and DC side.	[10]	CO2	BL4
	OR			
5.	(a) Briefly explain about the converters used in DC transmission. (b) Distinguish between CSC (classical HVDC) and VSC-HVDC systems.	[10]	CO2	BL3
6.	(a) State the differences in power control in HVDC and HVAC systems and explain the necessity of power control in an HVDC link. (b) An HVDC link delivers DC power at 250 kV at the inverter when the AC line voltage to the rectifier is 220 kV and that at the inverter is 210 kV. The current order of the rectifier is 1000 A and that of the inverter is 950 A. Estimate the delay/extinction angle of the rectifier/inverter. Assume the DC resistance of the line as 20 Ω.	[10]	CO3	BL4
	OR			
7.	Explain the necessity of VDCOL control used in HVDC systems.	[10]	CO3	BL3
8.	(a) What do you understand by characteristic harmonics in HVDC systems? Using Fourier analysis, obtain an expression for n^{th} harmonic voltage on the DC side of the converter system. (b) A 12-pulse converter is supplied from two Y–Y and Y–Δ transformers with 1:1 and 1: 1.732 ratio. What is the peak AC current on the secondary side Y and Δ of the transformer with DC link current 1200 A with (a) $\alpha = 0, \mu = 0$; (b) $\alpha = 15°, \mu = 15°$.	[10]	CO4	BL3
	OR			
9.	(a) State the various sources of harmonics generation in HVDC-VSC systems and mention the adverse effects caused by these harmonics. (b) What are the different types of filters used on the AC side of an HVDC system? How are they located and arranged?	[10]	CO4	BL3

10. (a) State the advantages of ground return in HVDC systems. Give a neat sketch of the circuit using metallic return mode in case one of the poles develops a fault. [10] CO5 BL4

(b) Determine the resistance of hemispherical electrode situated in a non-uniform field each of resistivities p1 = 10 Ω-m and p2 = 10 p1.With Id = 10 A. Also estimate the potential of the earth electrode with respect to remote earth. Assume upper layer of lower resistivity is up to radius 10 m.

OR

11. (a) Derive an expression for the voltage rise of a land electrode. Explain how a land electrode is designed for large currents of the order of 1000 A. [10] CO5 BL4

(b) What are the effects of ground return currents on the buried objects? Suggest remedies to minimize them.

*****

1a)

Their major usefulness and applications are as follows:

(i) Multiterminal DC grid operation. The polarity of operation of converter does not change with power flow direction. Hence, the system can be built into blocks of multiterminals of HVDC system. Any number of HVDC-VSC converters can be connected to a DC bus with fixed polarity. Hence, a mesh DC system can be built similar to an AC system.

(ii) Highly suitable for cable transmission of electric power. The break-even distance with cable transmission is much less (≈50 km) as seen from Fig. 1.9.

(iii) Is a better choice compared to thyristor converter station. The power and voltage ranges of classical and HVDC-VSC systems are shown in Fig. 1.15.

(iv) For interconnecting nonconventional sources like wind power, etc., to the main grid. Some of the HVDC-VSC light projects that are under operation or installation are given in Table 1.3.

1b)

Among DC power transmission systems, the Thury system of HVDC transmission as designed by a French engineer was the first one to be put into operation in Europe, when AC system was in its infancy. It had a number of series-wound DC machines connected at the both ends of the transmission line and was operated at constant current. The first commercially successful DC system rated 100 kV, 20 kW was commissioned by the Gotland scheme in Sweden in 1954. Since then interest in HVDC power transmission has been increasing and many HVDC projects have been executed throughout the world (Table 1.1 to Table 1.5). Up to 1970, only mercury-valves were being used in HVDC projects in rectifier and inverter stations. Subsequently, thyristors and lately IGBTs have been developed and are being used extensively in bridge converters of HVDC systems. Locations of a few HVDC projects around the world are depicted in Fig. 1.2. The rapid advance in DC transmission technology has taken place because it has numerous advantages over EHVAC transmission in transporting bulk power through long-distance transmission lines. It reaps definite economic benefits when the transmission line length exceeds 500 km. Some advantages of HVDC transmission are

1c)

In case of a six-pulse converter, since the phase difference between successive SCRs is 60°, maximum overlap angle can go up to 60° ($\mu \leq 60°$), whereas in a 12-pulse converter, the phase difference is 30° only. Hence, commutation or overlap angle should be less than 30°. In order to maintain stable operation of rectifier, it is preferable to have both α and μ in the range $0 \leq \alpha, \mu \leq 30°$, in which case 4 or 5 valve conduction exists and with $30° \leq \mu \leq 60°$, 5 and 6 valve conduction mode takes place, for $60° \leq \mu \leq 90°$ 6 and 7 valve conduction takes place.

1d)

In the Fig. 3.24, the 6-pulse converter bridge along with AC side reactors is shown with IGBT valves as switches. For a 12-pulse connection, two 6-pulse converters, one with Y connected transformer secondary and another with Δ connected transformer secondary will be feeding similar bridge circuits, and the two bridges will be connected in series. The single line diagram of the VSC connection is shown in

1e)

2a)

1.4 COMPARISON OF AC AND DC TRANSMISSION

The relative merits of the two modes of transmission of AC and DC should be compared based on the following facts to assess the suitability:

(1) Economics of transmission
(2) Technical performance
(3) Reliability

1.4.1 Economics of Power Transmission

DC transmission of bulk power over long distances has certain distinct advantages over conventional AC power transmission such as the following:

(1) In DC transmission, inductance and capacitance of the line has no effect on the power transfer capability of the line and the line drop. Also, there is no leakage or charging current of the line under steady conditions. DC has more decided advantages when power is transmitted through cables as there is no charging current in the cable.
(2) For long distance power transmission over 500 km, the saving in cost is substantial as shown in Fig. l.8(a). A DC line requires only 2 conductors whereas an AC line requires 3 conductors in 3-phase AC systems. The cost of the terminal equipment is more in DC lines than in AC line. Break-even distance is one at which the cost of the two systems is the same. It is understood from Fig. 1.8(a) that a DC line is economical for long distances which are greater than the break-even distance. The break-even distance also varies with the power transmitted over the line as shown in Fig. 1.8(b). Table l.6 below shows the comparative capability of HVDC systems for power transfer over various distances with that of an EHVAC system at different voltages.

1.4.2 Technical Performance

DC transmission has some positive features which are not present in AC transmission, but are mainly due to the fast controllability of power in DC lines through converter control. Following are some technical advantages:

(1) Full control over power transmitted in either direction.

(2) The ability to improve the transient and dynamic stability of AC system when embedded with DC link.
(3) Fast control to limit fault currents in DC lines.
(4) A DC link can be used as an asynchronous tie which can tie down the small variations in system frequency of different AC systems.
(5) Two large AC systems when interconnected by AC link may sustain instability. But DC link may dampen the system oscillations due to its inherent short over load capacity.
(6) The choice of high voltage DC transmission system mainly depends on the economic suitability for a particular application. Primarily economy lies in the fact that DC transmission requires only two conductors per circuit (bipolar) rather than three conductors required for an AC system. Consequently, the towers carry less conductor weight in DC system and are smaller in size and hence are less costly.

1.6 RELIABILITY OF HVDC SYSTEMS

A study of the existing HVDC links in the world indicates that the reliability of DC transmission system is quite good and comparable to that of AC systems. The performance of thyristor valves is much more reliable than mercury arc valves. Further, developments like direct light triggered thyristor (LTT) and new techniques of control and protection have improved reliability levels.

