Department of Electrical & Electronics Engineering

Course File

Flexible AC Transmission Systems (FACTS)
(Course Code: EE851PE)

IV B.Tech II Semester

2023-24

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Department of Electrical & Electronics Engineering

Flexible AC Transmission Systems (FACTS)

Check List

S.No	Name of the Format	Page No
1	Syllabus	3
2	Timetable	5
3	Vision, Mission & Quality policy	6
4	Program Educational Objectives	7
5	Program Objectives	8
6	Course Objectives	8
7	Course Outcomes	9
8	Guidelines to study the course	10
9	Course Schedule	12
10	Course Plan	12
11	Lesson Plan	20
12	Assignment Sheets	23
13	Tutorial Sheets	25
14	Assessment in relation to COb's and CO's	28
15	Mappings of CO's and PO's	28
16	Rubric for course	29
17	Mid-I and Mid-II question papers	31
18	Mid-I mark	33
19	Mid-II mark	35
20	Sample answer scripts and Assignments	37
21	Course materials like Notes, PPT's, etc.	55

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Int. Marks: 25 Ext. Marks: 75 Total Marks:100

Syllabus

ANURAG ENGINEERING COLLEGE

(An Autonomous Institution)

IV Year B.Tech. EEE - II Sem	L	T/P/D	C
	3	-/-/-	3

(EE851PE) FLEXIBLE AC TRANSMISSION SYSTEMS

(Professional Elective-V)

Prerequisites: Power Electronics, Power System Analysis & Power System Operation and Control

Course Objectives:

- To understand the fundamentals of FACTS Controllers and its types.
- To know the importance of controllable parameters and their benefits.
- To understand the objectives of static shunt compensation.
- To Control STATCOM and SVC and their comparison and the regulation of STATCOM.
- To understand the functioning and control of static series compensators.

UNIT-I: FACTS CONCEPTS

Transmission interconnections power flow in an AC system, loading capability limits, Dynamic stability considerations, importance of controllable parameters basic types of FACTS controllers, benefits from FACTS controllers.

UNIT-II: VOLTAGE SOURCE CONVERTERS

Single phase three phase full wave bridge converters transformer connections for 12 pulse operation. Three level voltage source converter, pulse width modulation converter, basic concept of current source Converters, and comparison of current source converters with voltage source converters.

UNIT-III: STATIC SHUNT COMPENSATION

Objectives of shunt compensation, mid-point voltage regulation, voltage instability prevention, improvement of transient stability, Power oscillation damping, Methods of controllable VAR generation, variable impedance type static VAR generators, switching converter type VAR generators, hybrid VAR generators.

UNIT-IV: SVC AND STATCOM

Static Var Compensator (SVC): Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR), Thyristor Switched Capacitor (TSC)- Thyristor Controlled Reactor (TCR).

Static Synchronous Compensator (STATCOM): The regulation and slope. Comparison between SVC and STATCOM.

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UNIT-V: STATIC SERIES COMPENSATORS

Concept of series capacitive compensation, improvement of transient stability, power oscillation damping, and functional requirements of GTO thyristor controlled series capacitor (GSC), thyristor switched series capacitor (TSSC), and thyristor controlled series capacitor (TCSC) Control schemes for GSC TSSC and TCSC.

Text Books:

1. Narain G.Hingorani, Laszlo Gyugyi, "Understanding FACTS – Concepts and Technology of Flexibile AC Transmission Systems", Wiley-IEEE Press, 1999.
2. Yong Hua Song & Allan T Johns, "Flexible AC Transmission Systems (FACTS)", IEE power and energy series, 2008.

Reference Books:

1. K.R. Padiyar, "Facts Controllers in Power Transmission and Distribution", New Age International Publishers, 2016.
2. R. Mohan Mathur and Rajiv K. Varma, "Thyristor- Based FACTS controllers for electrical transmission systems", IEEE Press, 2002.

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Timetable

Name of the Faculty: Mr.T.Raghu, Asst. Professor							No. of Hrs: 06	
DAY	**9:30-10:20**	**10:20-11:10**	**11:20-12:10**	**12:10-1:00**	**1:00-1:40**	**1:40-2:25**	**2:25-3:10**	**3:15-4:00**
MON	FACTS (IV EEE)				LUNCH			
TUE			FACTS (IV EEE)					
WED							FACTS (IV EEE)	
THU		FACTS (IV EEE)						
FRI				FACTS (IV EEE)				
SAT				FACTS (IV EEE)				

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Vision of the Institute

To be a premier Institute in the country and region for the study of Engineering, Technology and Management by maintaining high academic standards which promotes the analytical thinking and independent judgment among the prime stakeholders, enabling them to function responsibly in the globalized society.

Mission of the Institute

To be a world-class Institute, achieving excellence in teaching, research and consultancy in cutting-edge Technologies and be in the service of society in promoting continued education in Engineering, Technology and Management.

Quality Policy

To ensure high standards in imparting professional education by providing world-class infrastructure, top-quality-faculty and decent work culture to sculpt the students into Socially Responsible Professionals through creative team-work, innovation and research

Vision of the Department

Impart futuristic technical education and instil high patterns of discipline through our dedicated staff, which shall set global standards, making our students technologically superior and ethically strong, who in turn shall improve the quality of life of the human race.

Mission of the Department

To Impart Quality higher education and to undertake research and extension with emphasis on application and innovation that cater to the emerging societal needs of students of all sections enabling them to be globally competitive and socially responsible citizens with intrinsic values.

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Program Educational Objectives (B.Tech. – EEE)
Graduates will be able to

PEO 1: To prepare students to excel in technical profession/industry and/or higher education by acquiring knowledge in mathematics, science and engineering principles.

PEO 2: Able to formulate, analyze, design and create novel products and solutions to electrical and electronics engineering problems those are economically feasible and socially acceptable.

PEO 3: Able to adopt multi-disciplinary environments, leadership qualities, effective communication, professional ethics and lifelong learning process.

Program Outcomes (B.Tech. – EEE)
At the end of the Program, a graduate will have the ability to

PO 1: An ability to apply the knowledge of mathematics, science and engineering fundamentals.

PO 2: An ability to conduct Investigations using design of experiments, analysis and interpretation of data to arrive at valid conclusions.

PO 3: An ability to design Electrical and Electronics Engineering components and processes within economic, environmental, ethical and manufacturability constraints.

PO 4: An ability to function effectively in multidisciplinary teams.

PO 5: An ability to identify, formulate, analyze and solve Electrical and Electronics Engineering problems.

PO 6: An ability to understand professional, ethical and social responsibility.

PO 7: An ability to communicate effectively through written reports or oral presentations.

PO 8: The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.

PO 9: An ability to recognize the need and to engage in independent and life-long learning.

PO 10: Knowledge on contemporary issues.

PO 11: An ability to use the appropriate techniques and modern engineering tools necessary for engineering practice.

PO 12: An ability to demonstrate knowledge and understanding of engineering and management principles and apply these to manage projects.

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COURSE OBJECTIVES

On completion of this Subject/Course the student shall be able:

S.No	Objectives
1	To understand the fundamentals of FACTS Controllers and its types
2	To know the importance of controllable parameters and their benefits.
3	To understand the objectives of static shunt compensation.
4	To Control STATCOM and SVC and their comparison and the regulation of STATCOM.
5	To understand the functioning and control of static series compensators.

COURSE OUTCOMES

The expected outcomes of the Course/Subject are:

After completion of this course, the student will be able to

S.No	Outcomes
1.	Choose proper controller for the specific application based on system requirements.
2.	Understand various systems thoroughly and their requirements.
3.	Analyze the control circuits of Shunt Controllers for various functions viz. Transient stability Enhancement, voltage instability prevention and power oscillation damping.
4.	Control STATCOM and SVC and their comparison and the regulation of STATCOM
5.	Understand the Power and control circuits of Series Controllers

Note: Please refer to Bloom's Taxonomy, to know the illustrative verbs that can be used to state the outcomes.

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GUIDELINES TO STUDY THE COURSE / SUBJECT

Course Design and Delivery System (CDD):

- The Course syllabus is written into number of learning objectives and outcomes.
- 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, journals, etc.

The faculty be able to –

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

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COURSE SCHEDULE

The Schedule for the whole Course / Subject is:

S. No.	Description	Duration (Date)		Total No. of Periods
		From	To	
1.	**UNIT-I: FACTS CONCEPTS** Transmission interconnections power flow in an AC system, loading capability limits, Dynamic stability considerations, importance of controllable parameters basic types of FACTS controllers, benefits from FACTS controllers.	15.11.2023	02.12.2023	15
2.	**UNIT-II: VOLTAGE SOURCE CONVERTERS** Single phase three phase full wave bridge converters transformer connections for 12 pulse operation. Three level voltage source converter, pulse width modulation converter, basic concept of current source Converters, and comparison of current source converters with voltage source converters.	04.12.2023	23.12.2023	17
3.	**UNIT-III: STATIC SHUNT COMPENSATION** Objectives of shunt compensation, mid-point voltage regulation, voltage instability prevention, improvement of transient stability, Power oscillation damping, Methods of controllable VAR generation, variable impedance type static VAR generators, switching converter type VAR generators, hybrid VAR generators	27.12.2023	20.01.2024	16
4.	**UNIT-IV: SVC AND STATCOM** Static Var Compensator (SVC): Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR), Thyristor Switched Capacitor (TSC)- Thyristor Controlled Reactor (TCR). Static Synchronous Compensator (STATCOM): The regulation and slope. Comparison between SVC and STATCOM	22.01.2024	13.02.2024	16
5.	**UNIT-V: STATIC SERIES COMPENSATORS** Concept of series capacitive compensation, improvement of transient stability, power oscillation damping, and functional requirements of GTO thyristor controlled series capacitor (GSC), thyristor switched series capacitor (TSSC), and thyristor controlled series capacitor (TCSC) Control schemes for GSC TSSC and TCSC.	14.02.2024	04.04.2024	14

Total No. of Instructional periods available for the course: 78 Hours

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SCHEDULE OF INSTRUCTIONS - COURSE PLAN

Unit No.	Lesson No.	Date	No. of Periods	Topics / Sub-Topics	Objectives & Outcomes Nos.	References (Textbook, Journal)
1.	1	15.11.2023	1	Introduction to FACTS	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	2	16.11.2023	1	Need for Transmission interconnections	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	3	17.11.2023 & 18.11.2023	2	Power flow in an AC system	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	4	20.11.2023	1	Loading capability limits	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	5	21.11.2023 & 22.11.2023	2	Dynamic stability considerations	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	6	23.11.2023	1	Importance of controllable parameters	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	7	24.11.2023	1	Basic types of FACTS controllers	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	8	25.11.2023 & 28.11.2023	2	Basic types of FACTS controllers	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
	9	01.12.2023 & 02.12.2023	2	Benefits from FACTS controllers	1 1	Understanding FACTS – N G Hingorani, L Gyugyi
2.	1	04.12.2023	1	Basic concepts of voltage source converter	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
	2	05.12.2023 & 06.12.2023	2	Single phase full wave bridge converters	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
	3	07.12.2023 & 08.12.2023	2	Three phase full wave bridge converters	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
	4	11.12.2023 & 12.12.2023	2	Transformer connections for 12 pulse operation	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
	5	13.12.2023 & 14.12.2023	2	Three level voltage source converter	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
	6	15.12.2023 & 16.12.2023	2	Pulse width modulation converter	2 2	Understanding FACTS – N G Hingorani, L Gyugyi

	7	18.12.2023 & 19.12.2023	2	Basic concept of current source converters	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
	8	21.12.2023	1	Comparison of CSI and VSI	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
	9	23.12.2023	1	Revision	2 2	Understanding FACTS – N G Hingorani, L Gyugyi
3.	1	27.12.2023 & 28.12.2023	2	Objectives of shunt compensation	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	2	29.12.2023	1	mid-point voltage regulation	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	3	02.01.2024 & 03.01.2024	2	voltage instability prevention	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	4	04.01.2024 & 05.01.2024	2	improvement of transient stability	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	5	06.01.2024	1	Power oscillation damping	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	6	08.01.2024	1	Methods of controllable VAR generation	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	7	09.01.2024	1	variable impedance type static VAR generators	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	8	18.01.2024 & 19.01.2024	2	switching converter type VAR generators	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
	9	20.01.2024	1	hybrid VAR generators	3 3	Understanding FACTS – N G Hingorani, L Gyugyi
4	1	22.01.2024	1	Static Var Compensator (SVC)	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	2	23.01.2024 & 24.01.2024	2	Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR)	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	3	25.01.2024 & 27.01.2024	2	Thyristor Switched Capacitor (TSC)	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	4	29.01.2024 & 30.01.2024	2	Thyristor Controlled Reactor (TCR)	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	5	31.01.2024	1	Static Synchronous Compensator (STATCOM)	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	6	01.02.2024	2	The regulation and slope	4	Understanding

		& 02.02.2024			4	FACTS – N G Hingorani, L Gyugyi
	7	05.02.2024 & 06.02.2024	2	Comparison between SVC and STATCOM.	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	8	07.02.2024	1	Comparison between SVC and STATCOM.	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	9	08.02.2024 & 09.02.2024	2	Revision	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
	10	13.02.2024	1	Revision	4 4	Understanding FACTS – N G Hingorani, L Gyugyi
5	1	14.02.2024 & 15.02.2024	2	Concept of series capacitive compensation	5 5	Understanding FACTS – N G Hingorani, L Gyugyi
	2	16.02.2024	1	improvement of transient stability	5 5	Understanding FACTS – N G Hingorani, L Gyugyi
	3	19.02.2024	1	power oscillation damping	5 5	Understanding FACTS – N G Hingorani, L Gyugyi
	4	20.02.2024 & 21.02.2024	2	GTO thyristor controlled series capacitor (GSC)	5 5	Understanding FACTS – N G Hingorani, L Gyugyi
	5	22.02.2024	1	Thyristor switched series capacitor (TSSC)	5 5	Understanding FACTS – N G Hingorani, L Gyugyi
	6	23.03.2024	1	Thyristor controlled series capacitor (TCSC)	5 5	Understanding FACTS – N G Hingorani, L Gyugyi
	7	26.03.2024 & 27.03.2024	2	Control schemes for GSC TSSC and TCSC	5 5	Understanding FACTS – N G Hingorani, L Gyugyi
	8	28.03.2024 & 01.04.2024	2	Revision of Unit I & II	1, 2 1, 2	Understanding FACTS – N G Hingorani, L Gyugyi
	9	02.04.2024 & 03.04.2024	2	Revision of Unit III & IV	3, 4 3, 4	Understanding FACTS – N G Hingorani, L Gyugyi

Note:

1. Ensure that all topics specified in the course are mentioned.
2. Additional topics covered, if any, may also be specified in bold.
3. Mention the corresponding course objective and outcome numbers against each topic.

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LESSON PLAN

FACTS				
Unit No.	**Lesson No.**	**Date**	**Day Of The Week**	**Topics / Sub-Topics**
1	1	15-11-2023	Wed	Introduction to FACTS
	2	16-11-2023	Thu	Transmission interconnections
	3	17-11-2023	Fri	power flow in an AC system
	4	18-11-2023	Sat	power flow in an AC system
	5	20-11-2023	Mon	loading capability limits
	6	21-11-2023	Tue	Dynamic stability considerations
	7	22-11-2023	Wed	Dynamic stability considerations
	8	23-11-2023	Thu	importance of controllable parameters
	9	24-11-2023	Fri	basic types of FACTS controllers
	10	25-11-2023	Sat	basic types of FACTS controllers
	11	28-11-2023	Tue	basic types of FACTS controllers
	12	1/12/2023	Fri	benefits from FACTS controllers
	13	2/12/2023	Sat	benefits from FACTS controllers
2	14	4/12/2023	Mon	Basic concepts of voltage source converter
	15	5/12/2023	Tue	Single phase full wave bridge converter
	16	6/12/2023	Wed	Single phase full wave bridge converter
	17	7/12/2023	Thu	Three phase full wave bridge converter
	18	8/12/2023	Fri	Three phase full wave bridge converter
	19	11/12/2023	Mon	transformer connections for 12 pulse operation
	20	12/12/2023	Tue	transformer connections for 12 pulse operation
	21	13-12-2023	Wed	Three level voltage source converter
	22	14-12-2023	Thu	Three level voltage source converter
	23	15-12-2023	Fri	pulse width modulation converter

	24	16-12-2023	Sat	pulse width modulation converter
	25	18-12-2023	Mon	basic concept of current source Converters
	26	19-12-2023	Tue	basic concept of current source Converters
	27	21-12-2023	Thu	comparison of current source converters with voltage source converters
	28	23-12-2023	Sat	Revision
3	29	27-12-2023	Wed	Objectives of shunt compensation
	30	28-12-2023	Thu	Objectives of shunt compensation
	31	29-12-2023	Fri	mid-point voltage regulation
	32	2/1/2024	Tue	voltage instability prevention
	33	3/1/2024	Wed	voltage instability prevention
	34	4/1/2024	Thu	improvement of transient stability
	35	5/1/2024	Fri	improvement of transient stability
	36	6/1/2024	Sat	Power oscillation damping
	37	8/1/2024	Mon	Methods of controllable VAR generation
	38	9/1/2024	Tue	variable impedance type static VAR generators
	39	18-01-2024	Thu	switching converter type VAR generators
	40	19-01-2024	Fri	switching converter type VAR generators
	41	20-01-2024	Sat	hybrid VAR generators
4	42	22-01-2024	Mon	Static Var Compensator (SVC)
	43	23-01-2024	Tue	Static Var Compensator (SVC)
	44	24-01-2024	Wed	Thyristor Controlled Reactor (TCR)
	45	25-01-2024	Thu	Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR)
	46	27-01-2024	Sat	Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR)
	47	29-01-2024	Mon	Thyristor Switched Capacitor (TSC)- Thyristor Controlled Reactor (TCR).
	48	30-01-2024	Tue	Thyristor Switched Capacitor (TSC)- Thyristor Controlled Reactor (TCR).

	49	31-01-2024	Wed	Static Synchronous Compensator (STATCOM)
	50	1/2/2024	Thu	The regulation and slope
	51	2/2/2024	Fri	The regulation and slope
	52	5/2/2024	Mon	Comparison between SVC and STATCOM
	53	6/2/2024	Tue	Comparison between SVC and STATCOM
	54	7/2/2024	Wed	Comparison between SVC and STATCOM
	55	8/2/2024	Thu	Revision
	56	9/2/2024	Fri	Revision
	57	13-2-2024	Tue	Revision
5	58	14-2-2024	Wed	Concept of series capacitive compensation
	59	15-2-2024	Thu	Concept of series capacitive compensation
	60	16-2-2024	Fri	improvement of transient stability
	61	19-2-2024	Mon	power oscillation damping
	62	20-2-2024	Tue	GTO thyristor controlled series capacitor (GCSC)
	63	21-2-2024	Wed	GTO thyristor controlled series capacitor (GCSC)
	64	22-2-2024	Thu	thyristor switched series capacitor (TSSC)
	65	23-3-2024	Sat	thyristor controlled series capacitor (TCSC)
	66	26-3-2024	Tue	Control schemes for GSC TSSC and TCSC
	67	27-3-2024	Wed	Control schemes for GSC TSSC and TCSC
	68	28-3-2024	Thu	Revision
	69	1/4/2024	Mon	Revision
	70	2/4/2024	Tue	Revision
	71	3/4/2024	Wed	Revision

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ASSIGNMENT – 1

Answer all the questions. Each question carry equal marks **Total Marks=5**

Q.NO	**Question**	**Course Outcome**	**Bloom's Level**
UNIT- I			
1.	Discuss the dynamic stability considerations of a transmission interconnection.	CO 1	L3
2.	What are the opportunities for FACTS technology? Describe the relative importance of controllable parameters.	CO 1	L2
UNIT- II			
3.	Explain the principle of 3-level voltage source converter.	CO 2	L2
4.	What is pulse number of a converter? With the help of schematic and waveforms, explain the transformer connections for 12-pulse operation of three-phase full bridge converter	CO 2	L3
UNIT- III			
5.	What are the objectives of reactive shunt compensation? Explain how improvement in transient stability can be obtained by providing shunt compensation.	CO 3	L3

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ASSIGNMENT – II

Answer all the questions. Each question carry equal marks **Total Marks=5**

Q.NO	**Question**	**Course Outcome**	**Bloom's Level**
UNIT- III			
1.	Describe the switching converter type VAR generators with necessary diagrams and expressions.	CO 3	L3
UNIT- IV			
2.	Compare SVC with STATCOM.	CO 4	L4
3.	With a neat circuit diagram and waveforms explain working of STATCOM.	CO 4	L3
UNIT- V			
4.	What is meant by variable impedance type series compensator? Explain the operation of GTO Thyristor Controlled Series Capacitor.	CO 5	L3
5.	Explain the objectives of static series compensation.	CO 5	L2

TUTORIAL – 1

This tutorial corresponds to Unit No. 1 (Objective Nos.: 1, Outcome Nos.: 1)

1. Define the term FACTS.
2. What are the main areas of application of FACTS devices?
3. What are the advantages of FACTS controllers?