Transient Reliability:

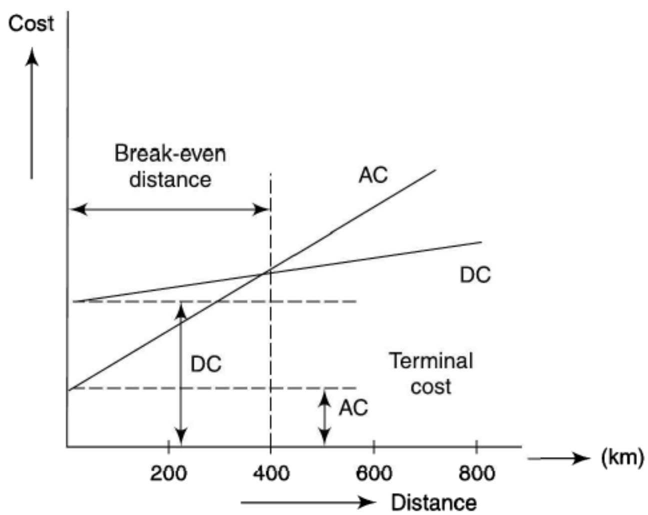
This is a factor specifying the performance of HVDC systems during recordable faults on the associated AC systems. The transient reliability can be defined as the ratio of

$$= \frac{\text{No. of times HVDC systems performed as designed}}{\text{No. of recordable AC faults}}$$

Recordable AC system faults are defined as those faults which cause one or more AC bus phase voltages to drop below 90% of the voltage prior to the fault. It is assumed that the short circuit level after the fault is not below the minimum specified for satisfactory converter operation.

2b)

The choice of DC transmission voltage for a given power has a direct impact on the total installation cost. The cost of losses is very important in the evaluation of energy losses cost and the time horizon for utilisation of the DC system. Hence, to estimate costs of an HVDC system, a life cycle cost analysis is done. Here a comparison between (i) EHVAC system and Thyristor valve DC system, and (ii) EHV AC system and VSC (IGBT) valves with cable is carried out. For the first one (i), the capital costs for HVDC converter are higher than that of EHVAC substations. On the other hand, the cost of transmission for lines, cables land cost, etc., are lower for a DC system. In Fig. 1.8 (c) and (d), the break-even distance arrived at is larger (>500 km). The break-even distance depends on several factors such as line or cable, cost of materials, labour costs, etc. Similar comparison is made for VSC based



3a)

(c) Homopolar Link Homopolar system has two or more conductors with the same polarity, usually negative, and they always operate with ground return. In the event of fault in one conductor, the whole

converter can be connected to a healthy pole and can carry more than half the power (2-pole) by overloading but at the expense of increased line loss. However, this is not possible in a bipolar system due to the use of graded insulation for negative and positive poles. When continuous ground currents are inevitable, homopolar system is preferable. The additional advantage is lower corona loss and radio interference due to negative polarity on the lines.

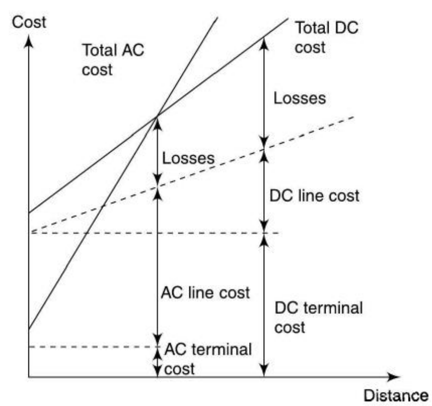
b)

DC transmission of bulk power over long distances has certain distinct advantages over conventional AC power transmission such as the following:

(1) In DC transmission, inductance and capacitance of the line has no effect on the power transfer capability of the line and the line drop. Also, there is no leakage or charging current of the line under steady conditions. DC has more decided advantages when power is transmitted through cables as there is no charging current in the cable.

(2) For long distance power transmission over 500 km, the saving in cost is substantial as shown in Fig. 1.8(a). A DC line requires only 2 conductors whereas an AC line requires 3 conductors in 3-phase AC systems. The cost of the terminal equipment is more in DC lines than in AC line. Break-even distance is one at which the cost of the two systems is the same. It is understood from Fig. 1.8(a) that a DC line is economical for long distances which are greater than the break-even distance. The break-even distance also varies with the power transmitted over the line as shown in Fig. 1.8(b). Table 1.6 below shows the comparative capability of HVDC systems for power transfer over various distances with that of an EHVAC system at different voltages.

(3) The choice of DC transmission voltage for a given power has a direct impact on the total installation cost. The cost of losses is very important in the evaluation of energy losses cost and the time horizon for utilisation of the DC system. Hence, to estimate costs of an HVDC system, a life cycle cost analysis is done. Here a comparison between (i) EHVAC system and Thyristor valve DC system, and (ii) EHV AC system and VSC (IGBT) valves with cable is carried out. For the first one (i), the capital costs for HVDC converter are higher than that of EHVAC substations. On the other hand, the cost of transmission for lines, cables land cost, etc., are lower for a DC system. In Fig. 1.8 (c) and (d), the break-even distance arrived at is larger (>500 km). The break-even distance depends on several factors such as line or cable, cost of materials, labour costs, etc. Similar comparison is made for VSC based



4a)

3.6.8 Equivalent Circuit of the Inverter

Equivalent circuit of the inverter based on the expression

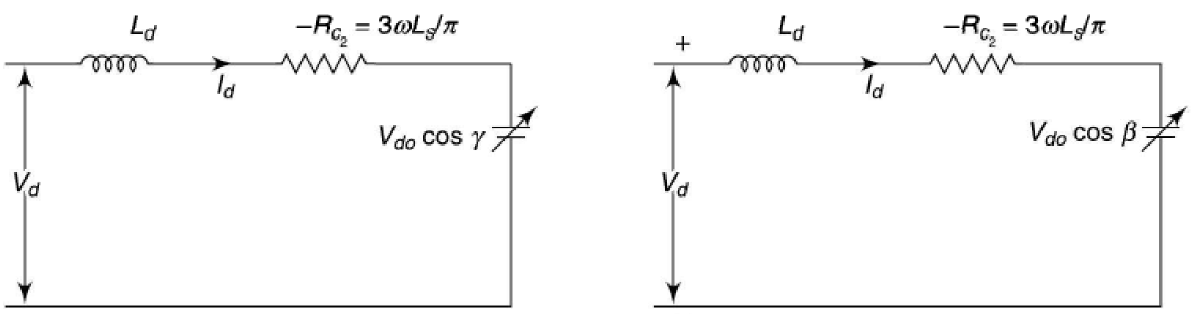
$$-V_d = V_{do} \cos \gamma - \frac{3\omega L_s I_d}{\pi} \qquad (3.33(a)) \text{ and}$$

$$-V_d = V_{do} \cos \beta + \frac{3\omega L_s I_d}{\pi} \qquad (3.33(b))$$

Omitting the negative sign of voltage of the inverter

$$V_d = V_{do} \cos \gamma + Rc_2 I_d \text{ where } Rc_2 = \frac{-3\omega L_s}{\pi} \qquad (3.33(c))$$

The equivalent circuit of the inverter is given in Fig. 3.14.