TUTORIAL – 2

This tutorial corresponds to Unit No. 2 (Objective Nos.: 2, Outcome Nos.: 2)

1. What is voltage source converter?
2. What is current source converter?
3. What is advantage of increasing the pulse number in converters?

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TUTORIAL – 3

This tutorial corresponds to Unit No. 3 (Objective Nos.: 3, Outcome Nos.: 3)

1. What is compensation?
2. What is shunt compensation?
3. What are the objectives of shunt compensation?

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TUTORIAL – 4

This tutorial corresponds to Unit No. 4 (Objective Nos.: 3, Outcome Nos.: 3)

1. What is Static synchronous compensator (STATCOM)?
2. What is static var compensator (SVC)?
3. Draw the schematic diagram for FC-TCR.

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TUTORIAL – 5

This tutorial corresponds to Unit No. 5 (Objective Nos.: 5, Outcome Nos.: 5)

1. What is series compensation?
2. What are the objectives of series compensation?
3. What is static synchronous series compensator (SSSC)?

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EVALUATION STRATEGY

Target (s)

a. Percentage of Pass : 95%

Assessment Method (s) (Maximum Marks for evaluation are defined in the Academic Regulations)

a. Assignments
b. Online Quiz (or) Seminars
c. Continuous Internal Assessment
d. Semester / End Examination

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COURSE COMPLETION STATUS

Actual Date of Completion & Remarks if any

Units	Remarks	Objective No. Achieved	Outcome No. Achieved
Unit 1	completed on 02.12.2023	1	1
Unit 2	completed on 23.12.2023	2	2
Unit 3	completed on 20.01.2024	3	3
Unit 4	completed on 13.02.2024	4	4
Unit 5	completed on 03.04.2024	5	5

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Mappings

1. **Course Objectives-Course Outcomes Relationship Matrix**
(Indicate the relationships by mark "X")

Course-Outcomes Course-Objectives	1	2	3	4	5
1	H				
2		H			
3			H	M	
4				H	
5					H

2. **Course Outcomes-Program Outcomes (POs) & PSOs Relationship Matrix**
(Indicate the relationships by mark "X")

P-Outcomes C-Outcomes	a	b	c	d	e	f	g	h	i	j	k	l	PSO 1	PSO 2
1	H												L	
2	M		H	M	L						M		M	H
3	H	M	L		M			H			L		H	M
4	M	M	H		H			L			M		M	
5	L	H	M		H			M			M			L

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Rubric for Evaluation

Performance Criteria	**Unsatisfactory**	**Developing**	**Satisfactory**	**Exemplary**
	1	**2**	**3**	**4**
Research & Gather Information	Does not collect any information that relates to the topic	Collects very little information some relates to the topic	Collects some basic Information most relates to the topic	Collects a great deal of Information all relates to the topic
Fulfill team role's duty	Does not perform any duties of assigned team role.	Performs very little duties.	Performs nearly all duties.	Performs all duties of assigned team role.
Share Equally	Always relies on others to do the work.	Rarely does the assigned work - often needs reminding.	Usually does the assigned work - rarely needs reminding.	Always does the assigned work without having to be reminded
Listen to other team mates	Is always talking—never allows anyone else to speak.	Usually doing most of the talking-- rarely allows others to speak	Listens, but sometimes talks too much.	Listens and speaks a fair amount.

Department of Electrical & Electronics Engineering
Mid-I and Mid-II question papers

IV B.Tech II Semester I MID Examinations, Jan 2024

Branch: EEE		**Max. Marks: 20**
Date: 10.01.2024 AN	**Subject :Flexible AC Transmission Systems**	**Time: 90 Min.**

PART-A

Answer all the questions **5 X 1M=5 Marks**

Q.NO	Question	Course Outcome	Bloom's Level
1.	What are the basic types of FACTS controllers?	CO1	L1
2.	Mention any one benefit of using FACTS controllers.	CO1	L1
3.	What is voltage source converter?	CO2	L1
4.	What is advantage of increasing the pulse number in converters?	CO2	L1
5.	What is shunt compensation?	CO3	L1

PART-B

Answer the following **3 X 5M=15 Marks**

Q.NO	Question	Course Outcome	Bloom's Level
6.	What limits the loading capability of transmission lines?	CO1	L2
	OR		
7.	Explain briefly about the following FACTS controllers (a) Combined Series-Series Controller (b) Combined Series-Shunt Controller	CO1	L2
8.	With the help of neat sketch, explain the operation of three phase full wave bridge converter and draw its relevant waveforms.	CO2	L2
	OR		
9.	Discuss about the transformer connection for 12-pulse operation of converter.	CO2	L3
10.	What are the objectives of shunt compensation? Explain briefly about midpoint voltage regulation for line segmentation?	CO3	L2
	OR		
11.	Discuss about end of line voltage support to radial transmission system in order to prevent voltage instability.	CO3	L3

Department of Electrical & Electronics Engineering

IV B.Tech II Semester II MID Examinations, April 2024

Branch: EEE		**Max. Marks: 20**
Date: 08.04.2024	**Subject : FACTS**	**Time: 90 Min.**

PART-A

Answer all the questions **5 X 1M=5 Marks**

Q.NO	Question	Course Outcome	Bloom's Level
1.	What is thyristor switched capacitor?	CO3	L1
2.	List out any one major functions of TSC –TCR type var generator	CO4	L1
3.	Draw the schematic diagram for FC-TCR.	CO4	L1
4.	What is sub-synchronous resonance?	CO5	L1
5.	What is GTO thyristor controlled series compensator?	CO5	L1

PART-B

Answer the following **3 X 5M=15 Marks**

Q.NO	Question	Course Outcome	Bloom's Level
6.	Explain basic operation of Thyristor Controlled Reactor (TCR) with necessary waveforms.	CO3	L2
	OR		
7.	Describe the variable impedance type VAR generators with necessary diagrams and expressions.	CO3	L3
8.	Compare SVC and STATCOM with respect to transient stability.	CO4	L4
	OR		
9.	Compare between fixed capacitor thyristor controlled reactor (FC-TCR) with thyristor switched capacitor thyristor controlled reactor (TSC-TCR).	CO4	L4
10.	Explain the voltage stability enhancement and power oscillation damping with series capacitive compensation.	CO5	L2
	OR		
11.	Explain the working of thyristor controlled series capacitor (TCSC). Draw and discuss their V-I operating characteristics in voltage control mode and reactance control mode.	CO5	L3

Department of Electrical & Electronics Engineering
Mid-I marks

First Internal Examination Marks

Programme**: B.Tech** Year: **IV** Course: **Theory** **A.Y: 2023-24**

Course: FACTS Section: - Faculty Name: Mr.T.Raghu

S. No	Roll No	Assignment Marks (5)	Mid Marks (20)	Total Marks (25)
1	19C11A0201	5	19	24
2	20C11A0201	5	17	22
3	20C11A0202	5	16	21
4	20C11A0203	5	19	24
5	20C11A0204	5	15	20
6	20C11A0205	5	13	18
7	20C11A0206	AB	AB	AB
8	20C11A0207	5	10	15
9	20C11A0208	5	10	15
10	20C11A0209	5	9	14
11	20C11A0210	5	18	23
12	20C11A0211	5	17	22
13	20C11A0212	5	19	24
14	20C11A0214	AB	AB	AB
15	20C11A0215	5	13	18
16	20C11A0216	AB	AB	AB
17	20C11A0217	5	15	20
18	20C11A0218	5	17	22
19	20C11A0219	5	13	18
20	20C11A0220	5	14	19
21	20C11A0221	5	8	13
22	21C15A0201	5	19	24
23	21C15A0202	5	19	24
24	21C15A0203	5	14	19
25	21C15A0204	5	AB	05
26	21C15A0205	5	19	24
27	21C15A0206	5	9	14
28	21C15A0207	5	19	24
29	21C15A0208	5	17	22
30	21C15A0209	5	13	18
31	21C15A0210	5	12	17
32	21C15A0211	5	15	20
33	21C15A0212	5	18	23
34	21C15A0213	5	15	20
35	21C15A0214	5	17	22
36	21C15A0215	5	14	19

37	21C15A0216	5	12	17
38	21C15A0217	5	13	18
39	21C15A0218	5	15	20
40	21C15A0219	5	19	24
41	21C15A0220	5	17	22
42	21C15A0221	5	14	19
43	21C15A0222	5	19	24
44	21C15A0223	5	18	23
45	21C15A0224	5	13	18
46	21C15A0225	5	15	20
47	21C15A0226	5	17	22
48	21C15A0227	5	20	25
49	21C15A0228	5	19	24
50	21C15A0229	5	11	16
51	21C15A0230	5	15	20
52	21C15A0231	5	17	22
53	21C15A0232	5	11	16
54	21C15A0233	5	18	23
55	21C15A0234	5	13	18
56	21C15A0235	5	16	21
57	21C15A0236	5	11	16
58	21C15A0237	5	15	20
59	21C15A0238	5	12	17

No. of Absentees: 04

Total Strength: 59

Department of Electrical & Electronics Engineering
Mid-II marks

Second Internal Examination Marks

Programme**: B.Tech** Year: **IV** Course: **Theory** **A.Y: 2023-24**

Course: FACTS Section: - Faculty Name: Mr.T.Raghu

S. No	Roll No	Assignment Marks (5)	Mid Marks (20)	Total Marks (25)
1	19C11A0201	5	12	17
2	20C11A0201	5	12	17
3	20C11A0202	5	11	16
4	20C11A0203	5	16	21
5	20C11A0204	5	10	15
6	20C11A0205	5	11	16
7	20C11A0206	AB	AB	AB
8	20C11A0207	5	8	13
9	20C11A0208	5	12	17
10	20C11A0209	5	8	13
11	20C11A0210	5	17	22
12	20C11A0211	5	15	20
13	20C11A0212	5	17	22
14	20C11A0214	AB	AB	AB
15	20C11A0215	5	13	18
16	20C11A0216	AB	AB	AB
17	20C11A0217	5	10	15
18	20C11A0218	5	16	21
19	20C11A0219	5	14	19
20	20C11A0220	5	14	19
21	20C11A0221	5	11	16
22	21C15A0201	5	20	25
23	21C15A0202	5	20	25
24	21C15A0203	5	8	13
25	21C15A0204	5	12	17
26	21C15A0205	5	18	23
27	21C15A0206	5	9	14
28	21C15A0207	5	18	23
29	21C15A0208	5	17	22
30	21C15A0209	5	15	20
31	21C15A0210	5	13	18
32	21C15A0211	5	8	13
33	21C15A0212	5	18	23
34	21C15A0213	5	16	21
35	21C15A0214	5	17	22
36	21C15A0215	5	11	16

37	21C15A0216	5	12	17
38	21C15A0217	5	9	14
39	21C15A0218	5	14	19
40	21C15A0219	5	11	16
41	21C15A0220	5	17	22
42	21C15A0221	5	11	16
43	21C15A0222	5	18	23
44	21C15A0223	5	16	21
45	21C15A0224	5	9	14
46	21C15A0225	5	9	14
47	21C15A0226	5	8	13
48	21C15A0227	5	17	22
49	21C15A0228	5	18	23
50	21C15A0229	5	13	18
51	21C15A0230	5	13	18
52	21C15A0231	5	13	18
53	21C15A0232	5	13	18
54	21C15A0233	5	16	21
55	21C15A0234	5	9	14
56	21C15A0235	5	15	20
57	21C15A0236	5	12	17
58	21C15A0237	5	12	17
59	21C15A0238	5	11	16

No. of Absentees: **03**

Total Strength: **59**

ANURAG ENGINEERING COLLEGE

(An Autonomous Institution)

(Approved by AICTE, New Delhi, Affiliated to JNTUH, Hyderabad, Accredited by NAAC with A+ Grade)

Ananthagiri (V & M), Kodad, Suryapet (Dist), Telangana.

Program		
B.Tech. ✓	M.Tech.	M.B.A.

YEAR	SEMESTER	MID EXAMINATION
IVth	IInd	1st

Regulation : R18

Branch or Specialization: ECE

HALL TICKET NO.

2	1	C	1	5	A	0	2	1	5

Signature of Student: K Pavan Sai

Course: Flexible AC transmission Sytems

Signature of invigilator with date: Reddy 10/1/24

Q.No. and Marks Awarded

1	2	3	4	5	6	7	8	9	10	11
1	1	0	0	0	-	4	4	-	4	-

Signature of the Evaluator:

Maximum Marks: 20

Marks Obtained: 14

(Start Writing From Here)

1) i) shunt Controller
ii) series Controller
(iii) series-series Controller
iv) shunt - series Controller
v) STATCOM
vi) ~~SSTA~~.

2) i) Flexible control of transmission line according to the needs of the loads
(ii) calculation of thermal and elasticity losses and work according to them and make transmission efficiently.

3) VSS is used to control the Voltage according to the needs and stable the system.
i) VSS can helpful to control the heavy load
ii) cheap in cost compared to the CSS

4) i) It helps to control over high current and Voltage losses and helps to Increase efficiency

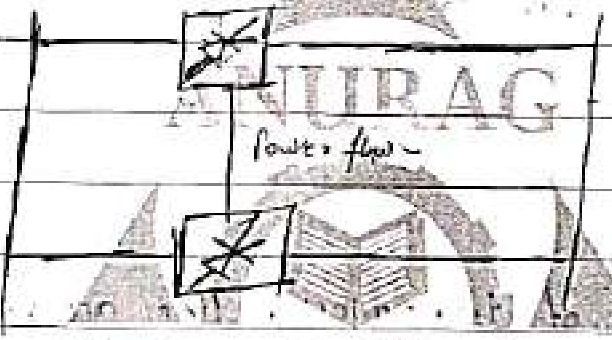
5) Compensation of current according to the required controls by adjusting the controllers Impedence is known for Shunt Compensation.

PART-B

6) The limitations for the loading Capability of transmission line mostly depends upon three factors those are
i) thermal.
ii) ~~Dielectricity~~ Dielarity.
iii) stability

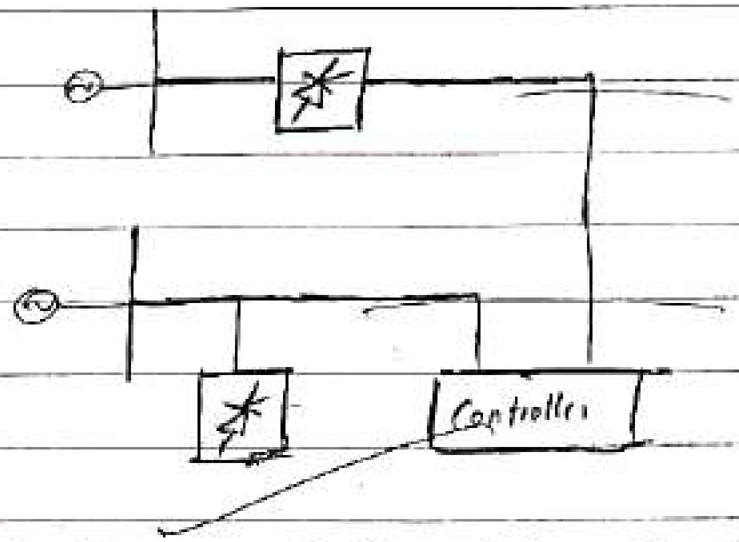
PART-B

7) a) **Combined Series - Series Controllers:-**



the series Controller helps to inject the Voltage according to the ph angle and Impedence of system according to the transmission system requirement and power flow without Interference in this type of Series-series Controller and helps to Control the ph angle and direction of the supply.

b) Combined Series-shunt Controllers:

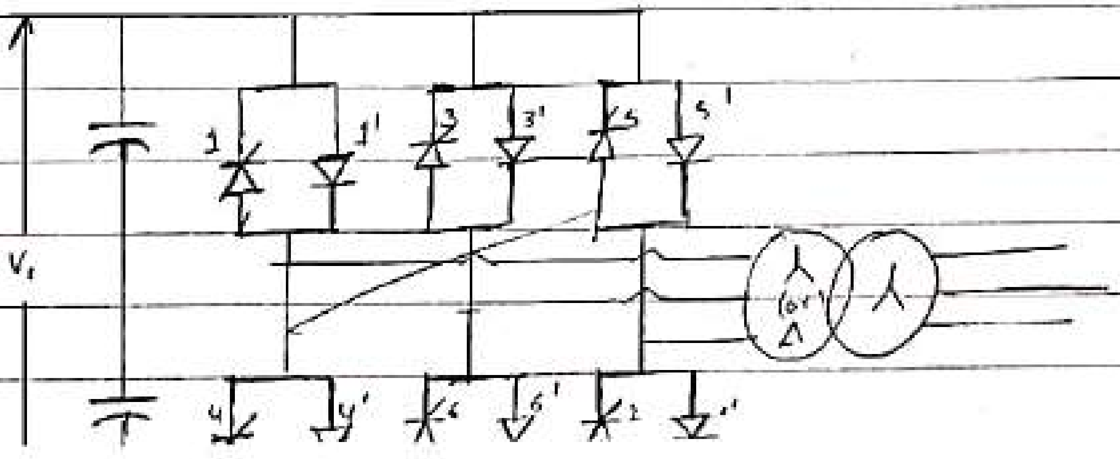


* shunt type controller helps to Inject the Current according system requirement in order to maintain the Voltage stability and to reduce power Interference

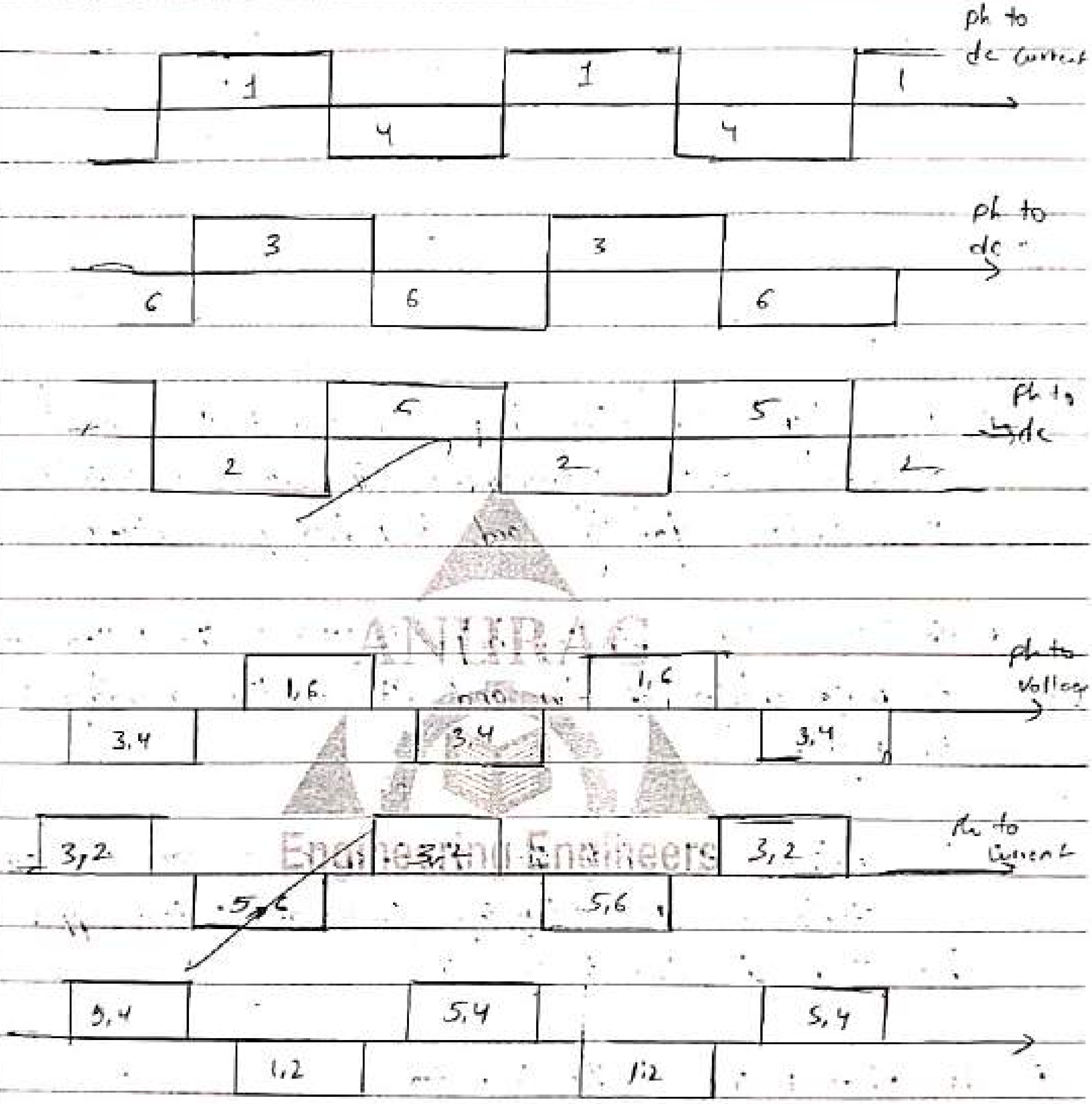
* the Series type Controller helps to Inject the Voltage and to make changes of flux and flow direction according to the required.