(a) Based on extinction angle γ (b) Based on angle of advance β

3.6.9 Complete Equivalent Circuit of HVDC Link

Combining the equivalent circuit of the rectifier and inverter, the total equivalent circuit of HVDC link is shown in Fig. 3.15.

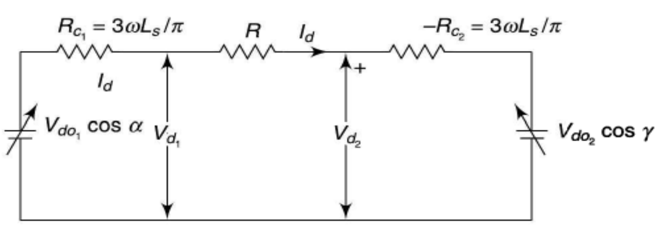


Fig. 3.15 Equivalent circuit of an HVDC link

The expression for the direct current I_d can be obtained from the figure above as

$$I_d = (V_{d_1} - V_{d_2})/R$$

or

$$I_d = \frac{V_{do_1} \cos \alpha - V_{do_2} \cos \beta}{R_{c_1} + R + R_{c_2}} \qquad (3.36)$$

4b)

4(b) AC Line to line Voltage on the Converter side of transformer

$$V_{SL} = 400 \times \sqrt{1.5} = 489.89\,kV \left(\because \frac{V_{SL}}{\sqrt{3}} \times \sqrt{2} = V_d \right)$$

$$I_S = \text{AC current} = \frac{400 \times 10^6}{\sqrt{3} V_{SL} \times 0.9}$$

$$\text{AC line current} = \frac{400 \times 10^6}{\sqrt{3} V_{SL} \times 0.9} = \frac{400 \times 10^6}{\sqrt{3} \times 489.89 \times 10^3}$$

$$= \frac{1\,400 \times 10^6}{848.514 \times 10^3}$$

$$= ~~471.41A~~ \; 1178.53.$$

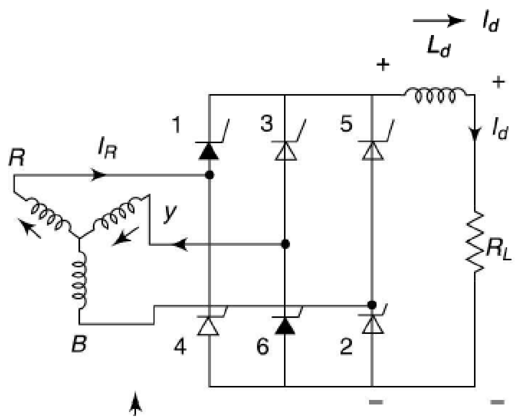
$$\text{DC current} = I_d = \frac{1000 \times 10^6}{2 \times 10^5} = 5000\,A.$$

5a)

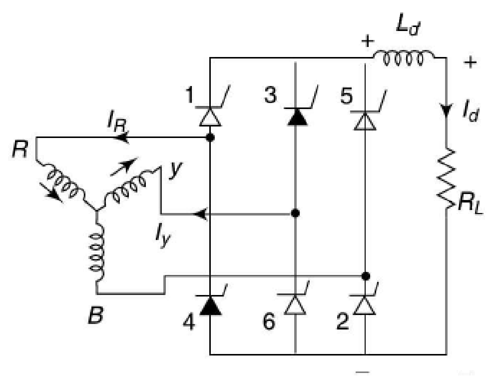
3.2 CONDUCTION SEQUENCE IN 6-PULSE CONVERTER CONFIGURATION

All modern HVDC systems use either 6-pulse or 12-pulse converters. The 3-phase bridge shown in Fig. 3.1 is the only configuration used in HVDC transmission. The bridge configuration provides better utilisation of converter transformer and a lower peak inverse voltage across the converter valves when compared with other possible alternatives.

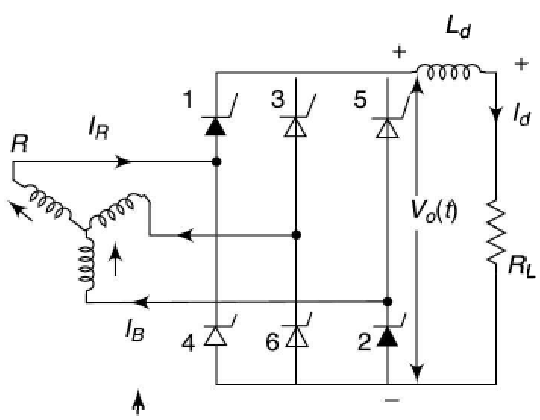
In Fig. 3.1 conducting valves are indicated by thick lines. The bridge indicates that two valves are connected to each phase (for example, 1, 4 with phase *R*). In the upper part of the bridge, the anodes of the valves 1, 3, 5 are connected to the phase *R*, *Y*, *B* respectively. Similarly in the lower half of the bridge, the cathodes of valves 4, 6, 2 are connected to the phases *R*, *Y*, *B* respectively. The figure indicates that at any time two valves will be conducting in series (6, 1; 1, 2; 2, 3; 3, 4; 4, 5; 5, 6) simultaneously when the source inductance of the transformer is neglected. This is not considered a drawback in high voltage applications, particularly with solid state converter, because it is necessary to connect many thyristor units in series to withstand the voltage levels being used.