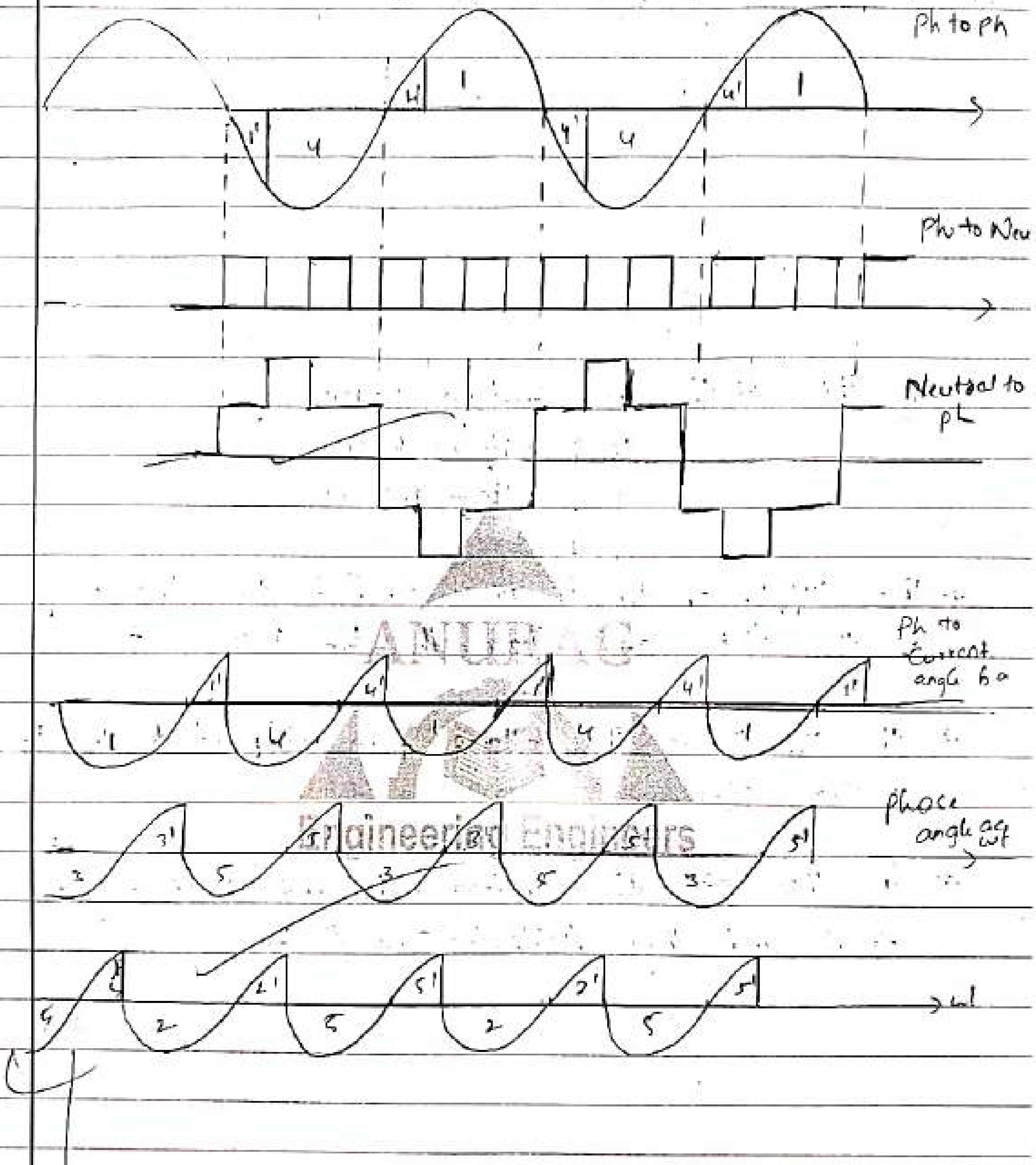
* by combining the both the shunt-series we can maintain the stable and Non Interupting Current and Voltage supply but it maybe slow in operation.

3) three phase fullwave bridge Converter:

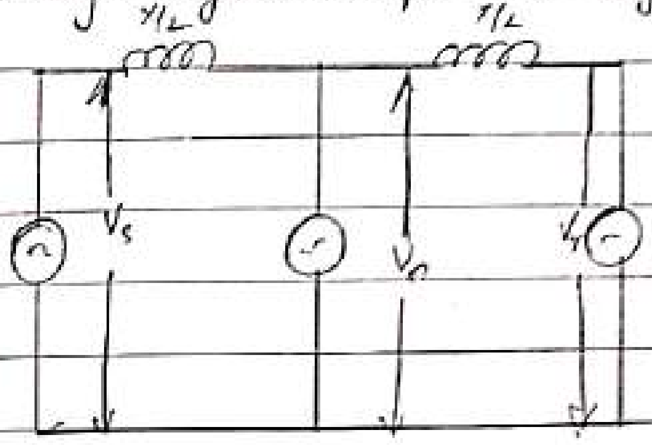


wave forms:-


ph to dc current
1
4
1
4
1
ph to dc
3
6
6
3
6
ph to dc
5
2
2
5
2
ph to voltage
1,6
1,6
3,4
3,4
3,4
ph to current
3,2
3,2
3,2
5,6
5,6
5,4
5,4
5,4
1,2
1,2

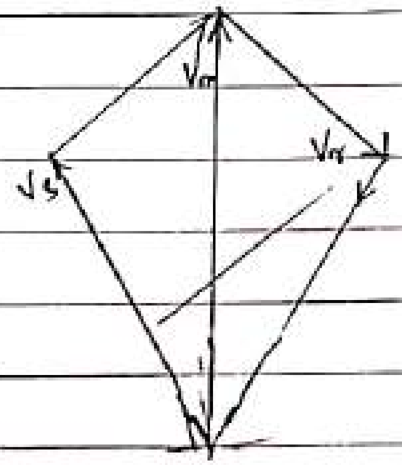

Ph to ph
1'
4
4'
1
4'
4
4'
1
Ph to Neu
Neutral to ph
Ph to Current angle 6 α
1'
1
4'
4
1'
1
4'
4
1'
1
phase angle 90 ωt
2
3'
5
5'
3
5'
5
3
5'
5
5'
2
2'
5
5'
2
2'
5
5'
ωt

10) Mid-point Voltage regulation for line Segmentation:

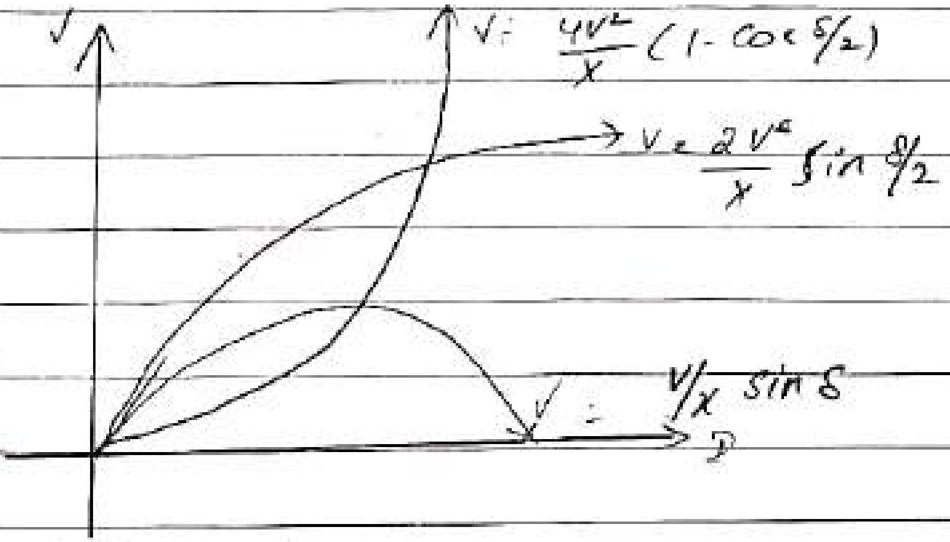


In this ckt the V_s = Voltage source
V_m = midpoint Voltag
V_r = Voltage receiver.

- the supply of V_s is now sended to the midpoint of the ckt and there the V_m receives it
- the V_m sends the Voltage from midpoint to the V_r reciever side
- In this ckt the Sending end and Recieving end equal and they distributed by the V_m



$V_m = V_s = V_r = V_g$



Objectives of shunt Compensation:-

* the shunt Compensation is more expensive because of th predetermictic values of it and it makes it expensive compared to series

*

MID II ASSIGNMENT

NAME : M. SaiVarun.

HTNO : 20C11A0218.

BRANCH : EEE

YEAR : IV Year II Semester

SUBJECT : FACTS.

$\frac{25}{5}$ = ⑤

1. Discuss the dynamic stability considerations of a transmission interconnection?

A: Powerflow & dynamic stability considerations of a transmission interconnection:

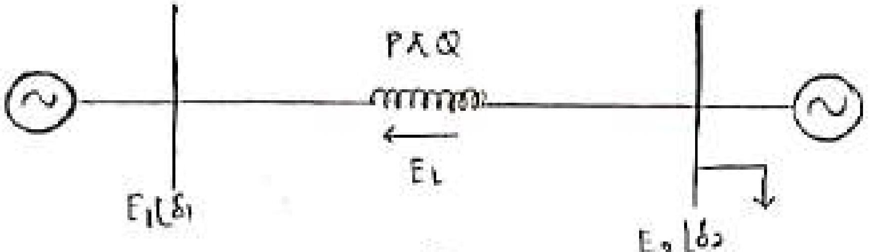


Fig ⓐ

E_L is the difference between $E_1\angle\delta_1$ and $E_2\angle\delta_2$.

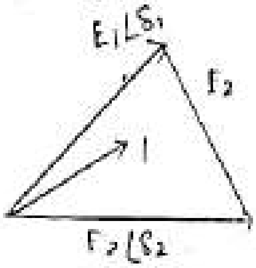


Fig ⓑ

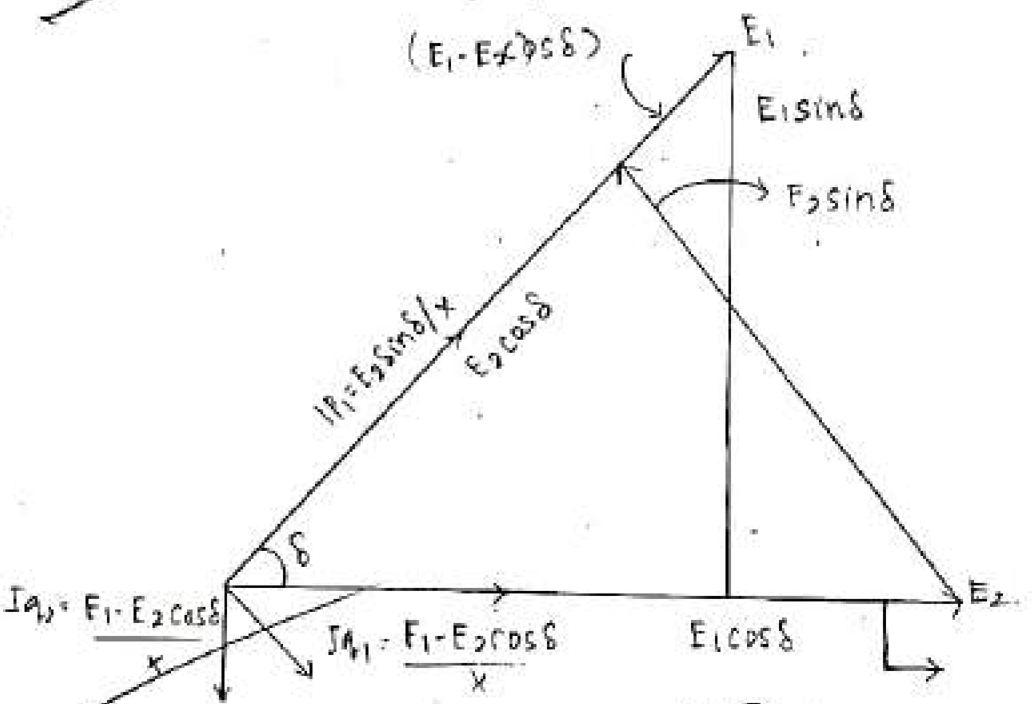


Fig ⓒ

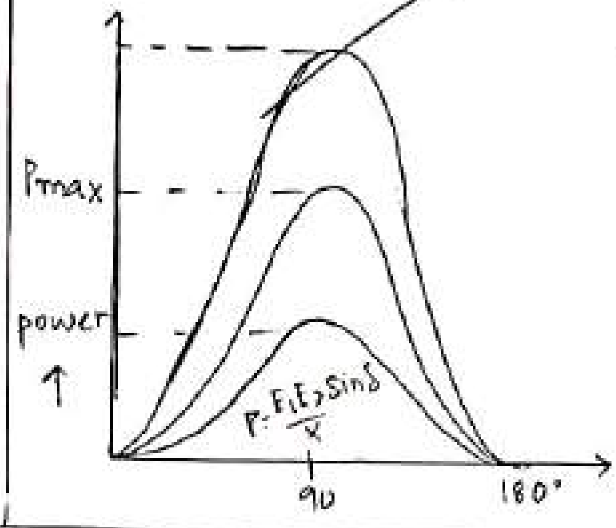


Fig ⓓ

Fig ⓔ

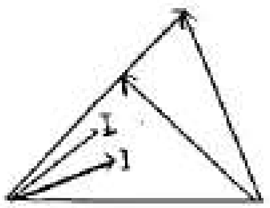


Fig ⓕ

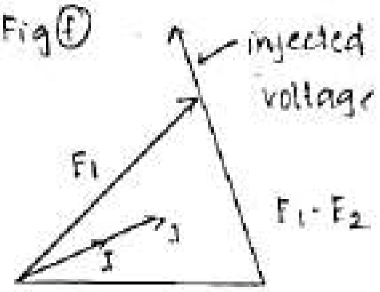


Fig ⓖ

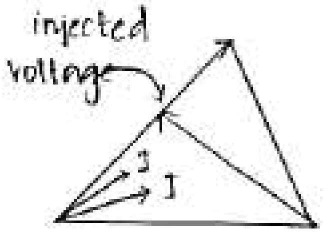


Fig ⓐ shows a simplified case of power flow on a transmission line. Locations 1 and 2 could be any transmission substations connected by a transmission line.

Where E_1 and E_2 are the magnitudes of the bus voltages with an angle δ b/w the two. The line is assumed to have inductive impendence x, and the line resistance & capacitance are ignored.

Fig ⓑ The driving voltage drop (E_L) in the line is the phasor difference b/w E_1 and E_2 the two line voltage phasors. The line current magnitude is given by

$I = E_L L_x$ and lags E_L by 90°.

For a typical line, angle δ and corresponding driving voltage (or) voltage drop along the line, is small compared to line voltages.

From the phasor diagram (c)

→ The active component of current flow at E_1 is:

$$IP_1 = E\sin\delta/_x$$

→ Reactive component of current flow at E_2 is:

$$IP_1 = (E_1 - E_2\cos\delta)/_x$$

Thus, active power at the E_1 end: $P_1 = E_1(E_2\sin\delta)/_x$.

→ Reactive power at the E_1 end:

$$Q_1 = E_1(E_1 - E_2\cos\delta)/x \quad \text{-----}\rightarrow (1.1)$$

Similarly, active component of currentflow at E_2 is:

$$I_{P_2} = E_1\sin\delta/x$$

→ Reactive component of currentflow at E_2 is:

$$I_{P_2} = E_2 - E_1\cos\delta/x$$

Thus, active power at E_2 end is $P_2 = E_2(E_1\sin\delta)/x$.

→ Reactive power at E_2 end is $Q_2 = E_2(E_2 - E_1\cos\delta)/x$ --→(1.2)

Naturally P_1 & P_2 are same : $P = E_1(E_2\sin\delta)/x$ --→ (1.3)

Because, it is assumed that there are no active power loses

2. What are the oppurtunities for FACTS technology? Describe the relative importance for controllable parameters.

Oppurtunities for FACTS :

- For controlling power and enhancing the usable capacity.
- FACTS controllers controls the interrelated parameters that govern the operation of tr.system including series impedence shunt impedance, current, voltage, phase angle & damping of oscillations at various frequencies below the rated freq.
- It enable a line to carry power closer to its thermal rating.
- The FACTS technology is not a single, high power controller but rather a collection of controllers, which can be applied individual (or) incoordination with others to control one (or) more of the interrelated system parameters.

Relative importance of controllable parameters:

* Control of the line impendence X can provide a powerful means of current control

* When the angle is not large, which is often the case, control of x

* Control of angle which in turn controls the driving voltage, provides a powerful means of controlling the current flow.

* Because per unit line impendence is usually small fraction of the line voltage, the MVA rating of a series controller will often be a small fraction of throughout line MVA

* When the angle is not large, controlling the magnitude of one or other line voltages can be a very cost-effective means control of reactive power flow throughout interconnection

* Combination of line impedence control with a series controllers and voltage regulation with a shunt controller can also provide a cost-effective means to control both the active and reactive power flow b/w 2 system.

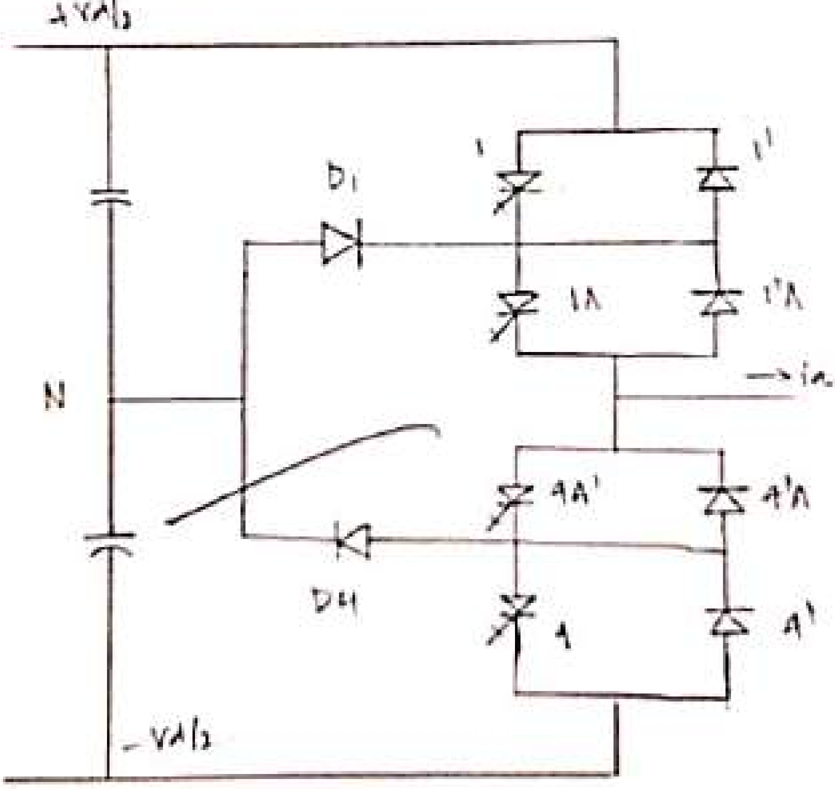
* Injecting voltage in series with the line & the phase angle with respect to driving voltage can control magnitude & the phase of line current. This means that injecting a voltage phasor with variable.

* Phase angle can provide a powerful means of precisely controlling the active & reactive power flow.