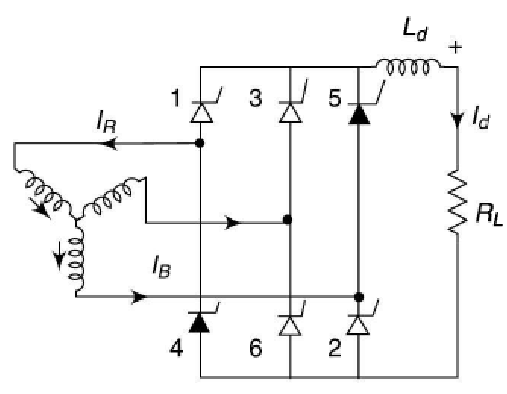
(a) Conducting valves 6,1



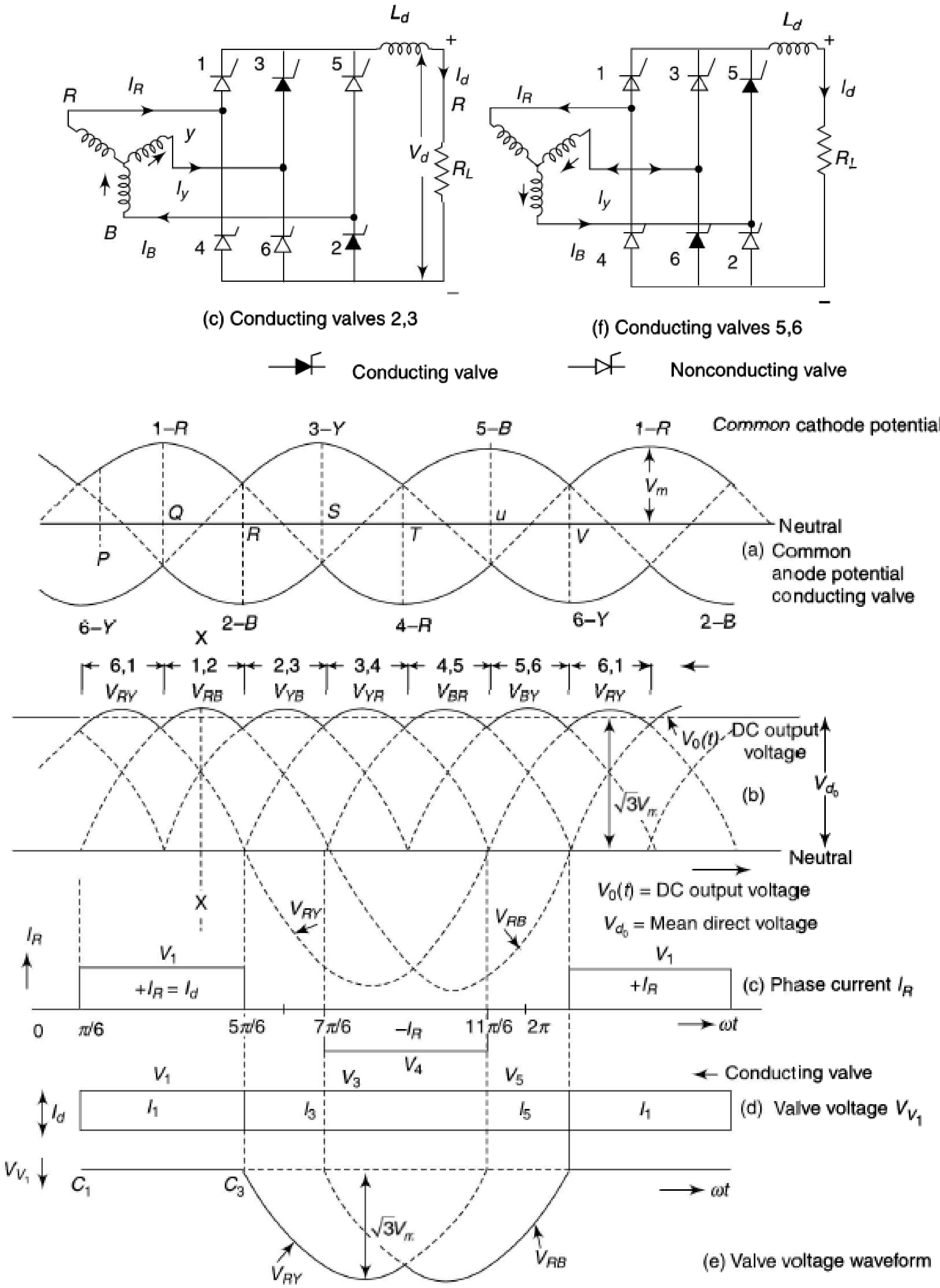
(d) Conducting valves 3,4



(b) Conducting valves 1,2



(e) Conducting valves 5,4,5



(c) Conducting valves 2,3
(f) Conducting valves 5,6
Conducting valve
Nonconducting valve
Common cathode potential
Neutral
(a) Common anode potential conducting valve
6,1 V_{RY} | 1,2 V_{RB} | 2,3 V_{YB} | 3,4 V_{YR} | 4,5 V_{BR} | 5,6 V_{BY} | 6,1 V_{RY}
$V_0(t)$ DC output voltage
(b)
$V_0(t)$ = DC output voltage
V_{d_0} = Mean direct voltage
(c) Phase current I_R
0 π/6 5π/6 7π/6 11π/6 2π ωt
Conducting valve
(d) Valve voltage V_{V_1}
(e) Valve voltage waveform

$$V_{do} = \frac{1}{\pi/3}\int_{-\pi/6}^{\pi/6} V_o(t)\,d(\omega t) = \frac{3}{\pi}\int_{-\pi/6}^{\pi/6} \sqrt{3}V_m \cos\omega t\,d(\omega t)$$

12 pulse Converter

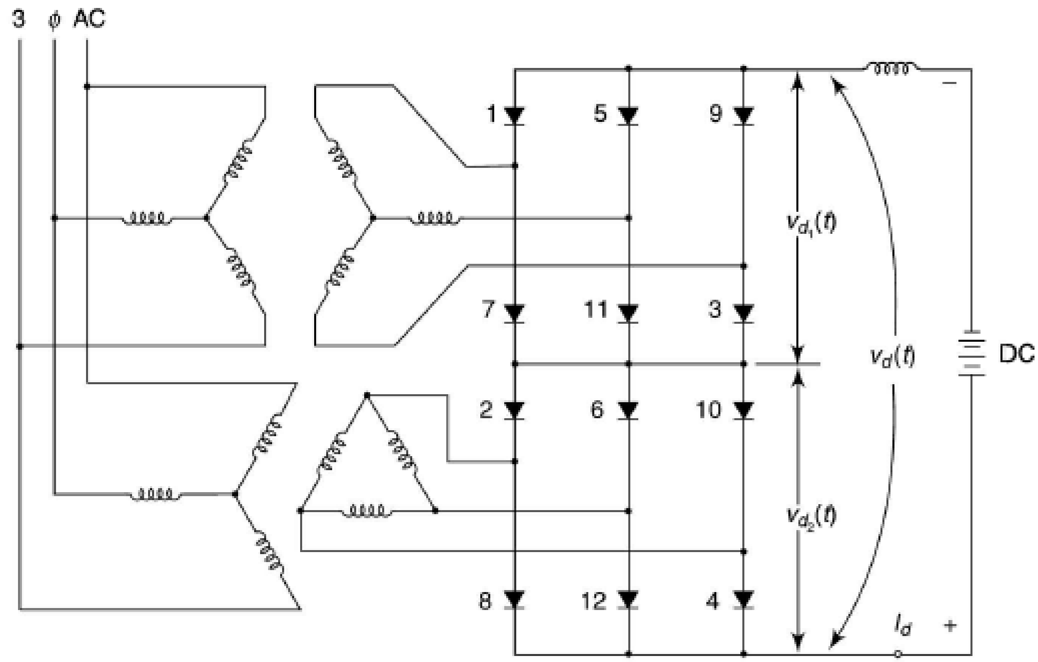


Fig. 3.22 12-pulse converter

5b)

Table 3.3 Comparison between HVDC-CSC and HVDC-VSC systems

S.No.	*HVDC (CLASSICAL CSC)*	*HVDC-VSC*
1	Acts as a constant current source on DC side	Constant voltage source on DC side
2	Current on DC side is unidirectional	Polarity on DC side is unidirectional
3	Polarity on DC side changes with power flow	Direction of current changes with the power flow
4	DC reactor maintains constant current	DC capacitor maintains constant voltage
5	DC filter capacitance is used on line side of smoothing reactor	DC smoothing reactor is used on the line side of DC filter capacitor
6	Line commuted or forced commuted	Self-commuted
7	PWM control is very rarely applied	PWM control is usually applied
8	CSC and VSC are dual systems	CSC and VSC are dual systems
9	For given power rating, costs are less	Overall costs are more
10	Cannot feed reactive power into AC system	Reactive power control is possible

6a)

In AC systems, the power transfer from one system to another depends entirely on the conditions of both the systems. The active power transmission through an AC link is given by the expression

$$P_{AC} = \frac{V_S V_R \sin \delta}{X} \tag{4.1}$$

where V_S is the sending end voltage
V_R is the receiving end voltage
X is the reactance of the AC link
δ is the phase angle between the voltages V_S and V_R

Similarly, the expression for reactive power transmitted from the sending end is

$$Q_s = \frac{V_S (V_S - V_R \cos) \delta}{X} \tag{4.2}$$

and reactive power at the receiving end is

$$Q_R = \frac{V_R (V_R - V_S \cos \delta)}{X} \tag{4.3}$$

From the above expressions, it is understood that the active power transmitted depends upon the angle δ. As δ is related to the demand for transmitted power via the rotating machines (rotors) of both the ends, the AC system adapts automatically. It means that the angle δ increases with an increase in load on the AC system as the rotor gets retarded w.r.t. to the synchronously revolving magnetic field produced by the stator.