* Injecting a voltage in series with the line, ⊥^{ct} to current flow an ↑se (or) ↓se the magnitude of current flow. Since the current flow lags the driving voltage by 90°, this means injection of reactive power in series can provide a powerful means by controlling the line current & hence active power when the angle is not large.

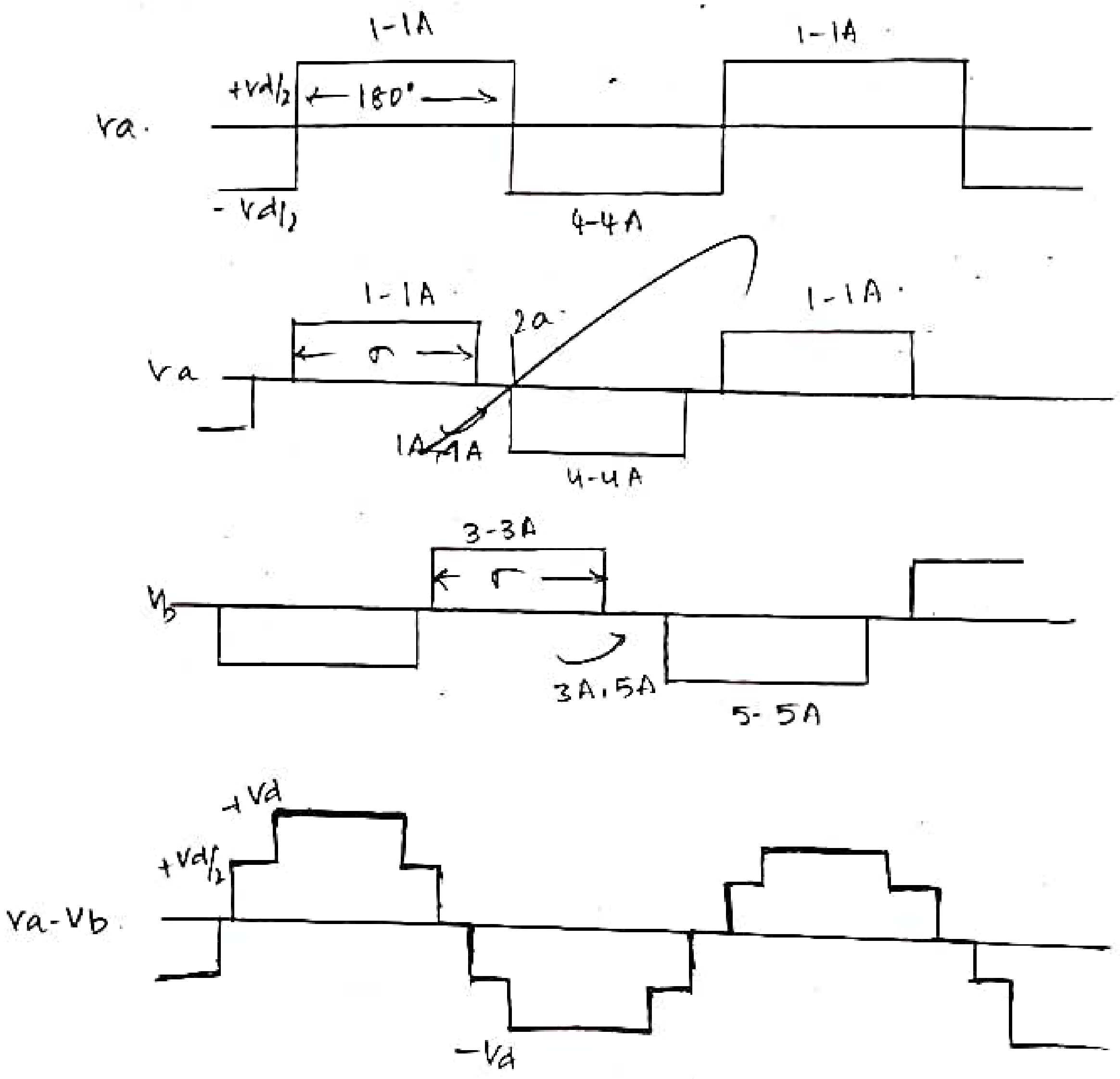
5. Explain the principle of a level voltage source convertor?

Three-level voltage-sourced convertor:



One phase-leg of a three level converter is shown in fig above. The other two phase legs would be connected across the same dc bus bars and the clamping diodes connected to the same midpoint N of dc capacitor. It is seen that each half of phase leg is split into two series connected valves ie, 1-1' is sp' into 1-1' and 1A - 1'A. The midpoint of split valves is

connected by diodes and D4 to the midpoint N as shown.
On face of it, this may seem like doubling the no. of valves from two to two to four extra diode valves.



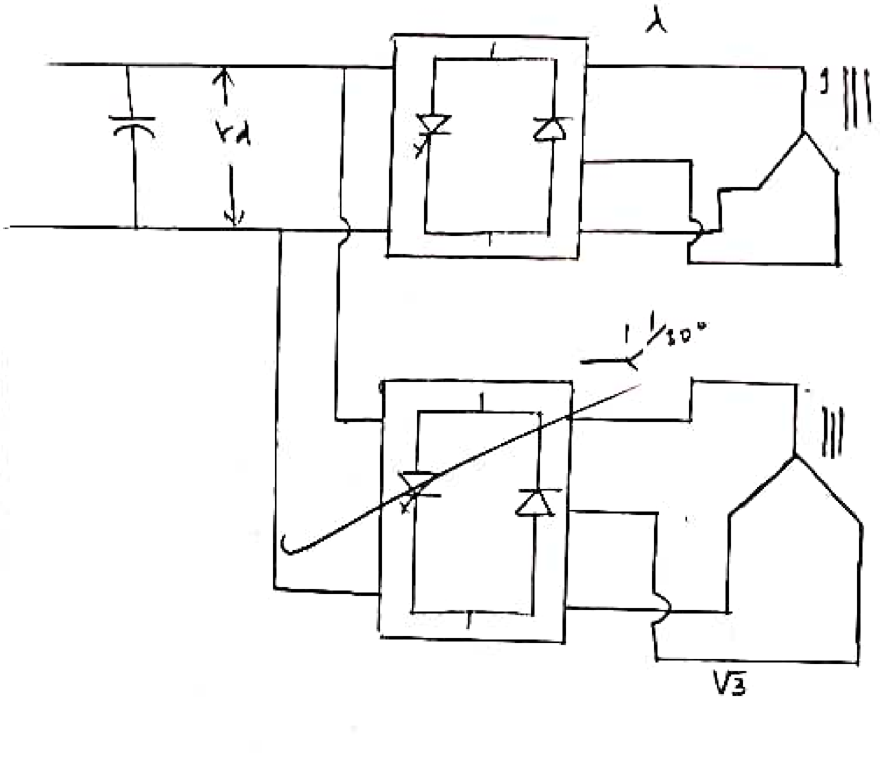
Rating would double the dc voltage & hence the power capacity of the convertor. Thus only, the addition of diode clamping valves D_1 & D_2, per phase-leg, figure adds to convertor cost. If the convertor is a high-voltage : Convertor with devices in series then the no. of main devices would be about the same

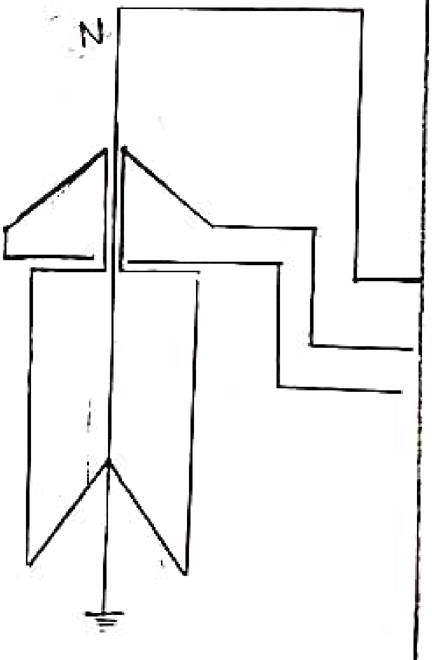
A diode clamp at midpoint may also, help ensure a more decisive voltage sharing b/w the two valves-halves. On other hand requirement that convertor continue safe operation with one failed device in a string of series connected devices.

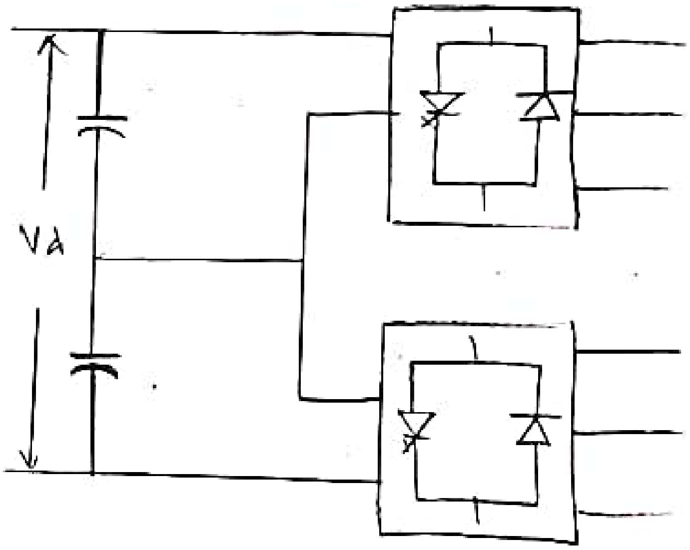
4. What is pulse number of a convertor? With the help of waveforms Explain transformer connections for 12-pulse operation of 3-ϕ full bridge convertor?

Transformer connections for 12 pulse operations:

If the phase to phase voltage of a second convertor were connected to a delta connected secondary of a second transformer with √3 times the turns compound to star connected secondary & the pulse train of one convertol was shifted by 30° wrt other the combined voltage would've a 12-pulse waveform with harmonics of order of 12n±1.

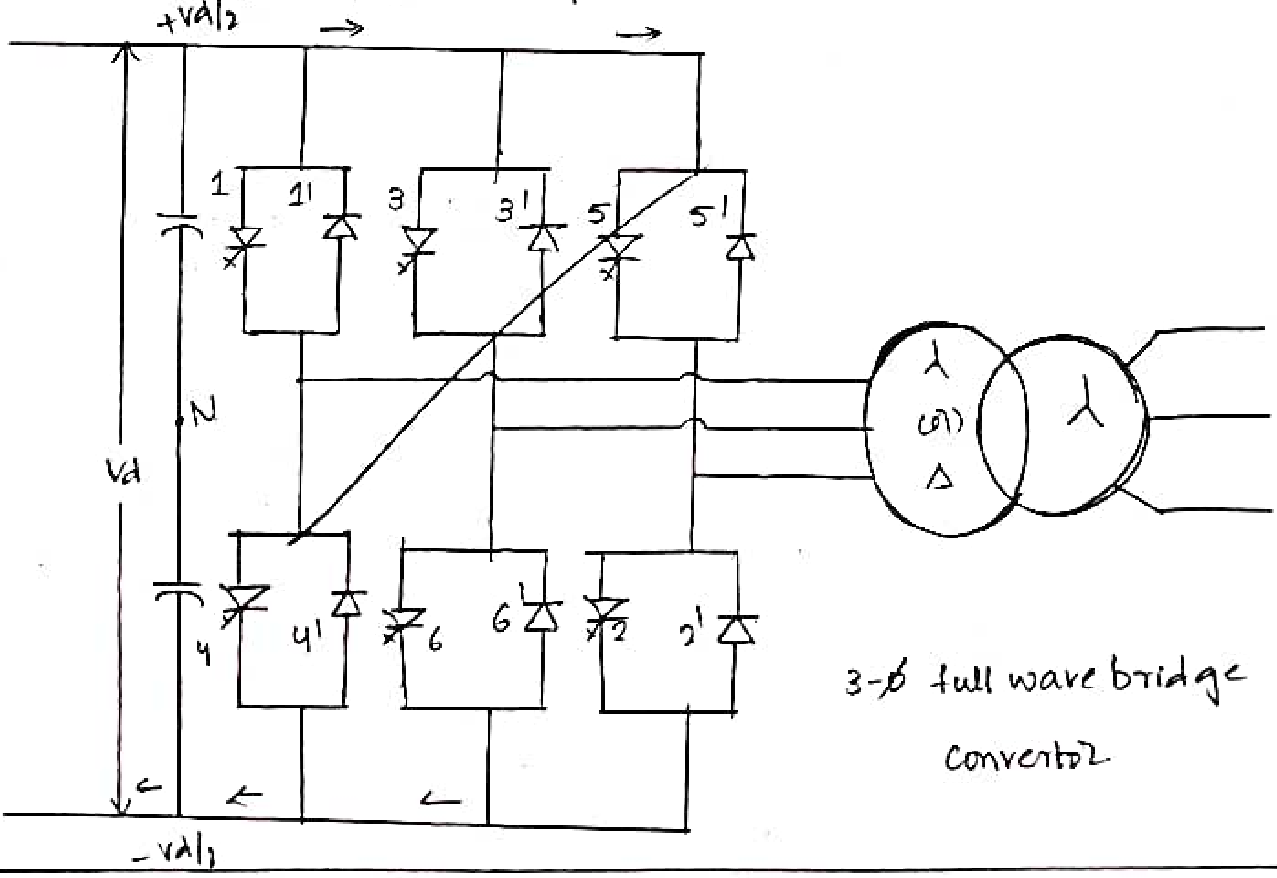






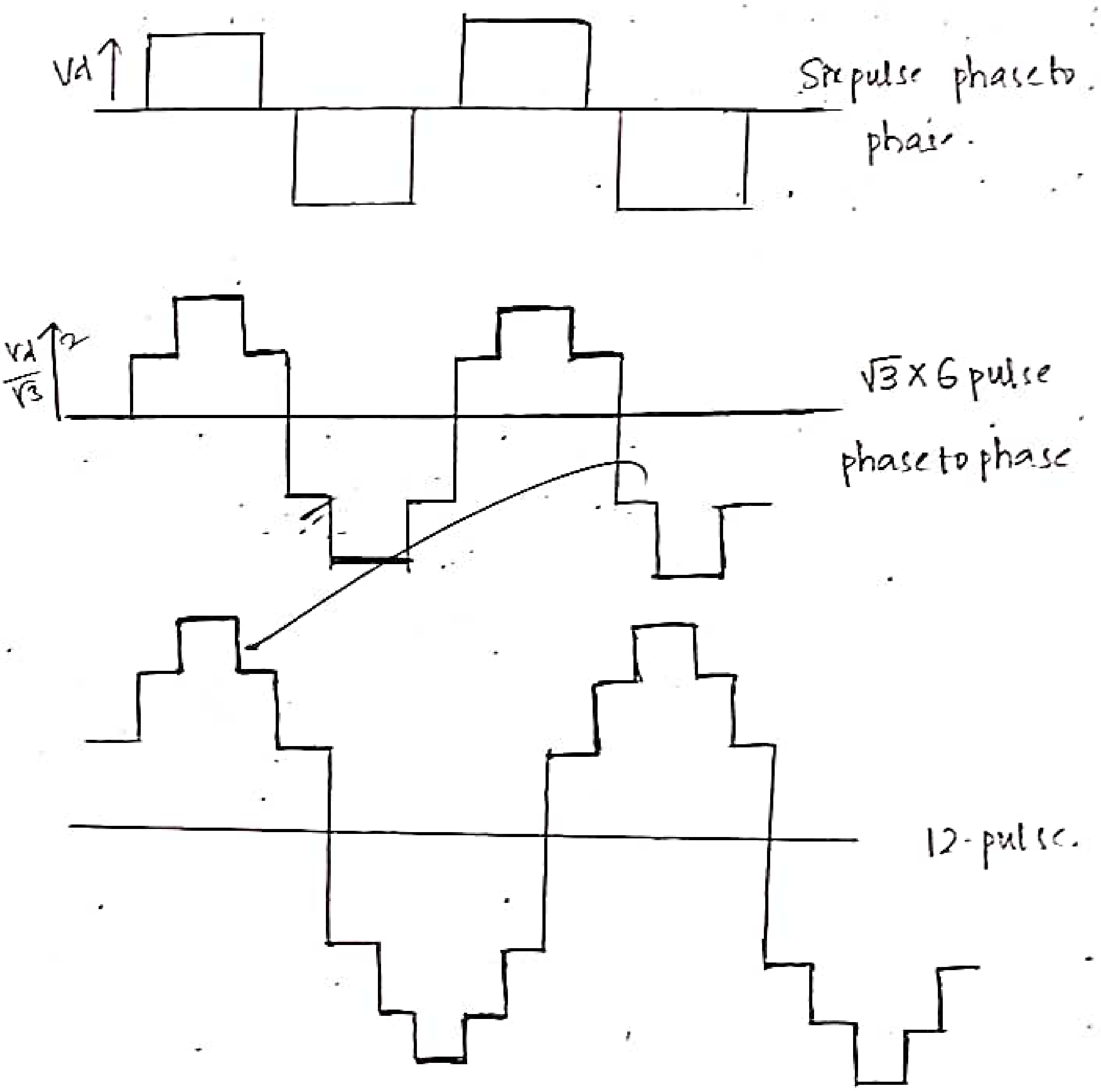
To the non-pulse voltage harmonic, common core flux will represent a near short circuit. Also for some reason, the 2 primary side windings should not be directly connected in parallel to same 3-ϕ ac busbars on primary side. Again this is because the non 12-pulse voltage harmonics i.e., 5th, 7th, 17th, ... while they cancel out looking into ac system. The circulating current of each non-12-pulse harmonic is given by.

$$I_n/I_1 = 100/(X_T \times n^2) \text{ percent.}$$

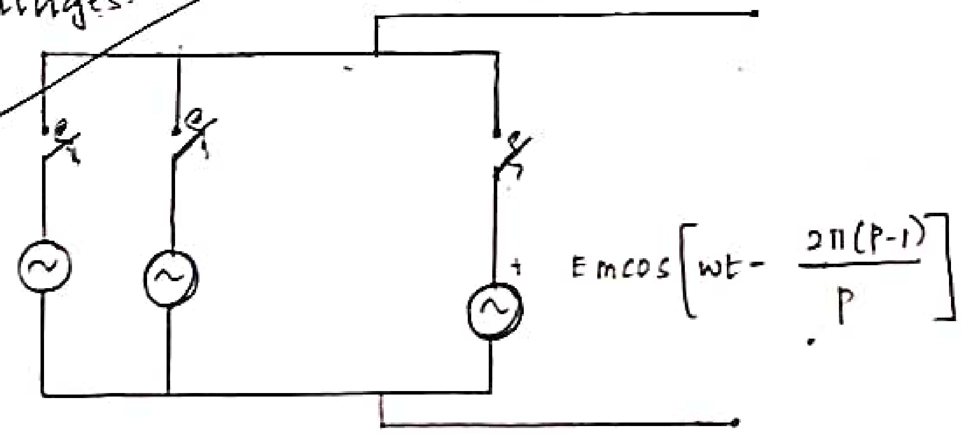


3-ϕ full wave bridge convertor

waveforms:



The pulse number of a convertor is defined as the no of pulsations of direct voltage per cycle of alternating voltage. The conversion from AC to DC involves switching sequentially sinusoidal voltages.



5. What are the objectives of reactive shunt compensation? Explain how improvement in transient stability can be obtained by providing shunt compensation?

Objectives of shunt compensation:

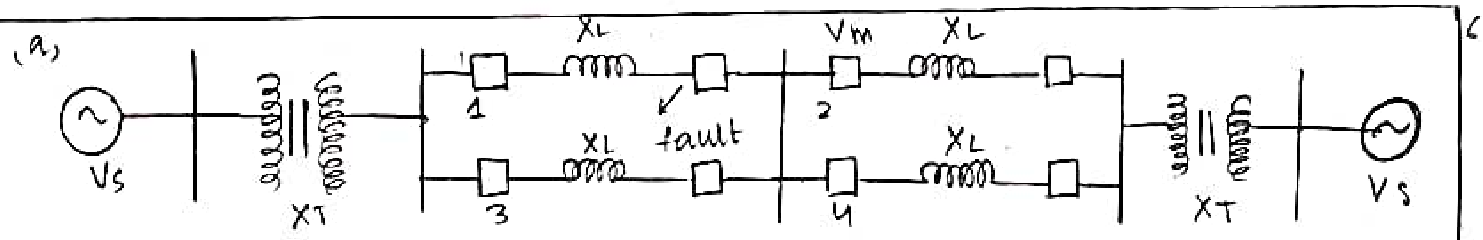
It has long been recognized that the steadystate transmittable power can be increased & voltage profile along that line controlled by appropriate reactive shunt compensation. The purpose of this reactive compensation is to change the natural electrical characteristics of tr.line to make it more compatible with prevailing load demand. Thus, shunt connected, fixed (or) mechanically switched reactors are applied to minimize line over voltage underlight load conditions & shunt connected.

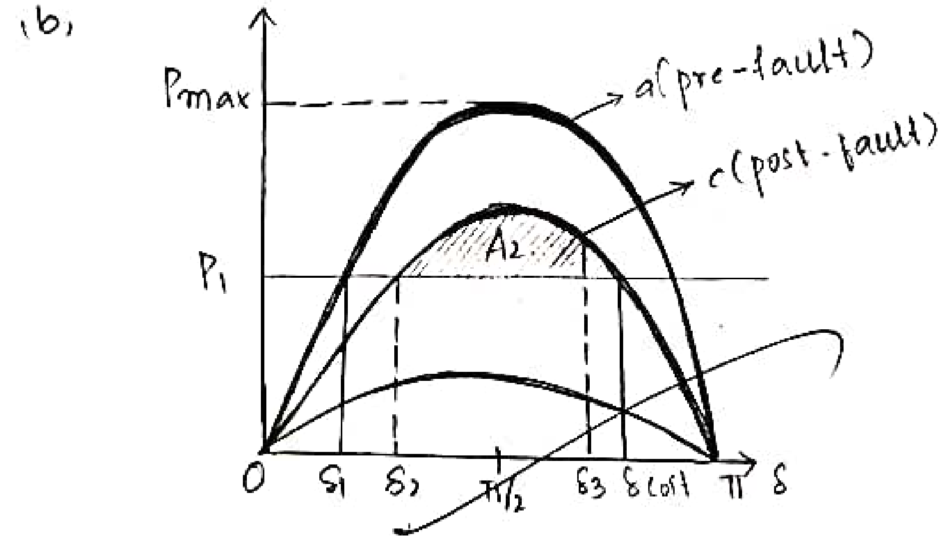
The ultimate objective of applying reactive shunt compensation in a tr-system is to inc the transmittable power. This may be required to improve the steady-to state tr. characte as well as stability of system.

Improvement of Transient stability:

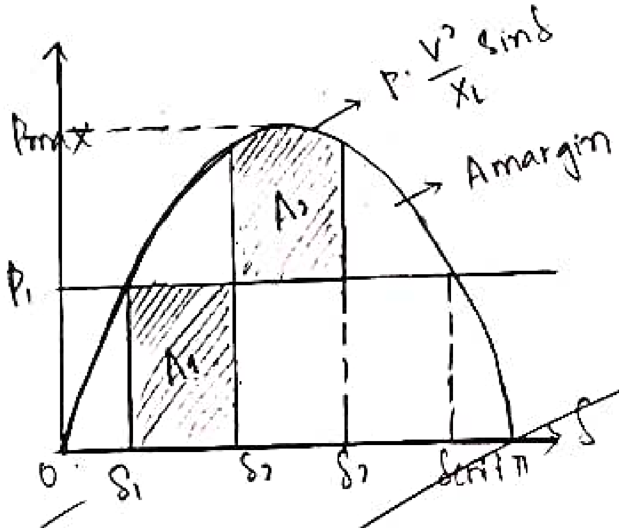
The potential effectiveness of shunt on transient stability improvement can be convienently evaluated by equal area criterion.

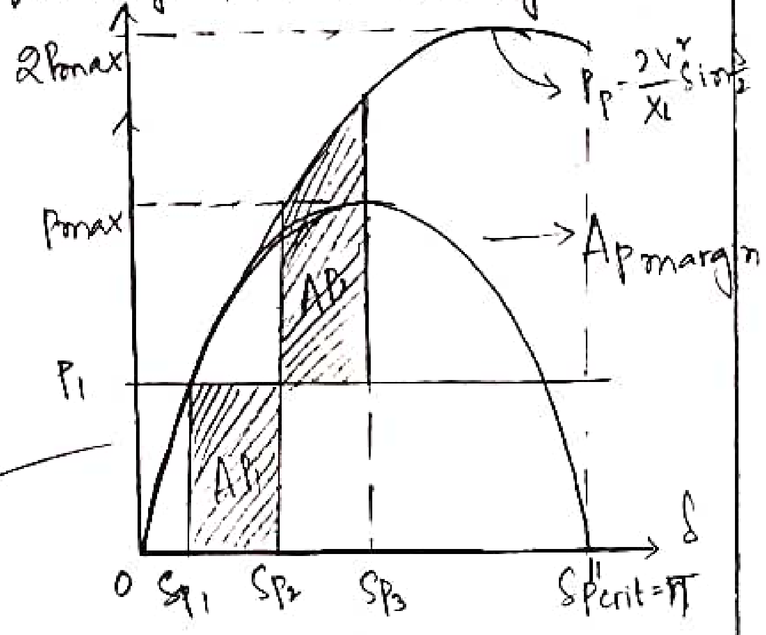
→The transient stability, at a given power to level & fault clearing time, is determined by P versus δ characteristics of the post-fault system.





Compensation can provide effective voltage support, it can inc. the tr capability of post-fault system and thereby enhance transient stability





During the fault, the transmitted electric power becomes zero. The areas b/w P versus δ curve & the constant Pm line over the intervals defined by angles δ3 and δcrit, δp3 & δpcrit respectively determine the margin of stability

UNIT-I

FACTS Concept and General System Considerations

Why We Need Transmission Interconnections

We need these interconnections because, apart from delivery, the purpose of the transmission network is to pool power plants and load centers in order to minimize the total power generation capacity and fuel cost. Transmission interconnections enable taking advantage of diversity of loads, availability of sources, and fuel price in order to supply electricity to the loads at minimum cost with a required reliability. In general, if a power delivery system was made up of radial lines from individual local generators without being part of a grid system, many more generation resources would be needed to serve the load with the same reliability, and the cost of electricity would be much higher. With that perspective, transmission is often an alternative to a new generation resource. Less transmission capability means that more generation resources would be required regardless of whether the system is made up of large or small power plants.

The power systems of today, by and large, are mechanically controlled. There is a widespread use of microelectronics, computers and high-speed communications for control and protection of present transmission systems; however, when operating signals are sent to the power circuits, where the final power control action is taken, the switching devices are mechanical and there is little high-speed control. Another problem with mechanical devices is that control cannot be initiated frequently, because these mechanical devices tend to wear out very quickly compared to static devices. In effect, from the point of view of both dynamic and steady-state operation, the system is really uncontrolled. Power system planners, operators, and engineers have learned to live with this limitation by using a variety of ingenious techniques to make the system work effectively, but at a price of providing greater operating margins and redundancies. These represent an asset that can be effectively utilized with prudent use of FACTS technology on a selective, as needed basis.

Opportunities for FAGTS

What is most interesting for transmission planners is that FACTS technology opens up new opportunities for controlling power and enhancing the usable capacity of present, as well as new and upgraded, lines. The possibility that current through a line can be controlled at a reasonable cost enables a large potential of increasing the capacity of existing lines with larger conductors, and use of one of the FACTS Controllers to enable corresponding power to flow through such lines under normal and contingency conditions. These opportunities arise through the ability of FACTS Controllers to control the interrelated parameters that govern the operation of transmission systems including series impedance, shunt impedance, current, voltage, phase angle, and the damping of oscillations at various frequencies below the rated frequency. These constraints cannot be overcome, while maintaining the required system reliability, by mechanical means without lowering the useable transmission capacity. By providing added flexibility, FACTS Controllers can enable a line to carry power closer to its thermal rating. Mechanical switching needs to be supplemented by rapid-response power electronics. It must be emphasized that FACTS is an enabling technology, and not a one-on-one substitute for mechanical switches

FLOW OF POWER IN AN AC SYSTEM

In ac power systems, given the insignificant electrical storage, the electrical generation and load must balance at all times. To some extent, the electrical system is self-regulating. If generation is less than load, the voltage and frequency drop, and thereby the load, goes down to equal the generation minus the transmission losses. However, there is only a few percent margin for such a self-regulation. If voltage is Chapter 1 f FACTS Concept and General System Considerations propped up with reactive power support, then the load will go up, and consequently frequency will keep dropping, and the system will collapse. Alternately, if there is inadequate reactive power, the system can have voltage collapse.

Power Flow in Parallel Paths

consider a very simple case of power flow [Figure 1.1(a)], through two parallel paths (possibly corridors of several lines) from a surplus generation area, shown as an equivalent generator on the left, to a deficit generation area on the right. Without any control, power flow is based on the inverse of the various transmission line impedances. Apart from ownership and contractual issues over which lines carry how much power, it is likely that the lower impedance line may become overloaded and thereby limit the loading on both paths even though the higher impedance path is not fully loaded. There would not be an incentive to upgrade current capacity of the overloaded path, because this would further decrease the impedance and the investment would be self-defeating particularly if the higher impedance path already has enough capacity. Figure 1.1(b) shows the same two paths, but one of these has HVDC transmission. With HVDC, power flows as ordered by the operator, because with HVDC power electronics converters power is electronically controlled. Also, because power is electronically controlled, the HVDC line can be used to its full thermal capacity if adequate converter capacity is provided. Furthermore, an HVDC line, because of its high-speed control, can also help the parallel ac transmission line to maintain stability. However, HVDC is expensive for general use, and is usually considered when long distances are involved, such as the Pacific DC Intertie on which power flows as ordered by the operator

Power Flow in a Meshed System

To further understand the free flow of power, consider a very simplified case in which generators at two different sites are sending power to a load center through a network consisting of three lines in a meshed connection (Figure 1.2). Suppose the lines AB, BC, and AC have continuous ratings of 1000 Mw, 1250 MW, and 2000 MW, respectively, and have emergency ratings of twice those numbers for a sufficient length of time to allow rescheduling of power in case of loss of one of these lines. If on J of the generators is generating 2000 MW and the other 1000 MW, a total of 3000 MW would be delivered io the load center. For the impedances shown, the three lines would carry 600, 1600, and L400 Mw, respectively, as shown in Figure 1'.2(a). Such a situation would overload line BC (loaded at 1600 MW for its continuous rating of 1250 MW), and therefore generation would have to be decreased at B, and increased at A. in order to meet the load without overloading line BC' power, in short, flows in accordance with transmission line series impedances (which are 907o inductive) that bear no direct relationship to transmission ownership, contracts, thermal limits, or transmission losses

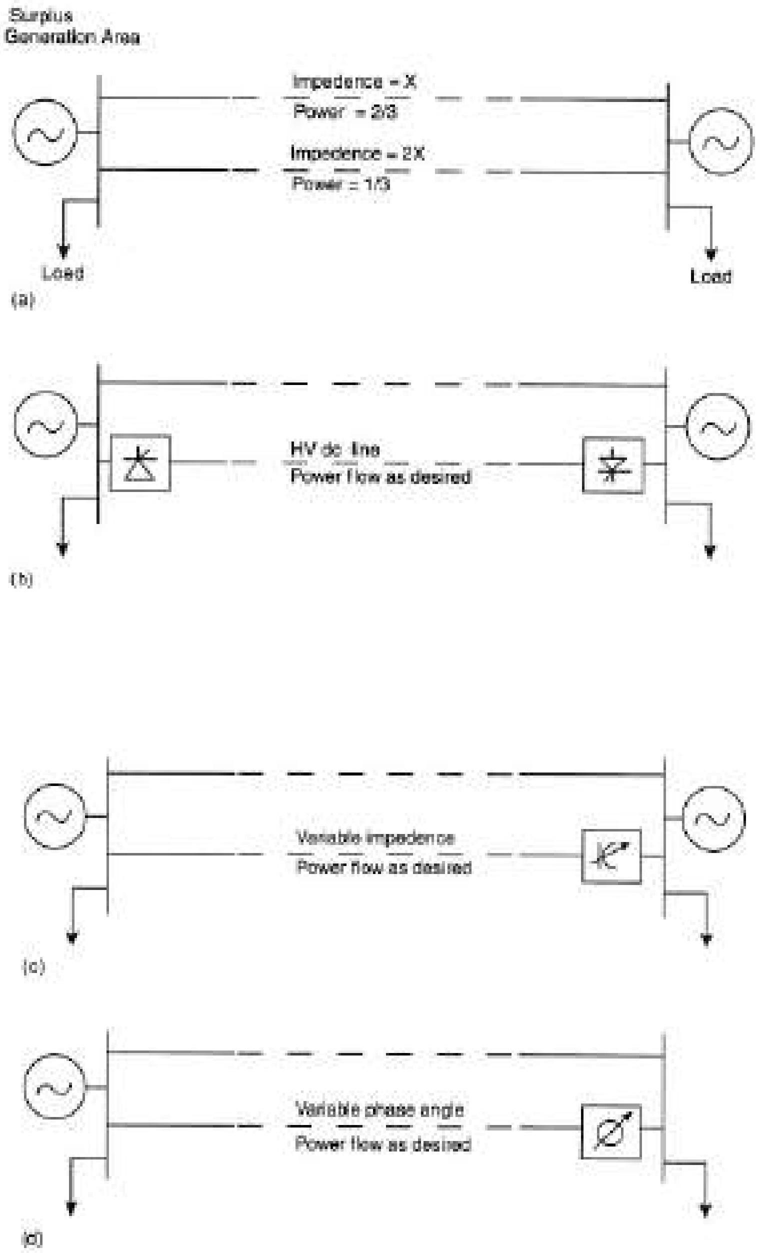


Fig: Power flow as desired in parallel paths: (a) ac power flow with parallel paths; (b) control with HVDC; (c) power flow control with variable (d) power flow control with variable phase angle

Other complications may arise if the series capacitor is mechanically controlled. A series capacitor in a line may lead to subsynchronous resonance (typically at 10-50 Hz for a OOgz system). This resonance occurs when one of the mechanical resonance frequencies of tle shaft of a multiple-turbine generator unit coincides with 60 Hz minus the electrical resonance frequency of the capacitor with the inductive impedance of the line. If such resonance persists, it will soon damage the shaft. Also while the outage of one line forces other lines to operate at their emergency ratings and carry higher loads, power flow oscillations at low frequency (typically 0.3-3 Hz) may cause generators to lose synchronism, perhaps prompting the system's collapse.

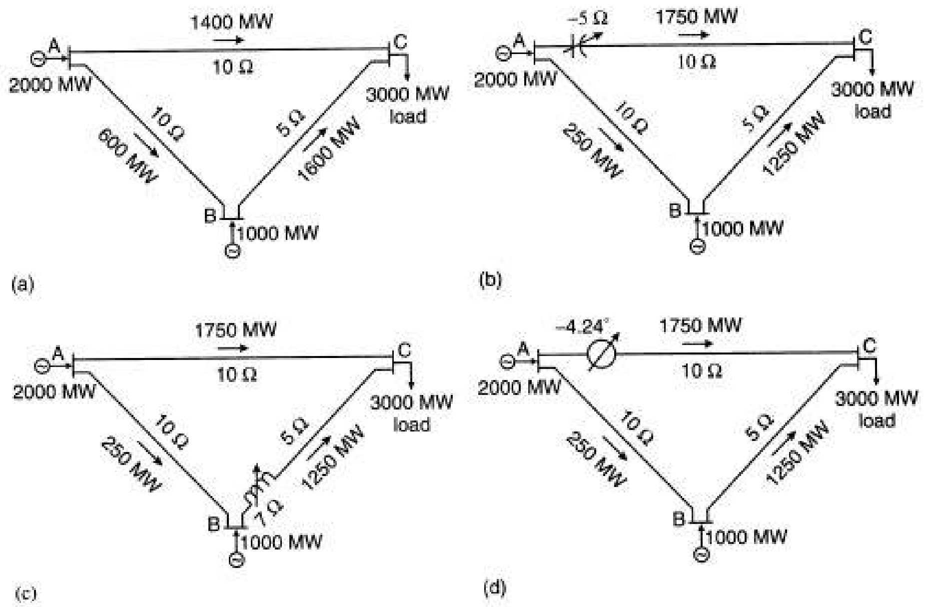


Figure L.2 power flow in a mesh network: (a) system diagram; (b) system diagram with Thyristor-Controlled Series Capacitor in line AC; (c) system diagram with Thyristor-Controlled Series Reactor in line BC; (d) system diagram with Thyristor-Controlled Phase Angle Regulator in line AC.

WHAT LIMITS THE LOADING CAPABILITY?

Assuming that ownership is not an issue, and the objective is to make the best use of the transmission asset, and to maximize the loading capability (taking into account contingency conditions), what limits the loading capability, and what can be done about it?

Basically, there are three kinds of limitations:

1. Thermal
2. Dielectric
3. Stability

Thermal Thermal capability of an overhead line is a function of the ambient temperature, wind conditions, condition of the conductor, and ground clearance. It varies perhaps by a factor of 2 to 1 due to the variable environment and the loading history. The nominal rating of a line is generally decided on a conservative basis, envisioning a statistically worst ambient environment case scenario. Yet this scenario occurs but rarely which means that in reality, most of the time, there is a lot more real time capacity than assumed. Some utilities assign winter and summer ratings, yet this still leaves a considerable margin to play with. There are also off-line computer programs that can calculate a line's loading capability based on available ambient environment and recent loading history. Then there are the on-line monitoring devices that provide a basis for on-line real-time loading capability. These methods have evolved over a period of many years, and, given the age of automation (typified by GPS systems and low-cost sophisticated communication services), it surely makes sense to consider reasonable, day to day, hour to hour, or even real-time capability information. Sometimes, the ambient conditions can actually be worse than assumed, and having the means to determine actual rating of the line could be useful.

Dielectric From an insulation point of view, many lines are designed very conservatively. For a given nominal voltage rating, it is often possible to increase normal operation by +10Vo voltage (i.e., 500 kV-550 kV) or even higher. Care is then needed to ensure that dynamic and transient over voltages are within limits. Modern gapless arresters, or line insulators with internal gapless arresters, or powerful thyristor-controlled overvoltage suppressors at the substations can enable significant increase in the line and substation voltage capability. The

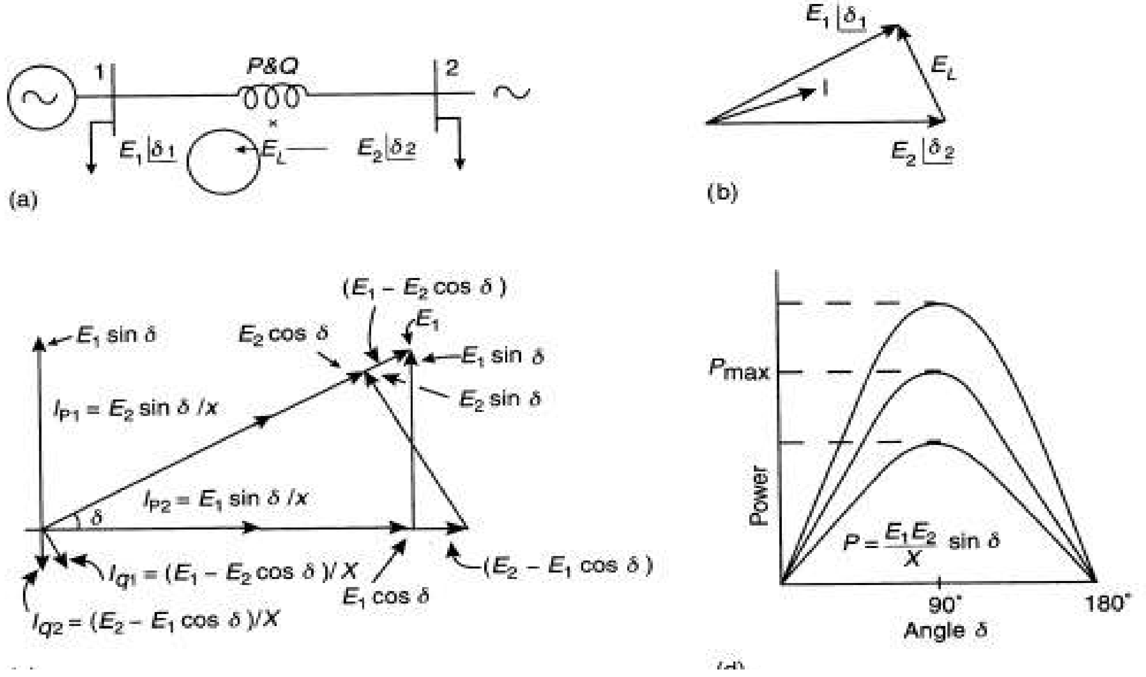
FACTS technology could be used to ensure acceptable over-voltage and power flow conditions. **Stability** There are a number of stability issues that limit the transmission capability. These include:

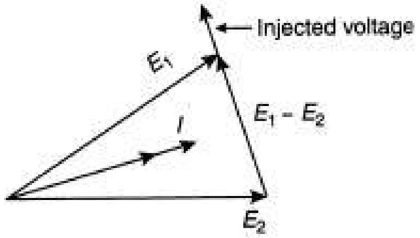
1. Transient stability
2. Dynamic stability r
3. Steady-state stability
4. Frequency collapse
5. Voltage collapse
6. Subsynchronous resonance

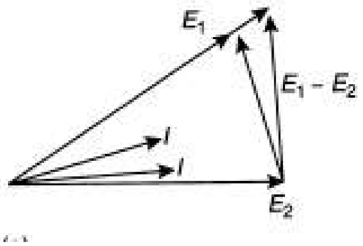
POWER FLOW AND DVNAMIC STABILITY CONSIDERATIONS OF A TRANSMISSION INTERCONNECTION

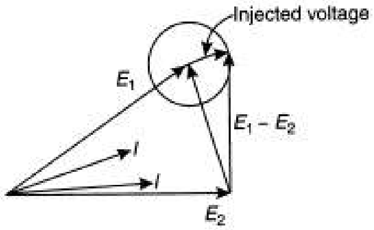
The current flow on the line can be controlled by controllingEyor Xor d. In order to achieve a high degree of control on the current in this line, the equipment required in series with the line would not have a very high power rating. For example, a 500 kv (approximately 300 kv phase-ground), 2000 A line has a three-phase throughput power of 1800 MVA, and, for a 200 km length, it would have a voltage drop of about 60 kV. For variable series compensation of say,25Vo,the series equipment required would have a nominal rating of 0.25 x 60 kv x 2000 A : 30 MVA per phase, or 90 MVA for three phases, which is only SVo of the throughput line rating of 1800 MVA. Voltage across the series equipment would only be 15 kV at full load, although it would require high-voltage insulation to ground (the latter is not a significant cost factor). However, any series-connected equipment has to be designed to carry contingency

Nevertheless the point of this very simple example is that generally speaking the rating of series FACTS Controllers would be a fraction of the throughput rating of a line. Figure 1.3(b) shows that the current flow phasor is perpendicular to the driving voltage (90'phase lag). If the angle between the two bus voltages is small, the current flow largely represents the active power. Increasing or decreasing the inductive impedance of a line will greatly affect the active power flow. Thus impedance control, which in reality provides current control, can be the most cost-effective means of controlling the power flow.