The reactive power is only slightly influenced by the angle δ but it depends a lot upon the magnitude of the voltages.

4.3 PRINCIPLES OF CONTROL

The typical HVDC systems of Fig. 1.4 can be conveniently represented by an equivalent circuit (derived in Chapter 3) as shown in Fig. 3.15. As the mid-point of each terminal station is at earth potential and the upper and lower halves of the system are symmetrical, therefore only one-half of the circuit needs to be considered for analysis.

The equivalent circuit representation shown in Fig. 3.15 is sufficient for steady-state analysis of power transfer. The station on the left-hand side is a rectifier and on the right-hand side is an inverter. Both stations are assumed to operate at constant delay angles α and β or γ respectively. The direct current through the line is given by the equation (3.36) as

$$I_d = \frac{V_{do_1} \cos \alpha - V_{do_2} \cos(\beta \text{ or } \gamma)}{R_{c_1} + R \pm R_{c_2}} \tag{4.4}$$

A change of current and therefore power transfer can be achieved by altering any one of the four possible parameters —

(a) The control angle of the rectifier α
(b) The control angle of the invertor β or γ
(c) The rectifier-transformer secondary winding voltage by the tap-changer
(d) The inverter-transformer secondary winding voltage by the tap-changer

The cases (c) and (d) can be effected by employing tap-changing of the converter transformer to change the AC voltage.

4.4 NECESSITY OF CONTROL IN CASE OF A DC LINK

From the expression for current through a DC link it can be observed that the denominator has only resistances which are small when compared with the reactance of an AC system. Hence, current is sensitive to change in voltage resulting in large fluctuations, which can damage the thyristors. Thus, control of current and hence power, in case of a DC system is a must. The advantages of using control are

1. Current order setting can be quickly and reliably changed depending on the requirement
2. Power reversal can be done easily and quickly
3. Fault current levels are limited to rated values

6b)

6(b) V_{do1} = No load DC voltage at rectifier end

$= \frac{3\sqrt{2}}{\pi} \times V_{SL}$

$= 1.35 \times 250 = 337.5\,kV$.

V_{do2} = No load DC voltage at inverter end

$= \frac{3\sqrt{2}}{\pi} \times V_{SL} = 1.35 \times 220 = 297\,kV$.

Line drop in DC line = $20 \times 1000 = 20\,kV$.

DC Voltage at rectifier end = DC voltage at inverter + line drop

$V_{d1} = 220 + 20 = 240\,kV$.

$V_{d1} = V_{do1} \cos\alpha = 240$

$\cos\alpha = \frac{240}{337.5} = 0.711$

Delay Angle $\alpha = \underline{44.68^\circ}$

$V_{d2} = V_{do2} \cos\gamma = 220$

$\cos\gamma = \frac{220}{297} = 0.7407$

$\gamma = \underline{42.2^\circ}$

7a)

4.8 VOLTAGE DEPENDENT CURRENT ORDER LIMIT (VDCOL)—CHARACTERISTICS OF THE CONVERTER

Mainly due to faults in the AC system on the rectifier or inverter side, the voltage on the DC link is reduced. Low AC voltage due to faults on the inverter side can result in persistent commutation failure because of an

increase in the overlap angle. In such cases, it is necessary to reduce the DC current in the link to a level that leads to reduced DC voltage at the rectifier end. Reduction of current also relieves the valves in the inverter which are overstressed due to continuous overcurrent flow in them.

If the low voltage is due to faults on the rectifier side of the AC system, the inverter has to operate at larger value of γ, at very low power factor demanding excessive consumption of VAR which is undesirable.

Thus, it becomes useful to modify the control characteristics to include voltage dependent current order limits (VDCOL). This is illustrated in Fig. 4.12 which also shows current error characteristics to stabilise the mode when operating with DC current in the limits I_{d_1} and I_{d_2}.

The characteristic *CD* and *DH* show the limitation of current due to the reduction in voltage. When the system voltage drops considerably, the DC current is reduced from I_{d_1} to I'_{d_1} linearly and maintained at I'_{d_1} below the voltage V_{d_2}. The inverter characteristic also follows the rectifier characteristic to maintain the current margin except for $K'K$, which is due to the lower limit imposed on the delay angle of the inverter. VDCOL contains control unit to reduce the current order.

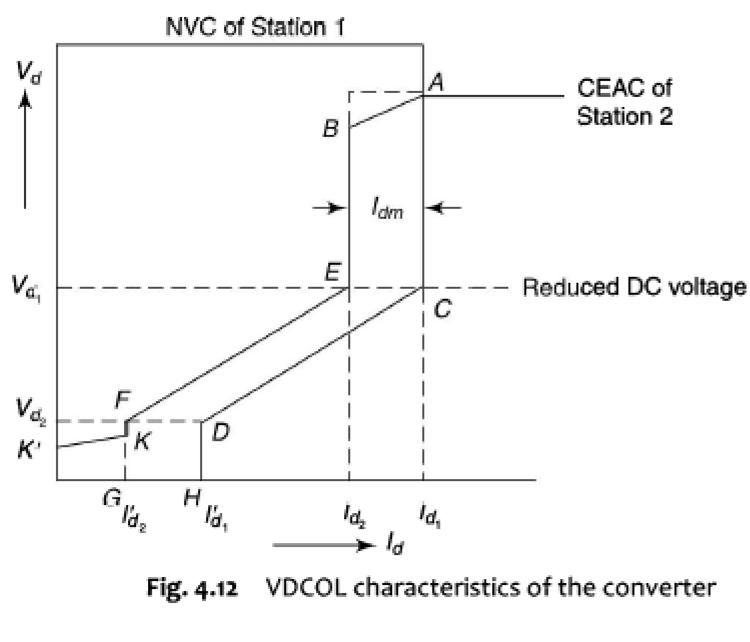


Fig. 4.12 VDCOL characteristics of the converter

8a)

The order of characteristic harmonics is related to the pulse number of the converter configuration and is defined as the number of nonsimultaneous commutations per cycle of fundamental frequency. A converter with pulse number p generates characteristic voltage harmonics of the order pk on the DC side, where k is any integer. The following assumptions are made while analysing characteristic harmonics.

1. The AC supply voltage is a perfectly balanced system of voltages and contains only fundamental components.
2. Direct current is of constant magnitude ($L_d \to \infty$).
3. Valves conduct sequentially at equal intervals of time.
4. The commutation reactance of each phase is same.

Consider the 6-phase bridge converter as shown in the Fig. 3.1; current and voltage waveforms are shown in Fig. 3.9 for delay angle α and commutation angle μ.

The output DC voltage is illustrated in Fig. 3.9(b). Taking time reference at the crossing of the voltage waveforms (C_1), the output DC voltage can be expressed as

$$V_0(t) = \sqrt{2}V_{SL}\cos\left(\omega t + \frac{2\pi}{6}\right) \text{ for } 0 < \omega t < \alpha$$

$$V_0(t) = \frac{(V_R + V_B)}{2} - V_y = \frac{\sqrt{6}V_{SL}}{2}\sin\omega t \text{ for } \alpha < \omega t < \alpha + \mu$$

$$V_0(t) = \sqrt{2}V_{SL}\cos\left(\omega t - \frac{2\pi}{6}\right) \text{ for } \alpha + \mu < \omega t < \frac{\pi}{3}$$

Using Fourier equations

$$A_0 = \frac{1}{\pi}\int_{\sigma}^{\sigma+2\pi} f(\theta)d\theta$$

$$A_n = \frac{1}{\pi}\int_{\sigma}^{\sigma+2\pi} f(\theta)\cos n\theta d\theta$$

$$B_n = \frac{1}{\pi}\int_{\sigma}^{\sigma+2\pi} f(\theta)\sin n\theta d\theta$$

where σ is any angle. The general trigonometric form of Fourier series is

$$F(\theta) = \frac{A_0}{2} + \sum_{n=1}^{\infty} [A_n \cos n\theta + B_n \sin n\theta] \tag{5.7}$$

where $\theta = \omega t$ and ω is the basic repetition frequency in rad/s; $\frac{A_0}{2}$ is the average value of the function $f(\theta)$ and A_n and B_n are the rectangular components of the n^{th} harmonic.

The peak value of the n^{th} harmonic and its continuous form are

$$\left.\begin{aligned} C_n &= \sqrt{A_n^2 + B_n^2} \; and \; C_n\underline{|\phi_n} = A_n - iB_n \\ \phi_n &= \tan^{-1}(-B_n/A_n) \end{aligned}\right\} \tag{5.8}$$

Using the above equations (5.4) to (5.6), the rms value of the h^{th} harmonic voltage is given by

$$V_h = \frac{V_{do}}{\sqrt{2}(h^2-1)}\Bigg[(h-1)^2 \cos^2\left\{(h+1)\frac{\mu}{2}\right\} + (h+1)^2 \cos^2\left\{(h-1)\frac{\mu}{2}\right\}$$
$$-2(h-1)(h+1)\cos\left\{(h+1)\frac{\mu}{2}\right\}\cos\left\{(h-1)\frac{\mu}{2}\right\}\cos(2\alpha+\mu)\Bigg]^{1/2} \tag{5.9}$$

Some interesting facts can be seen from the above equation when $\alpha = 0$ and $\mu = 0$ and the expression (5.9) reduces to

$$V_{ho} = \sqrt{2}\,V_{do}/(h^2-1) \tag{5.10}$$

$$\frac{V_{ho}}{V_{do}} = \sqrt{2}/(h^2-1) = \sqrt{2}/h^2 \tag{5.11}$$

8b) Peak AC current for α=0, μ=0 [2M]

Peak AC current for α=15, μ=15 [2M]

9a)

Voltage source converters are usually operated with different control schemes that use PWM to control AC fundamental frequency. From the converter side of the reactor, the voltage-to-ground is a square wave and thus requires AC filters to remove harmonics. The line side reactor usually removes the high frequency component in current wave and the DC capacitor high frequency voltage ripples on the DC side. Still depending on type of converter (6-pulse or 12-pulse), voltage harmonics of $6n \pm 1$ or $12n \pm 1$(n harmonic number) are generated in the rectifier side of the converter. Further with PWM and high dv/dt switching, high frequency voltage and noise are generated, the starting harmonic being pf_0, where f_0 fundamental frequency, p = ratio of modulation frequency to fundamental AC frequency. With $p = 9$, the harmonics generated will be 9, 17, 19, etc. The amplitude spectrum of typical harmonics with $p = 9$ and $M = 0.5$ (Ref. Sec. 3.11.2) of PWM inverter is shown in Fig. 5.15.

In a study carried out on a actual system with a long cable, the effect of switching frequency had larger effect when it is equal to one of the harmonic frequencies. The current harmonic has the largest magnitude. With $p = 9$, 11, 13, etc., ..., the predominant harmonics were 9, 11 and 13. The capacitance of the cable and that of the capacitor bank provided reduces the THD (total harmonic distortion) significantly. Further with an increase in capacitance value, the resonances that occur become damped because the interaction produced by DC harmonic currents gets reduced.

The studies at a VSC-based HVDC link in Australia (Terranora-Mullunbiby) showed that total harmonic distortion THD was about 1.5% and TIF 40% respectively (Ref. Sec. 6.3).

The high level of 5th harmonic was not due to converters, as it was present even when converters were re-energised. Some harmonics are present around once and twice the switching frequency. The 9th harmonic was present on the DC side due to cable resonance and was filtered off with the 9th harmonic filter. To

conclude, most harmonics that are present in the VSC system are either due to switching or due to resonance between capacitor and reactances present. A typical harmonic spectrum is shown in Fig. 5.16.