Active component of the current flow at E_1 is:

$$I_{p1} = (E_2 \sin \delta)/X$$

Reactive component of the current flow at E_1 is:

$$I_{q1} = (E_1 - E_2 \cos \delta)/X$$

Thus, active power at the E_1 end:

$$P_1 = E_1 (E_2 \sin \delta)/X$$

Reactive power at the E_1 end:

$$Q_1 = E_1 (E_1 - E_2 \cos \delta)/X$$

Similarly, active component of the current flow at E_2 is:

$$I_{p2} = (E_1 \sin \delta)/X$$

Reactive component of the current flow at E_2 is

$$I_{q2} = (E_2 - E_1 \cos \delta)/X$$

Thus, active power at the E_2 end:

$$P_2 = E_2 (E_1 \sin \delta)/X$$

Reactive power at the E_2 end

$$Q_2 = E_2 (E_2 - E_1 \cos \delta)/X$$

Naturally P_1 and P_2 are the same:

$$P = E_1 (E_2 \sin \delta)/X$$

RELATIVE IMPORTANCE OF CONTROLLABLE PARAMETERS

With reference to the above discussion and Figure 1.5, it is worth noting a few basic points regarding the possibilities of power flow control:

- Control of the line impedance *X* (e.g., with a thyristor-controlled series capacitor) can provide a powerful means of current control.
- When the angle is not large, which is often the case, control of *X* or the angle substantially provides the control of active power.
- Control of angle (with a Phase Angle Regulator, for example), which in turn controls the driving voltage, provides a powerful means of controlling the current flow and hence active power flow when the angle is not large.
- Injecting a voltage in series with the line, and perpendicular to the current flow, can increase or decrease the magnitude of current flow. Since the current flow lags the driving voltage by 90 degrees, this means injection of reactive power in series, (e.g., with static synchronous series compensation) can provide a powerful means of controlling the line current, and hence the active power when the angle is not large.
- Injecting voltage in series with the line and with any phase angle with respect to the driving voltage can control the magnitude and the phase of the line current. This means that injecting a voltage phasor with variable phase angle can provide a powerful means of precisely controlling the active and reactive power flow. This requires injection of both active and reactive power in series.
- Because the per unit line impedance is usually a small fraction of the line voltage, the MVA rating of a series Controller will often be a small fraction of the throughput line MVA.
- When the angle is not large, controlling the magnitude of one or the other line voltages (e.g., with a thyristor-controlled voltage regulator) can be a very cost-effective means for the control of reactive power flow through the interconnection.
- Combination of the line impedance control with a series Controller and voltage

BASIC TYPES OF FACTS CONTROLLERS

In general, FACTS Controllers can be divided into four categories:

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

Figure 1.4(a) shows the general symbol for a FACTS Controller: a thyristor arrow inside a box.

Series Controllers: [Figure 1.4(b)] The series Controller could be a variable impedance, such as capacitor, reactor, etc., or a power electronics based variable source of main frequency, subsynchronous and harmonic frequencies (or a combination) to serve the desired need. In principle, all series Controllers inject voltage in series with the line. Even a variable impedance multiplied by the current flow through it, represents an injected series voltage in the line. As long as the voltage is in phase quadrature with the line current, the series Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Shunt Controllers: [Figure 1.4(c)] As in the case of series Controllers, the shunt Controllers may be variable impedance, variable source, or a combination of these. In principle, all shunt Controllers inject current into the system at the point of connection. Even a variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt Controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well.

Combined series-series Controllers: [Figure 1.4(d)] This could be a combination of separate series controllers, which are controlled in a coordinated manner, in a multiline transmission system. Or it could be a unified Controller, Figure 1.4(d), in which series Controllers provide independent series reactive compensation for each line but also transfer real power among the lines via the power link. The real power transfer capability of the unified series-series Controller, referred to as *Interline Power Flow Controller*, makes it possible to balance both the real and reactive power flow in the lines and thereby maximize the utilization of the transmission system. Note that the term "unified" here means that the dc terminals of all Controller converters are all connected together for real power transfer.

Combined series-shunt Controllers: [Figures 1.4(e) and 1.4(f)] This could be a combination of separate shunt and series Controllers, which are controlled in a coordinated manner [Figure 1.4(e)], or a *Unified Power Flow Controller* with series and shunt elements [Figure 1.4(f)]. In principle, combined shunt and series Controllers inject current into the system with the shunt part of the Controller and voltage in series in the line with the series part of the Controller. However, when the shunt and series Controllers are unified, there can be a real power exchange between the series and shunt Controllers via the power link.

It is important to appreciate that the series-connected Controller impacts the driving voltage and hence the current and power flow directly. Therefore, if the purpose of the application is to control the current/power flow and damp oscillations, the series Controller for a given MVA size is several times more powerful than the shunt Controller.

As mentioned, the shunt Controller, on the other hand, is like a current source, which draws from or injects current into the line. The shunt Controller is therefore a good way to control voltage at and around the point of connection through injection of reactive current (leading or lagging), alone or a combination of active and reactive current for a more effective voltage control and damping

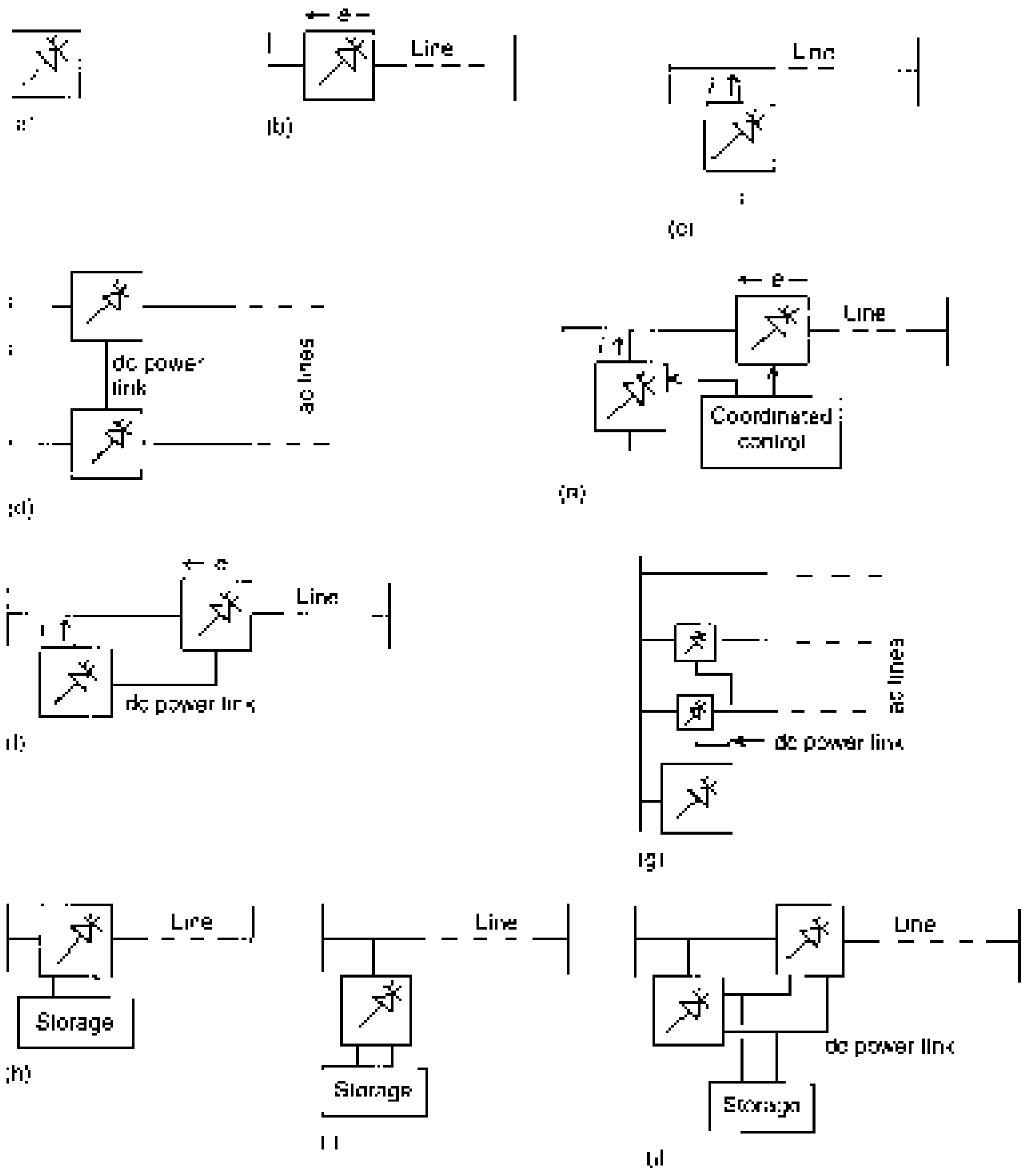


Figure 1.4 Basic types of FACTS Controllers: (a) general symbol for FACTS Controller; (b) series Controller; (c) shunt Controller; (d) unified series-series Controller; (e) coordinated series and shunt Controller; (f) unified series-shunt Controller; (g) unified Controller for multiple lines; (h) series Controller with storage; (i) shunt Controller with storage; (j) unified series-shunt Controller with storage.

The purpose of this section is to briefly describe and define various shunt, series, and combined Controllers, leaving the detailed description of Controllers to their own specific chapters.

Before going into a very brief description of a variety of specific FACTS Controllers, it is worth mentioning here that for the converter-based Controllers there are two principal types of converters with gate turn-off devices. These are the so-called voltage-sourced converters and the current-sourced converters. As shown in the left-hand side of Figure 1.5(a), the voltage-sourced converter is represented in symbolic form by a box with a gate turn-off device paralleled by a reverse diode, and a dc capacitor as its voltage source. As shown in the right-hand side of Figure 1.5(a), the current-sourced converter is represented by a box with a gate turn-off device with a diode in series, and a dc reactor as its current source.

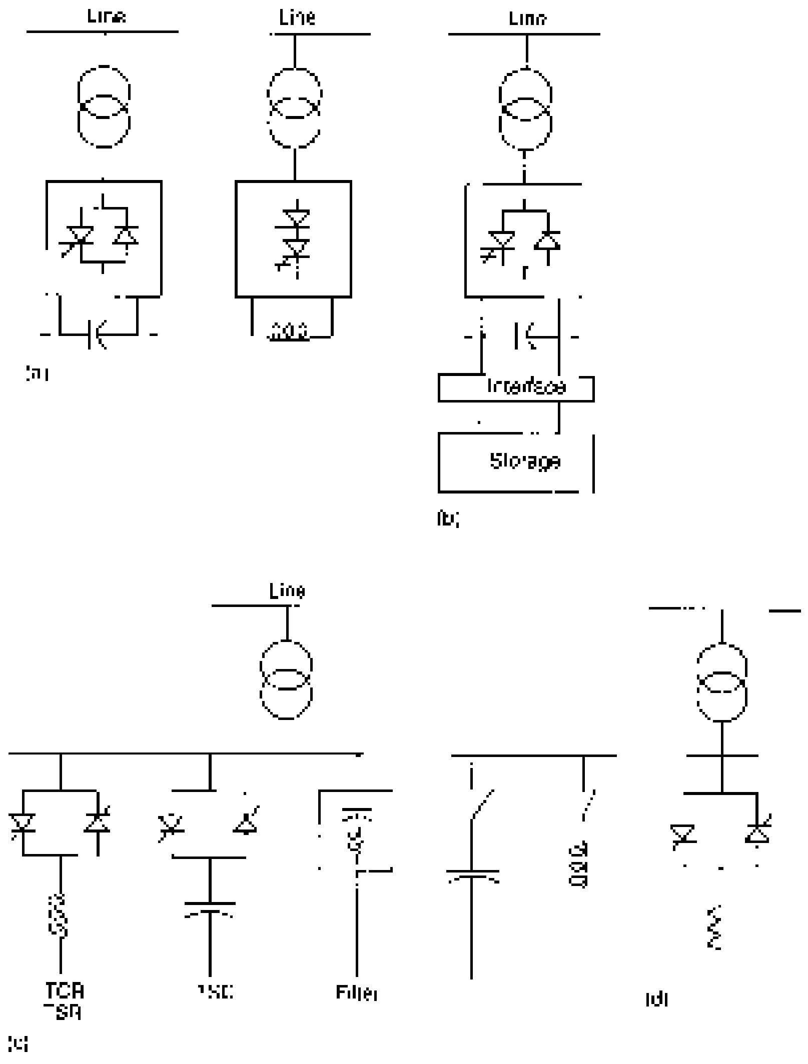


Figure 1.5 Shunt-connected Controllers: (a) Static Synchronous Compensator (STATCOM) based on voltage-sourced and current-sourced converters; (b) STATCOM with storage, i.e., Battery Energy Storage System (BESS), Superconducting Magnet Energy Storage and large dc capacitor; (c) Static VAR Compensator (SVC), Static VAR Generator (SVG), Static VAR System (SVS), Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor (TSC), and Thyristor Switched Reactor (TSR); (d) Thyristor Controlled Braking Resistor.

TSR [Figure 1.5(c)] is another a subset of SVC. TSR is made up of several shunt-connected inductors which are switched in and out by thyristor switches without any firing angle controls in order to achieve the required step changes in the reactive power consumed from the system. Use of thyristor switches without firing angle control results in lower cost and losses, but without a continuous control.

> ***Thyristor Switched Capacitor (TSC):*** *A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.*

TSC [Figure 1.5(c)] is also a subset of SVC in which thyristor based ac switches are used to switch in and out (without firing angle control) shunt capacitors units, in order to achieve the required step change in the reactive power supplied to the system. Unlike shunt reactors, shunt capacitors cannot be switched continuously with variable firing angle control.

Other broadbased definitions of series Controllers by IEEE include:

> ***Static Var Generator or Absorber (SVG):*** *A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power. Generally considered to consist of shunt-connected, thyristor-controlled reactor(s) and/or thyristor-switched capacitors.*

The SVG, as broadly defined by IEEE, is simply a reactive power (var) source that, with appropriate controls, can be converted into any specific- or multipurpose reactive shunt compensator. Thus, both the SVC and the STATCOM are *static var generators* equipped with appropriate control loops to vary the var output so as to meet specific compensation objectives.

> ***Static Var System (SVS):*** *A combination of different static and mechanically-switched var compensators whose outputs are coordinated.*

> ***Thyristor Controlled Braking Resistor (TCBR):*** *A shunt-connected thyristor-switched resistor, which is controlled to aid stabilization of a power system or to minimize power acceleration of a generating unit during a disturbance.*

TCBR involves cycle-by-cycle switching of a resistor (usually a linear resistor) with a thyristor-based ac switch with firing angle control [Figure 1.5(d)]. For lower cost, TCBR may be thyristor switched, i.e., without firing angle control. However, with firing control, half-cycle by half-cycle firing control can be utilized to selectively damp low-frequency oscillations.

1.7.2 Series Connected Controllers

> ***Static Synchronous Series Compensator (SSSC):*** *A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.*

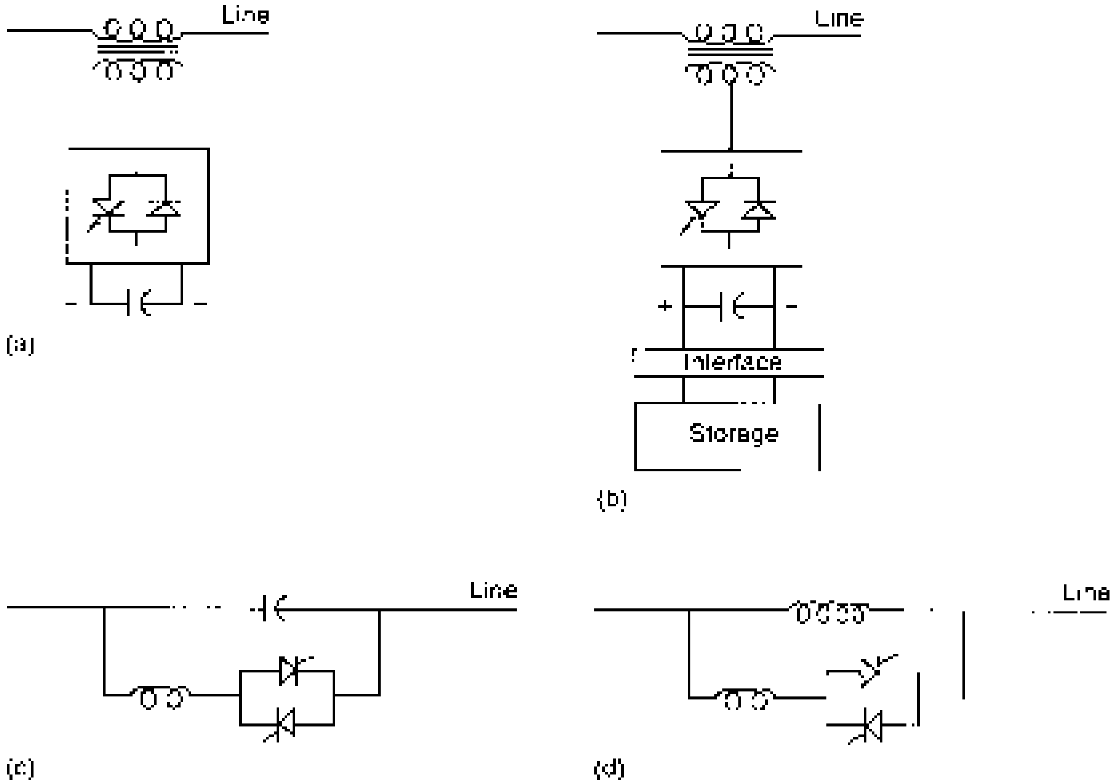


Figure 1.6 (a) Static Synchronous Series Compensator (SSSC); (b) SSSC with storage; (c) Thyristor-Controlled Series Capacitor (TCSC) and Thyristor-Switched Series Capacitor (TSSC); (d) Thyristor-Controlled Series Reactor (TCSR) and Thyristor-Switched Series Reactor (TSSR).