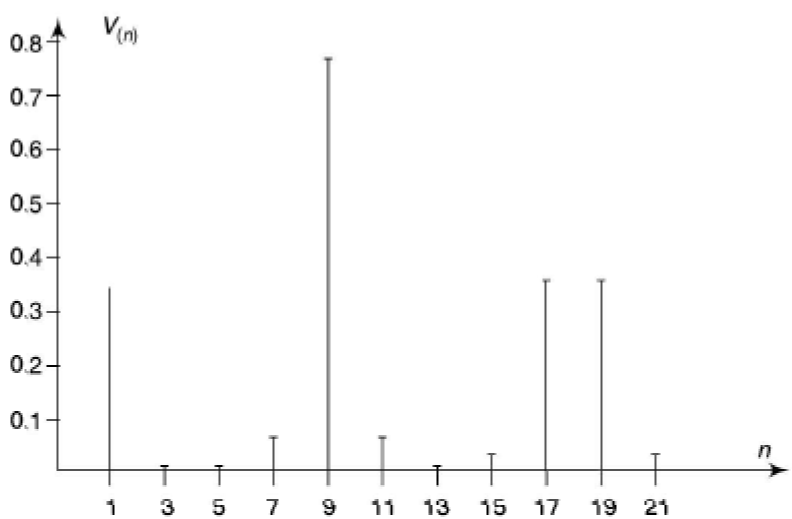


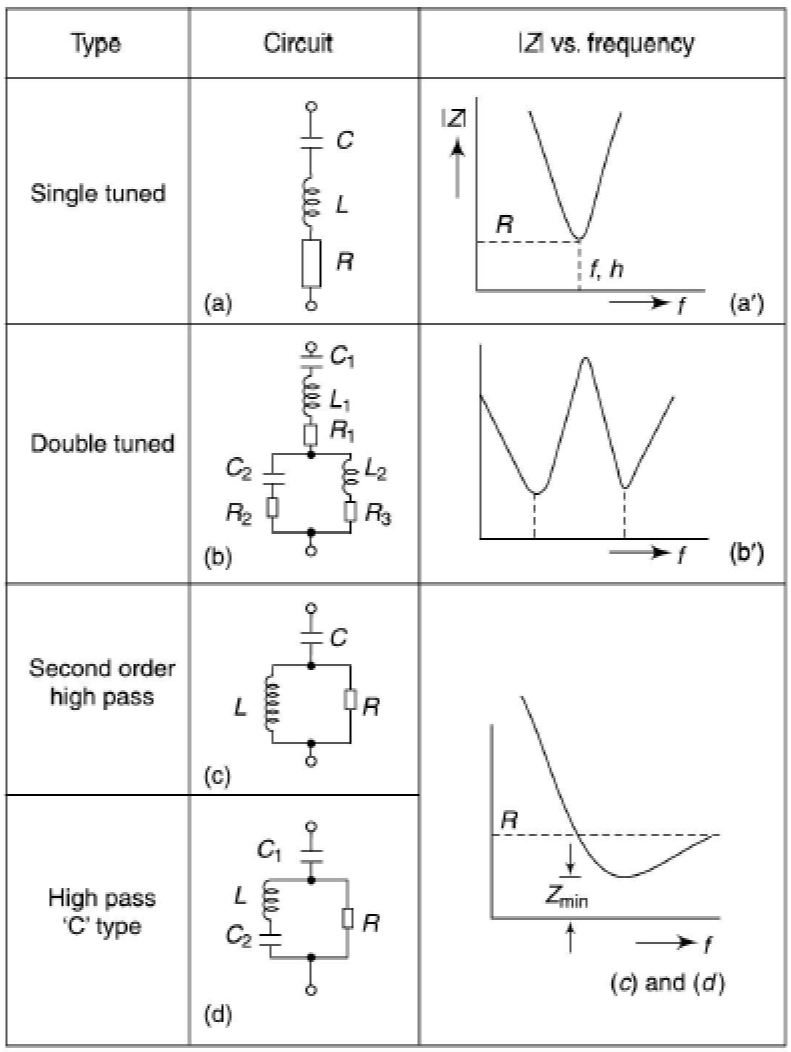
Fig. 5.15 Harmonics with sinusoidal PWM P = 9 and M = 0.5

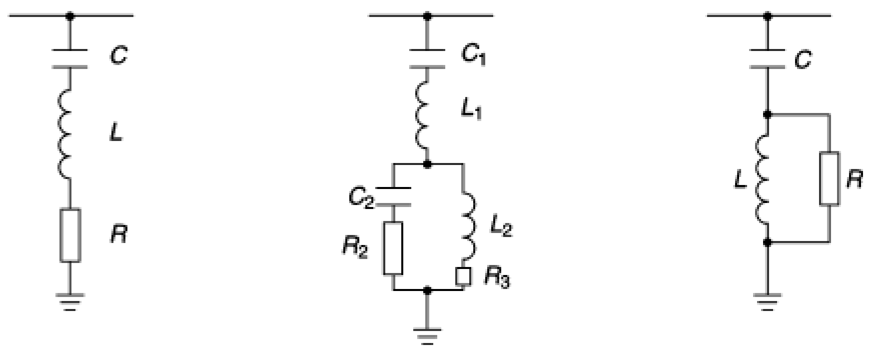
9b)

Filters used in HVDC stations not only absorb harmonics but also provide VAR support for the converters. Due to this reason, a co-ordinated design between filter performance and reactive power balance is essential. Following are the various types of AC filters that can be used—

(a) Single tuned filters
(b) Double tuned filters
(c) High-pass filters
  (i) Second order filters
  (ii) C-type filters

The configuration of these filters and their impedance characteristics as a function of frequency is shown in Figs. 6.5(a) to (e). Single tuned filters are designed to filter out characteristic harmonics of single frequency. Double tuned filters are used to filter out two discrete frequencies, instead of using two single





(a) Series resonance filter (Single tuned) (b) Double-tuned filter (c) High-pass filter

tuned filters. The main advantages are (i) only one inductor is subjected to full line impulse voltage and (ii) power loss at the fundamental frequency is considerably reduced.

High-pass filters of second order are designed to filter out the higher harmonics and the tuning of these filters is not critical. *C*-type filters can be used to minimise losses at fundamental frequency as the leg containing C_2 in series with *L* offers low impedance to fundamental frequency. The advantages of high-pass filters are (i) no sharp tuning is required, (ii) it tolerates relatively large steady state frequency variation, and (iii) it reduces transient voltage due to large resistance. However, it has higher losses. In Figs. 6.6(a) and (b), an arrangement in a 1000 MVA/1000 MW HVDC station is shown.

10a)

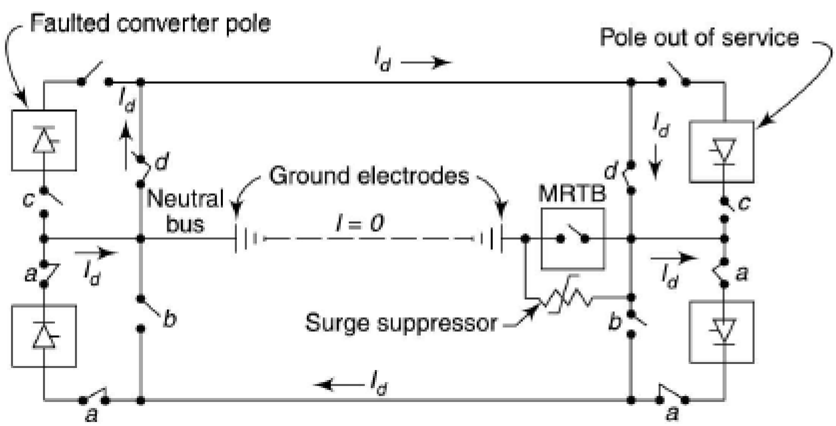
The following are certain advantages of use of ground return.

1. The ground path has a very low resistance and consequently low power loss in comparison with a metallic return conductor of economical size and equal length, provided ground electrodes are properly designed. The resistance of the ground path of DC currents is low because the DC current under steady state spreads over a very large cross-sectional area in both depth and width, and does not follow closely the route of the metallic conductor unlike transient AC current. The resistance of this path is independent of the length of the line as the resistance of the ground is negligible and mostly comprises ground electrodes at each end.
2. A bipolar line is more economical than a monopolar line with ground return. A bipolar line has twice as many conductors and can carry twice as much power at slightly higher efficiency than the monopolar line. Its cost is surely less than twice that of a monopolar line with overhead conductors. Apart from this, a bipolar line can be built in two stages if the power demand on the line at the initial stages is

less. It can operate in the first stage as a monopolar line with ground return and in the second stage as a bipolar line without ground current. This saves initial capital investment except the cost of ground electrodes, which are required for monopolar operation at the first stage.

3. A bipolar line in the second stage can supply almost 50% of its rated power in the event of fault on one of the poles. Therefore, the reliability of a bipolar DC line is almost equal to that of a double circuit 3-phase AC line, even though it has only two conductors instead of six. Monopolar, homopolar and unbalanced HVDC system must have ground electrodes rated for continuous operation. HVDC transmission systems may have time restrictions during which ground transmission may be used or on the total number of ampere-hours per year. In case of an outage of a converter pole, the ground electrodes will automatically carry the load current of the healthy pole, but if there is a restriction in time or current for ground return, the system may be designed to eliminate ground current by using the conductor of the faulted pole as the return path.

This operation can be accomplished without interruption of supply by the use of a scheme known as the metallic return as shown in Fig. 7.1. A metallic return transfer breaker (MRTB) is used.



Switch positions

	Normal	Metallic return
a	Closed	Closed
b	Open	Open
c	Closed	Open
d	Open	Closed
MTRB	Closed	Open

10b)

3.024 Ω, 30.24 V

11a)

In the design of the first commercially operated ground electrode constructed on dry land, it was found that the best method of passing ground current into the earth was to increase the surface area of the electrode by the use of coke which is a high conductivity material with low cost per unit volume. The use of coke enables distribution of current from the entire electrode and effectively increases the electrode area. Even though, direct burial of carbon electrode with low rate of wastage is possible, but most of the DC transmission schemes use some form of coke filled for the ground electrode as shown in Fig. 7.10.