SSSC is one the most important FACTS Controllers. It is like a STATCOM, except that the output ac voltage is in series with the line. It can be based on a voltage-sourced converter [Figure 1.6(a)] or current-sourced converter. Usually the injected voltage in series would be quite small compared to the line voltage, and the insulation to ground would be quite high. With an appropriate insulation between the primary and the secondary of the transformer, the converter equipment is located at the ground potential unless the entire converter equipment is located on a platform duly insulated from ground. The transformer ratio is tailored to the most economical converter design. Without an extra energy source, SSSC can only inject a variable voltage, which is 90 degrees leading or lagging the current. The primary of the transformer and hence the secondary as well as the converter has to carry full line current including the fault current unless the converter is temporarily bypassed during severe line faults.

Battery-storage or superconducting magnetic storage can also be connected to a series Controller [Figure 1.6(b)] to inject a voltage vector of variable angle in series with the line.

Interline Power Flow Controller (IPFC): The IPFC is a recently introduced Controller and thus has no IEEE definition yet. A possible definition is: *The combination of two or more Static Synchronous Series Compensators which are coupled via a common dc link to facilitate bi-directional flow of real power between the ac terminals of the SSSCs, and are controlled to provide independent reactive compensation for the adjustment of real power flow in each line and maintain the desired distribution of reactive power flow among* *the lines. The IPFC structure may also include a STATCOM, coupled to the IPFC's common dc link, to provide shunt reactive compensation and supply or absorb the overall real power deficit of the combined SSSCs.*

Thyristor Controlled Series Capacitor (TCSC): *A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance*

The TCSC [Figure 1.6(c)], is based on thyristors without the gate turn-off capability. It is an alternative to SSSC above and like an SSSC, it is a very important FACTS Controller. A variable reactor such as a Thyristor-Controlled Reactor (TCR) is connected across a series capacitor. When the TCR firing angle is 180 degrees, the reactor becomes nonconducting and the series capacitor has its normal impedance. As the firing angle is advanced from 180 degrees to less than 180 degrees, the capacitive impedance increases. At the other end, when the TCR firing angle is 90 degrees, the reactor becomes fully conducting, and the total impedance becomes inductive, because the reactor impedance is designed to be much lower than the series capacitor impedance. With 90 degrees firing angle, the TCSC helps in limiting fault current. The TCSC may be a single, large unit, or may consist of several equal or different-sized smaller capacitors in order to achieve a superior performance.

Thyristor-Switched Series Capacitor (TSSC): *A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance.*

Instead of continuous control of capacitive impedance, this approach of switching inductors at firing angle of 90 degrees or 180 degrees but without firing angle control, could reduce cost and losses of the Controller [Figure 1.6(c)]. It is reasonable to arrange one of the modules to have thyristor control, while others could be thyristor switched.

Thyristor-Controlled Series Reactor (TCSR): *An inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance*

When the firing angle of the thyristor controlled reactor is 180 degrees, it stops conducting, and the uncontrolled reactor acts as a fault current limiter [Figure 1.6(d)]. As the angle decreases below 180 degrees, the net inductance decreases until firing angle of 90 degrees, when the net inductance is the parallel combination of the two reactors. As for the TCSC, the TCSR may be a single large unit or several smaller series units.

Thyristor-Switched Series Reactor (TSSR): *An inductive reactance compensator which consists of a series reactor shunted by a thyristor-controlled switched reactor in order to provide a stepwise control of series inductive reactance*

This is a complement of TCSR, but with thyristor switches fully on or off (without firing angle control) to achieve a combination of stepped series inductance [Figure 1.6(d)].

Combined Shunt and Series Connected Controllers

Details of various FACTS Controllers will be discussed throughout the book. It is

> ***Unified Power Flow Controller (UPFC):*** *A combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) which are coupled via a common dc link, to allow bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM, and are controlled to provide concurrent real and reactive series line compensation without an external electric energy source. The UPFC, by means of angularly unconstrained series voltage injection, is able to control, concurrently or selectively, the transmission line voltage, impedance, and angle or, alternatively, the real and reactive power flow in the line. The UPFC may also provide independently controllable shunt reactive compensation.*

In UPFC [Figure 1.7(b)], which combines a STATCOM [Figure 1.5(a)] and an SSSC [Figure 1.6(a)], the active power for the series unit (SSSC) is obtained from the line itself via the shunt unit STATCOM; the latter is also used for voltage control with control of its reactive power. This is a complete Controller for controlling active and reactive power control through the line, as well as line voltage control

Additional storage such as a superconducting magnet connected to the dc link via an electronic interface would provide the means of further enhancing the effectiveness of the UPFC. As mentioned before, the controlled exchange of real power with an external source, such as storage, is much more effective in control of system dynamics than modulation of the power transfer within a system.

> ***Thyristor-Controlled Phase Shifting Transformer (TCPST):*** *A phase-shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle.*

In general, phase shifting is obtained by adding a perpendicular voltage vector in series with a phase. This vector is derived from the other two phases via shunt connected transformers [Figure 1.7(a)]. The perpendicular series voltage is made variable with a variety of power electronics topologies. A circuit concept that can handle voltage reversal can provide phase shift in either direction. This Controller is also referred to as *Thyristor-Controlled Phase Angle Regulator* (TCPAR).

> ***Interphase Power Controller (IPC):*** *A series-connected controller of active and reactive power consisting, in each phase, of inductive and capacitive branches subjected to separately*

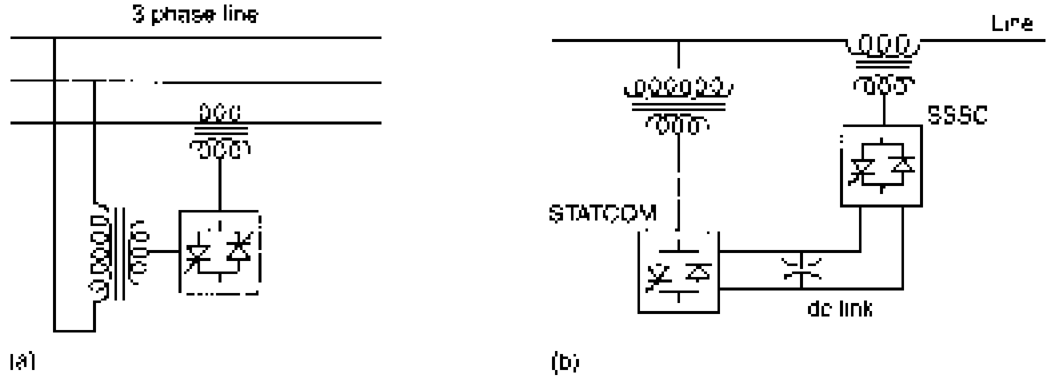


Figure 1.7 (a) Thyristor-Controlled Phase-Shifting Transformer (TCPST) or Thyristor Controlled Phase Angle Regulator (TCPR); (b) Unified Power Flow Controller (UPFC)

CHECKLIST OF POSSIBLE BENEFITS FROM FACTS TECHNOLOGY

UNIT-II

VOLTAGE SOURCE CONVERTERS

SINGLE.PHASE FULL.WAVE BRIDGE CONVERTER OPERATION

Although FACTS Controllers will generally utilize three-phase converters, a singlephase, full-wave bridge converter may also be used in some designs. In any case, it is important to first understand the operation of a single-phase bridge converter and operation of a phase-leg to further understand the principles of voltage-sourced converters. Figure 3.2(a) shows a single-phase full-wave bridge converter consisting of four valves, (1-1') to (4-4'), a dc capacitor to provide stiff dc voltage, and two ac connection points, a and b. The designated valve numbers represent their sequence of turn-on and turn-off. The dc voltage is converted to ac voltage with the appropriate valve turn-on, turn-off sequence as explained below.

As shown by the first waveform of Figure 3.2(b), with turn-off devices 7 and 2 turned on, voltage uo6 becomes *V4fot one half-cycle, and, with 3 and 4 turned on and devices 1, and2 turned otf, uo6 becomes -Vafor the other half-cycle. This voltage waveform occurs regardless of the phase angle, magnitude and waveform of the ac current flow. The ac current is the result of interaction of the converter generated ac voltage with the ac system voltage and impedance. For example, suppose that the current flow from the ac system, as shown by the second waveform, is a sinusoidal waveform io6, angle 0, leading with respect to the square-wave voltage waveform. Starting from instant fi, it is seen from the circuit and the waveform that:

1. From instant \ to t2, with turn-off devices 1 and 2 on and 3 and 4 off, uo6 is positive and io6 is negative. The current flows through device 1 into ac phase a, and then out of ac phase b through device 2, with power flow from dc to ac (inverter action).
2. . From instant t2 to fi, the current reverses, i.e., becomes positive, and flows through diodes 1'and 2'with power flow from ac to dc (rectifier action). Note that during this interval, although devices l and2 are still on and voltage uo6is *Va, devices 1, andZ cannot conduct in a reverse direction. In reality. devices 1, andZ are ready to turn on by turn-on pulses when required by the direction of actual current flow.
3. From instant ftto ta, devices 1 and2 are turned off and devices 3 and 4 are turned on, thereby uo6 becomes negative while lo6 is still positive. The current now flows through devices 3 and 4 with power flow from dc to ac (inverter action).
4. From instant tato t5, with devices 3 and 4 still on, and L and 2 off, anduo, negative, current io6 r€verses and flows through diodes 3' and 4' with power flow from ac to dc (rectifier action).

From instant /5, the cycle starts again as from I with devices 1 and 2 turned on and 3 and 4 turned off. Table 3.1 summarizes the four operating modes in a cycle. Figure 3.2(b) also shows the waveform of current flow i4 in the dc bus with the positive side flowing from ac to dc (rectifier action), and the negative side flowing from dc to ac (inverter action). Clearly the average dc current is negative. The current I contains the dc current and the harmonics. The dc current must flow into the dc system and for a large dc capacitor, virtually all of the harmonic current will flou through the capacitor. Being a single-phase, full-wave bridge, the dc harmonics have an order of 2k,wherc k is an integer, i.e.,2nd,4th, 6th, . . ., all of the even harmonics Voltage across valve 1-L' is shown as the last waveform in Figure 3'2(b). The relationship between ac voltage and current phasors is shown in Figure 3.2(c), showing power flow from ac to dc with a lagging power factor.

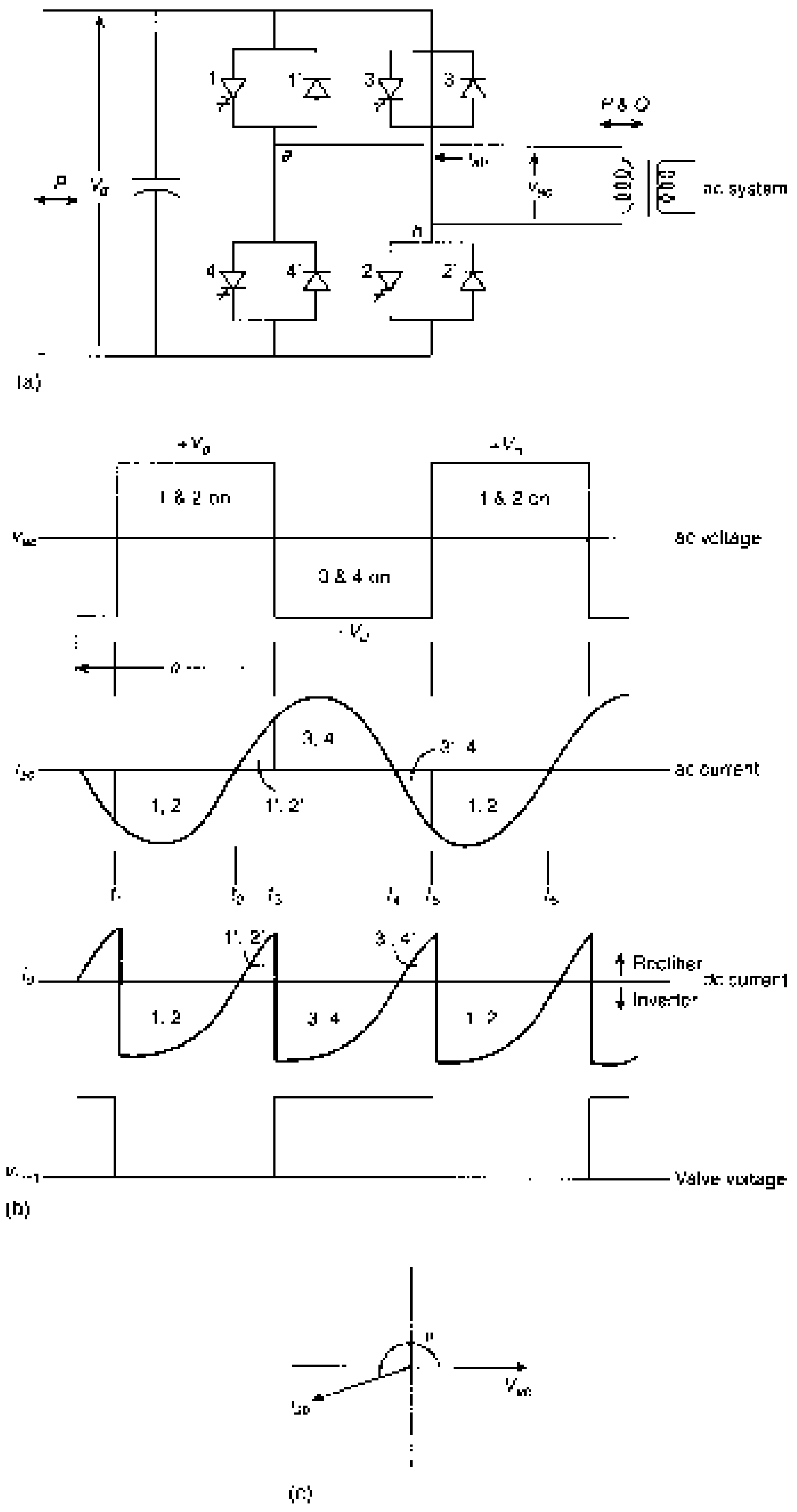


Figure 3.2 Single-phase, full-wave, voltage-sourced converter (a) Single-phase, full-wave circuit; (b) Operation waveform; (c) Phase relationship between current and voltage.

STNGLE PHASE-LEG (POLE) OPERATION

Now consider operation of just one-leg (single-pole) circuit shown in Figure 3.3, in which the capacitor is split into two series-connected halves with the neutral point of the ac side connected to the midpoint N of the dc capacitor. With the two turn-off devices alternately closing/opening, the ac voltage waveform is a square wave with peak voltage of Val2. Note that when two phase-legs are operated in a full-wave bridge mode, Figure 3.2(b), the ac square wave is the sum of the two halves of Figure 3.3(b), giving a peak voltage of Va. In a full-wave circuit, the neutral connection is no longer needed, because the current has a return path through the other phase-leg. It should now be obvious that:

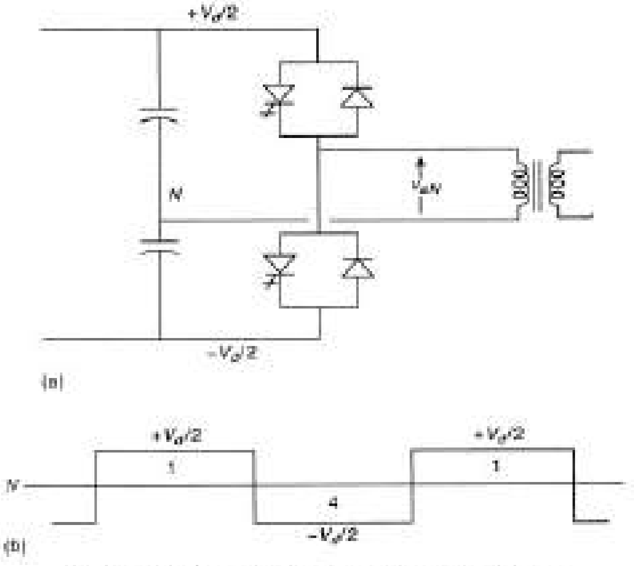


Figure 3.3 (a) One-phase-leg circuit; (b) Output ac voltage.

1. AC current and voltage can have any phase relationship, that is, the converter phase angle between voltage and current can cover all four quadrants, i.e., act as a rectifler or an inverter with leading or lagging reactive power. This
2. The active and reactive power can be independently controlled with control of magnitude and angle of the converter generated ac voltage with respect to the ac current.
3. Diodes carry out instantaneous rectifier function, and turn-off devices carry out instantaneous inverter function. Of course, each ac cycle is made up of periods of rectifier and inverter actions in accordance with the phase angle, and the average current determines the net power flow and hence the net rectifier or inverter operation. When the converter operates as a rectifier with unity power factor, only diodes are involved with conduction, and when it operates as an inverter with unity power factor, only turn-off devices are involved in conduction.
4. When any turn-off device turns off, the ac bus current is not actually interrupted at all, but is transferred from a turn-off device to a diode when the power factor is not unity, and to another turn-off device when power factor is unity.
5. Turn-off devices 1. and 4 (or turn-off devices 2 and 3) in the same phaseleg are not turned on simultaneously. Otherwise this would cause a "shootthrough" (short circuit) of the dc side and a very fast discharge of the dc capacitor through the shorted phase-leg, which will destroy the devices in that phase-leg. In a phaseJeg, when one turn-off device is on, the other is off. The gate control is arranged to ensure that only one of the two devices in a phaseleg receives a turn-on pulse, and that the current in the other device was indeed zero. Regardless, sensing and protection means are provided, usually to ensure safe shutdown of the converter

SQUARE.WAVE VOLTAGE HARMONICS FOR A SINGLE.PHASE BRIDGE

The square wave, shown in Figure 3.2(b) as the ac voltage uo6, has substantial harmonics in addition to the fundamental. These harmonics are of the order 2n -r L where n is an integer, i.e., 3rd, 5th, 7th . . . The magnitude of the 3rd is 1/3rd of the fundamental, the 5th is 1/5th of fundamental, and so on. As mentioned earlier, an inductive interface with the ac system (usually through an inductor and/or transformer) is essential to ensure that the dc capacitor does not discharge rapidly into a capacitive load such as a transmission line but it is also essential to reduce the consequent harmonic current flow. Generally, an ac filter would be necessary following the inductive interface to limit the consequent current harmonics on the system side although the filters will only increase the harmonic current in the converter itself. It would therefore be preferable if the converter generated less harmonics so that it does not require ac fllters in the first place. Integration of the waveform in Figure 3.2(b) gives the rms value of the square wave ac voltage with a peak voltage of V6:

$$V_{ab} = \sqrt{\frac{1}{\pi}\int_{-\pi/2}^{+\pi/2} V_d^2 \, d\omega t} = V_d$$

which includes the fundamental and the harmonics. The fundamental and individual harmonics are given by

$$v = \frac{4}{\pi}(V_d)\left[\cos \omega t - \frac{1}{3}\cos 3\omega t + \frac{1}{5}\cos 5\omega t - \frac{1}{7}\dots\right]$$