Table 7.6 Basic requirements for design of land electrodes

1. Current	1250 A maximum	—
2. Operating time	Bipolar	Continuously at 50 A
	Monopolar mode	8 hours at 1250 A, followed by 30 days at 1000 A, followed by 60 days cooling at 50 A
3. Dissipation	Maximum 730,000 Ah/year	—
4. Lifetime	30 years	—
5. Polarity	Reversible anode-cathode, equal time	—
6. Safety	Step voltage = $5 + 0.03\,\rho$ volts/m	—
7. Reliability	Consistent with system reliability	—

Before designing the ground electrode on land, basic specifications of requirements for typical ground electrode are listed in the Table 7.6. This information given in the table is applicable to any type of configuration of electrode and is the basic information necessary. However, the safety requirements specified may differ for sea electrodes.

11b)

Ground return of DC line can adversely affect the neighbouring services of public utilities like gas pipes, water pipes, rail roads, AC power systems, and telephone lines. Investigations have shown that the detrimental effects of ground current can be eliminated or reduced by locating the ground electrodes at sufficient distances (8 to 50 km) from public utility services.

The most serious problem posed by direct ground current is the electrolytic corrosion of buried metal objects pertaining to public utility services. Even without ground return currents, corrosion of metal objects occurs because of local ground currents due to thermo-emfs which are a result of contact of different metals. The superimposed DC current sometimes may aggravate corrosion depending upon the direction of current. A typical reaction between an iron anode and the soil is

$$Fe^{++} + 2OH^{-} \rightarrow Fe(OH)_2 \qquad (7.42)$$

These metal ions move in the direction of current in the electrolyte. The formation of doubly ionized ions releases two electrons which may traverse along the pipe and combine with positive ions at the point where the current enters, which results in the release of hydrogen given by the reaction

$$2e^{-} + 2H^{+} \rightarrow H_2 \qquad (7.43)$$

This reaction coats the pipe with a layer of hydrogen that protects it from oxidation and other corrosion. In the electrolyte, the current leaves the metallic anode and enters at the cathode. The metallic anodes are corroded and most cathodes are protected from corrosion. However, corrosion does not take place between two metallic contacts due to conduction by electrons. AC currents of commercial power frequency cause only about 1% corrosion of that of DC current of equal rms value.

Gokaraju Rangaraju Institute of Engineering & Technology

III B.Tech II Sem (EEE) Result Analysis

Academic Year: 2022-23 Total No. of Students Registered: 64

Course	Total No. of Students appeared	Total No. of Students Passed	No. of Students Failed	Count of Students with Grade Point					
				GP (10)	GP (9)	GP (8)	GP (7)	GP (6)	GP (5)
EAE	64	58	06	00	11	13	7	10	07
PLC	64	60	04	09	16	14	09	06	06
SMI	64	51	13	00	07	12	17	08	07
MPE	40	63	01	02	15	05	08	06	03
HVDCT	24	21	03	00	02	07	08	02	02
PSA Lab	64	58	06	02	14	16	11	11	04
SMI Lab	64	59	05	08	05	20	13	11	02
MINI Proj.	64	58	06	08	24	13	08	04	01
Cloud Computing (MOOCs)	64	52	12	00	10	23	16	13	00
DV	01	01	00	00	00	00	00	01	00
DV Lab	01	01	00	00	00	01	00	00	00

Arrears Position – III year / I Semester

No.of students	All Pass	One Arrear	Two Arrears	Three Arrears	More than three arrears	Over all % of pass
64	46	07	04	01	06	72%

Performance overall Class Three Toppers

ROLL NO.	NAME	SGPA
21245A0201	JAKINAPALLI CHANDHANA	9.48
20241A0257	SUSANI NEHA	9.30
20241A0223 20241A0233	M GAYATHRI PISINI SATHVIKA	9.18

Class coordinator

HOD, EEE

III B.Tech - I Sem (EEE)

SECTION	Course s	EAE	PLC	SMI	MPE	HVDCT	PSA Lab	SMI Lab	MINI Proj.	CC	DV	DV Lab
	Course codes	GR20A2004	GR20A3091	GR20A3092	GR20A3093	GR20A3094	GR20A3096	GR20A3097	GR20A3141	GR20A6007	GR20A3065	GR20A3068
A	TOTAL	64	64	64	40	24	64	64	64	64	01	01
	PASS	58	60	51	39	21	58	59	58	52	01	01
	PASS(%)	90.62%	93.75%	79.68%	97.5%	87.5%	90.62%	92.18%	90.62%	81.25%	100	100
	FACULTY NAME	K Sunil Kumar	P Prashanth Kumar	Dr P Srividya devi	Dr Pakkiraiah	Dr J Sridevi	G Sandhya Rani/M N Sandhya Rani	Dr P Srividya Devi/ Dr DG Padhan/ U Vijaya Lakshmi	Dr Phaneendra Babu / D Srinivasa Rao	P Ravikanth	Dr V Srilakshmi	N Krishna Chaitanya
	FACULTY ID	176	1055	931	1593	516	888/882	931/1283/692	1563/1540	1178	923	1397

Class coordinator **HOD, EEE**

GOKARAJU RANGARAJU INSTITUTE OF ENGNEERING AND TECHNOLOGGY
Approved By AICTE, Affiliated to JNTUH, Autonomous Under UGC
Nizampet Road, Bachupally, Kukatpally, Hyderabad - 500090, Telangana, India
Tel: 7207344440, Email:info@griet.ac.in, www.griet.ac.in

STUDENT FEEDBACK

Faculty : JAMI. SRIDEVI
Subject : HVDC Transmission Systems (B.Tech, III/IV B.Tech II Semester, EEE Sec-A)
Academic Year : 2022 - 2023
Phase : Phase-3

Sl.No	Question	Excellent	Good	Average	Poor	Q.Wise Total	Q.Wise %
1	Preparation and delivery of the lessons by the teacher	1	4	1	0	18	75.00
2	Subject Knowledge	1	4	1	0	18	75.00
3	Clarity in Communication	1	4	1	0	18	75.00
4	Using Modern Teaching Aids of ICT	1	4	1	0	18	75.00
5	Creating interest on the course in the class	1	4	1	0	18	75.00
6	Maintaining discipline in the class	1	4	1	0	18	75.00
7	Encouraging and clearing doubts in the class	2	3	1	0	19	79.00
8	Punctuality	1	4	1	0	18	75.00
9	Accessibility of the teacher	1	4	1	0	18	75.00
10	Overall grading of the teacher	1	4	1	0	18	75.00
	Total	11	39	10	0		
	Total Points	**44**	**117**	**20**	**0**	181	**75.00**

No.Of Students Posted	6
Total Percentage Awarded to The Faculty	75.00
Grade of Faculty	Good

*Excellent (4) : >=90 % *Good (3) : >=75 & <90%
*Average (2) : >=60 & <75 % *Poor (1) : Below 60 %

Formula: Total Obtained Points/(Max Points(i.Excellent-4) * No.Of.Students * NoOfQuestions)

Cognitive Level Mapping
HVDC Transmission

Co's	Cognitive level learning					
	1	2	3	4	5	6
1			X			
2				X		
3					X	
4	X					
5		X				

Cognitive Learning Levels

1-REMEMBER

2-UNDERSTAND

3-APPLY

4-ANALYSE

5-EVALUATE

6-CREATE