which gives

$$v_n = \frac{4}{\pi}(V_d)\left[\frac{1}{n}\cos n\omega t\right]$$

for $n = 1, 3, 5, 7, \dots$

and its rms value given by

$$V_n = \frac{1}{n}\frac{2\sqrt{2}}{\pi}V_d$$

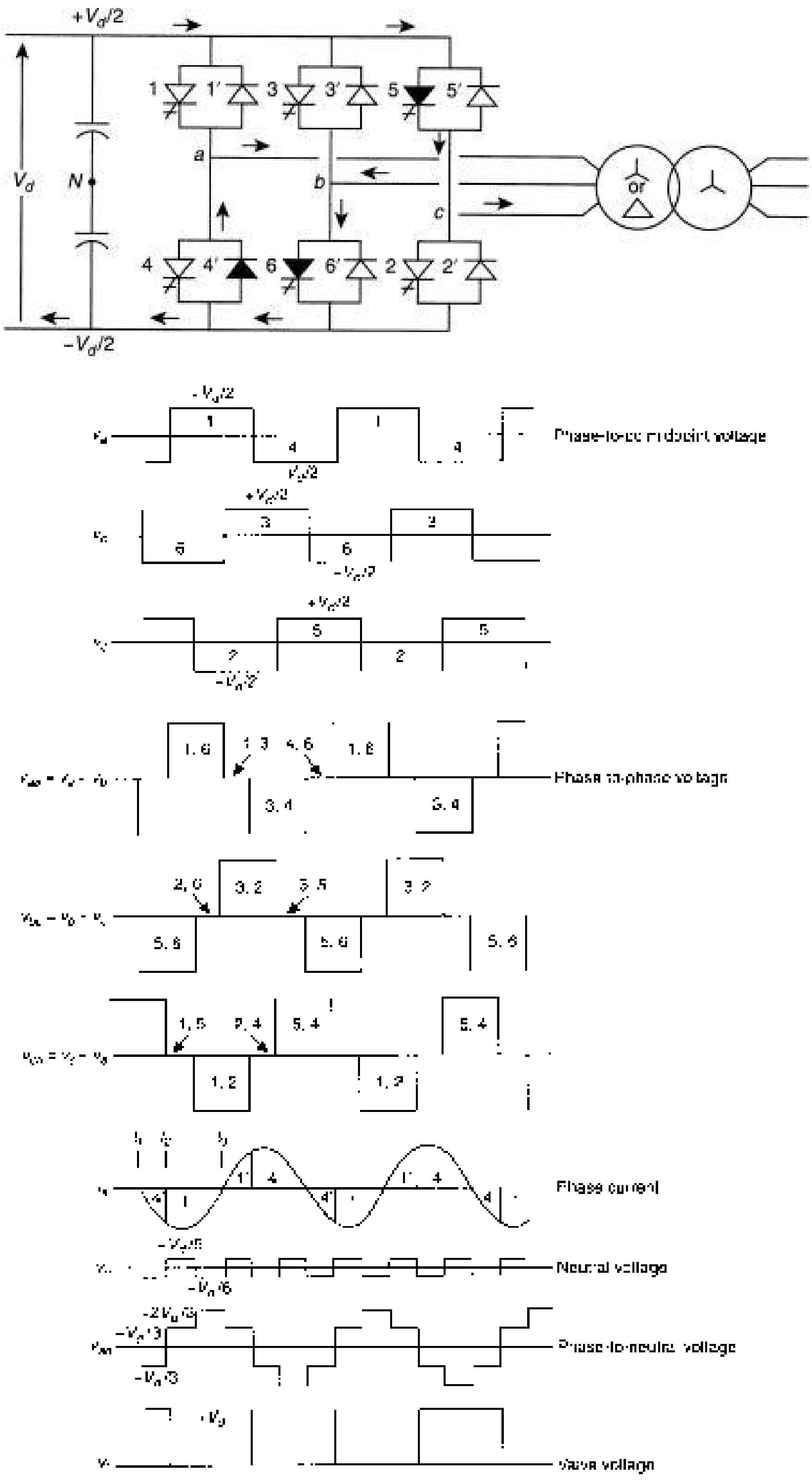
Thus, the rms fundamental component of a square wave ac voltage v_{ab} is

$$V_1 = \frac{2\sqrt{2}}{\pi}V_d = 0.9V_d$$

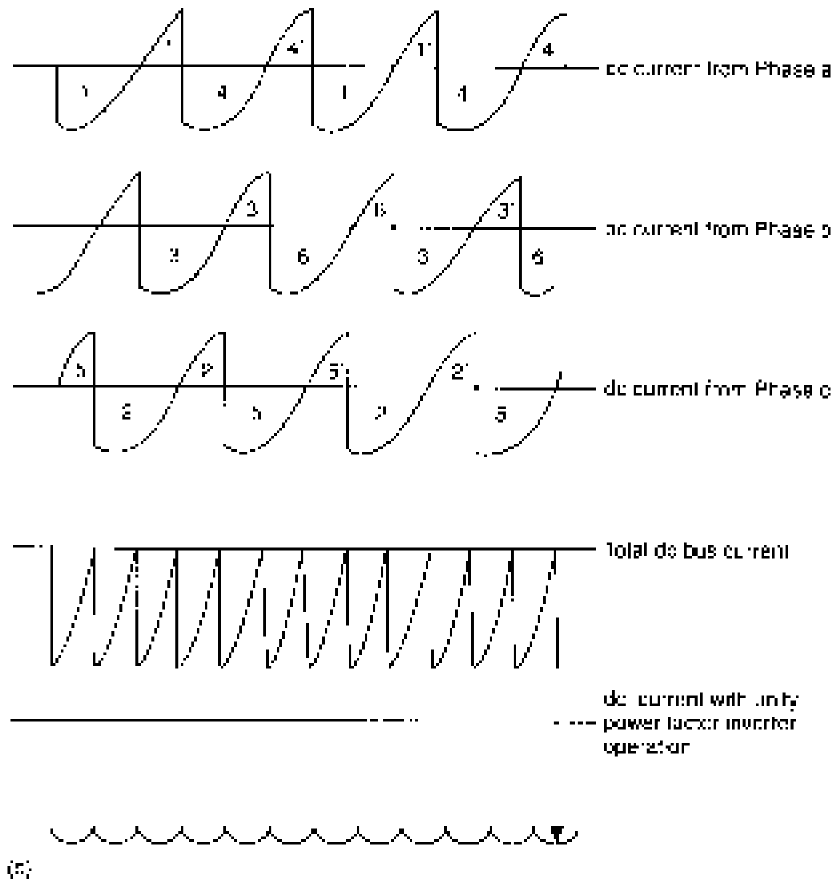
THREE.PHASE FULL.WAVE BRIDGE CONVERTER

Converter Operation

Figure 3.4(a) shows a three-phase, full-wave converter with six valves, (1-1') to (6-6'). The designated order 1 to 6 represents the sequence of valve operation in time. It consists of three phase-legs, which operate in concert,l20 degrees apart. The three phase-legs operate in a square wave mode, in accordance with the square wave mode described in the section above and with reference to Figure 3.3. Each valve alternately closes for L80 degrees as shown by the waveforms u6,u6, zrrd u. in Figure 3.4(b). These three square-wave waveforms are the voltages of ac buses a, b, and c Vza dat : Va Section 3.5 I Three-Phase Full-Wave Bridge Converter with respect to a hypothetical dc-capacitor midpoint, N, with peak voltages of *valT and -Val2. The three phase legs have their timing 120 degrees apart with respect to each other in what amounts to a 6-pulse converter operation. Phase-leg 3-6 switches 120 degrees after phase-leg7-4, and phaseJeg 5-2 switches 120 degrees after phaseleg 3-6, thus completing the cycle as shown by the valve close-open sequence. Figure 3.4(b) also shows the three phase-to-phase voltages ; n abt t) bc, and u 6", where uab: l)o - ub,ub": ub u", and u"o: t)" - uo. It is interesting to note that these phaseto-phase voltages have 120 degrees pulse-width with peak voltage magnitude of Va. The periods of 60 degrees, when the phase-to-phase voltages are zero, represent the condition when two valves on the same side of the dc bus are closed on their dc bus.


+V_d/2
1
1′
3
3′
5
5′
a
b
c
V_d
N
or
4
4′
6
6′
2
2′
−V_d/2
+V_d/2
1
4
−V_d/2
v_a
Phase-to-dc midpoint voltage
+V_d/2
3
6
−V_d/2
v_b
+V_d/2
5
2
−V_d/2
v_c
1, 6
1, 3
4, 6
3, 4
v_ab = v_a − v_b
Phase-to-phase voltage
2, 6
3, 2
3, 5
5, 6
v_bc = v_b − v_c
1, 5
2, 4
5, 4
1, 2
v_ca = v_c − v_a
t_1
t_2
t_3
i_a
4′
1
1′
4
Phase current
+V_d/6
−V_d/6
v_N
Neutral voltage
+2V_d/3
+V_d/3
v_aN
−V_d/3
Phase-to-neutral voltage
+V_d
v_1
Valve voltage

(b)



TRANSFORMER CONNECTIONS FOR 12.PULSE OPERATION

In Section 3.5, harmonic content of the phase-to-phase voltage and phase-to-neutral voltage was discussed, and it was mentioned that the two voltages were 30 degrees out of phase. If this phase shift is corrected, then for the phase to neutral voltage, i.e., u*, the harmonics, other than those of the order of. 72n -r L, w_ould be in phase opposition to those of the phase-to-phase voltage ua6 arfid with 1/V3 times the amplitude. It follows then, as shown in Figure 3.6(a), that if the phase-to-phase voltages of a second converter were connected to a delta-connected secondary of a second transformer, with \6 times the turns compared to the wye-connected slcondary, and the pulse train of one converter was shifted by 30 degrees with respect to the other (in order to bring us6 dnd uo,tobe in phase), the combined output voltage would have a 12-pulse waveform, with harmonics of the order of lZn + 1, i.e., l1th, 13th, 23rd, 25th ..., and with amplitudes of 1/11th, 7l!3th,1l23rd,Ilzsth..., respectively, compare,.l to the fundamental. Figure 3.6(b) shows the two waveforms u* and uo6, adjusted for the transformer ratio and one of them phase displaced by 30 degrees. These two waveforms are then added to give the third waveform, which is seen to be a 12-pulse waveform, closer to being a sine wave than each of the six-pulse waveform. In the arrangement of Figure 3.6(a), the two six-pulse converters, involving a total of six phase-legs are connected in parallel on the same dc bus, and work together t as a 12-pulse converter. It is necessary to have two separate transformers, otherwise phase shift in the non-12-pulse harmonics, i.e.,5th,7th,17th,19th . . . in the secondaries will result in a large circulating current due to common core flux. To the non-1"2-pulse voltage harmonics, common core flux will represent a near short circuit. Also for the same reason, the two primary side windings should not be directly connected in parallel to the same three-phase ac busbars on the primary side. Again this is because the non-1"2-pulse voltage harmonics, i.e., 5th, 7th, t7th,19th . . ., while they cancel out looking into the ac system, would be in phase for the closed loop. Consequently, a large current corresponding to these harmonics will also flow in this loop, limited only by the impedance of the loop, which is essentially the leakage inductance of the transformers

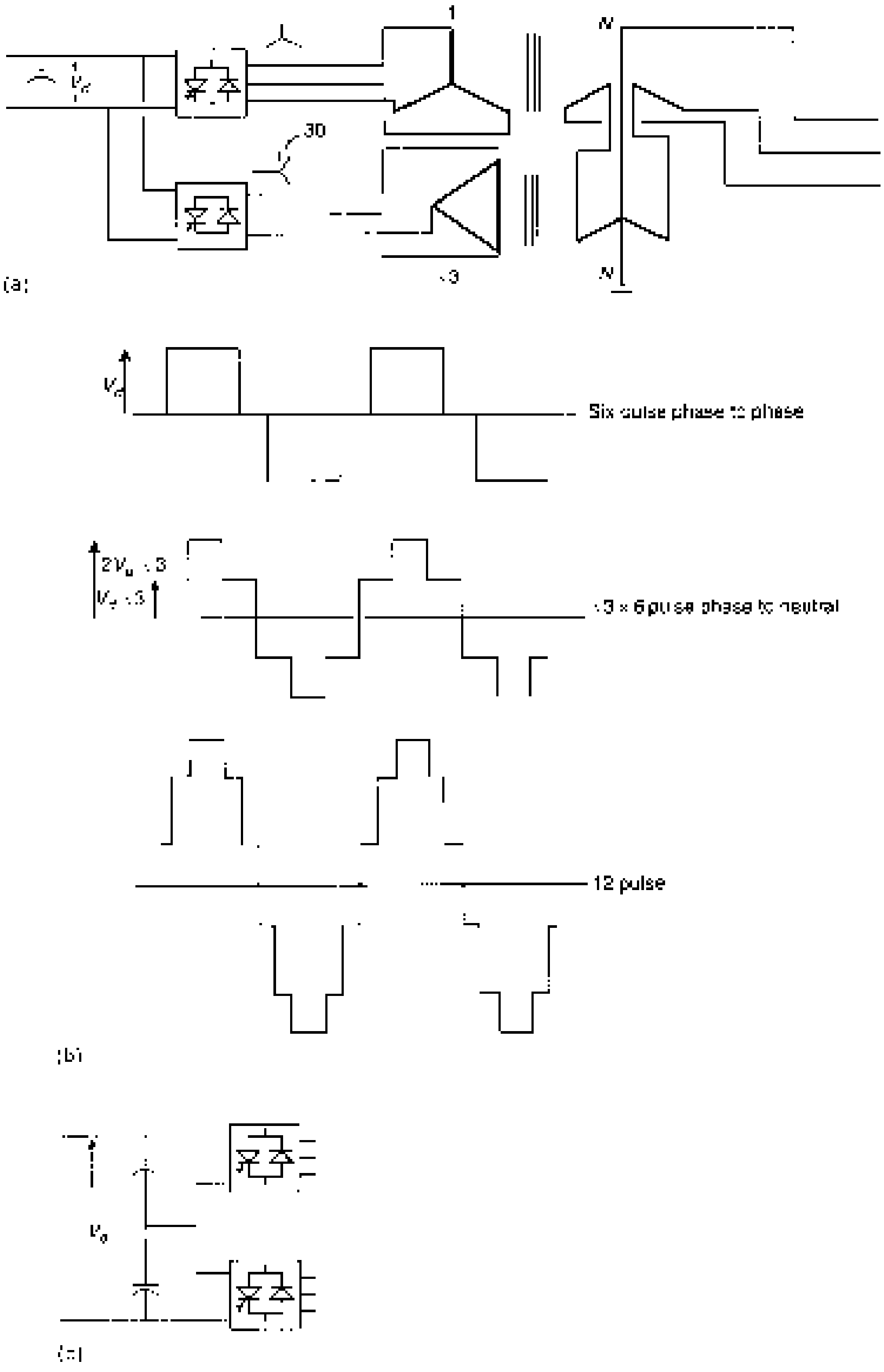


Figure 3.6 Twelve-pulse voltage sourced converter: (a) 12-pulse converter with wye and delta secondaries; (b) 12 pulse waveform from two six-pulse waveforms; (c) 12-pulse converter with two series connected six-pulse converters.

THREE.LEVEL VOLTAGE-SOURCED CONVERTER

Operation of Three-Level Converter

It was mentioned earlier in this chapter that it would be desirable to vary the magnitude of ac output voltage without having to change the magnitude of the dc voltage. The three-level converter is one concept that can accomplish that to some extent. One phase-leg of a three-level converter is shown in Figure 3.8(a). The other two phase-legs (not shown) would be connected across the same dc busbars and thr clamping diodes connected to the same midpoint N of the dc capacitor. It is seen tha each half of the phase leg is split into two series connected valves, i.e., 1-f is spl into L-1' and 1A-1'A. The midpoint of the split valves is connected by diodes and Da to the midpoint N as shown. On the face of it, this may seem like doubling the number of valves from two to four per phaseJeg in addition to providing two extra diode valves. However, doubling the number of valves with the same voltage rating would double the dc voltage and hence the power capacity of the converter. Thus only the addition of the diode clamping valves, Dl and D2,pet phase-leg, Figure 3.8(a), adds to the converter cost. If the converter is a high-voltage converter with devices in series, then the number of main devices would be about the same. A diode clamp at the midpoint may also help ensure a more decisive voltage sharing between the two valvehalves. On the other hand, requirement that a converter continue safe operation with one failed device in a string of series connected devices, may require some extra devices.

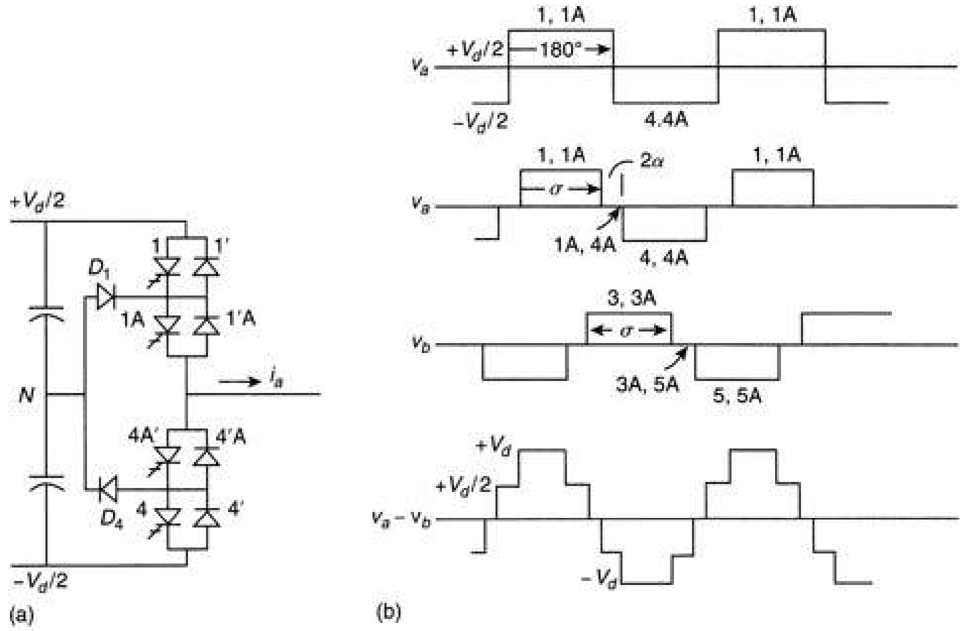
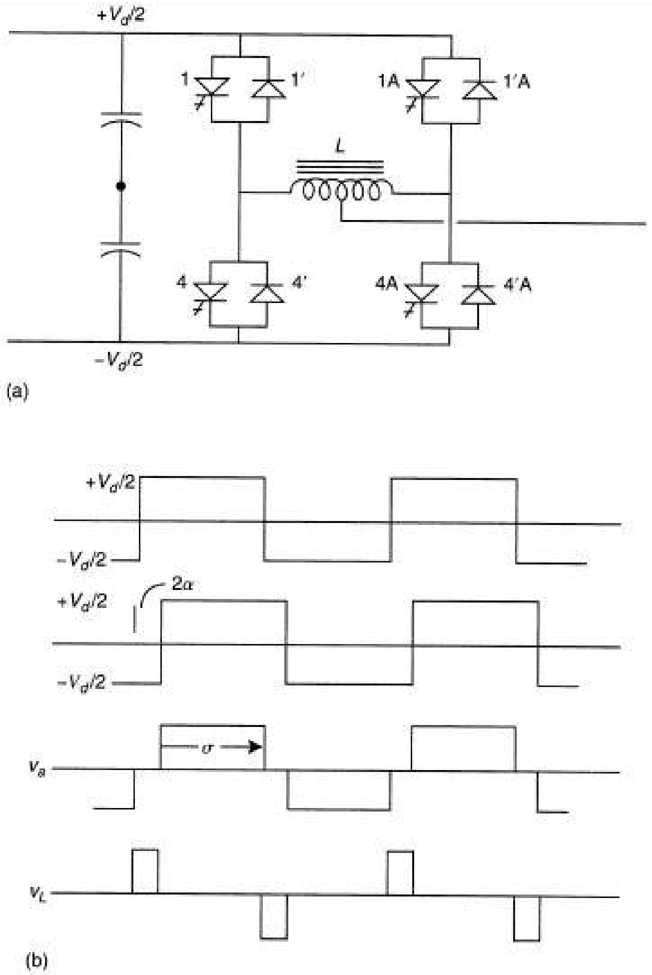


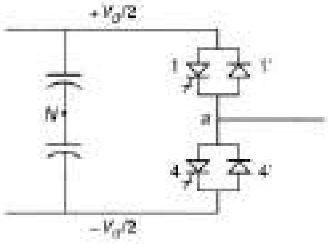
Figure 3.8 Operation of a three-level converter: (a) One phase-leg of a three-level converter; (b) Output ac voltage.

PULSE-WTDTH MODULATTON (PWM) CONVERTER

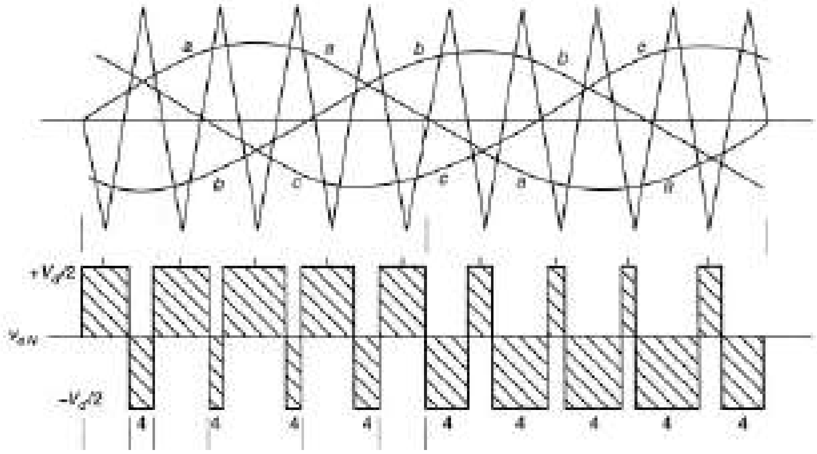
In two-level or multilevel converters, there is only one turn-on, turn-off per device per cycle. With these converters, the ac output voltage can be controlled, by varying the width of the voltage pulses, and/or the amplitude of the dc bus voltage. Another approach is to have multiple pulses per half-cycle, and then vary the width of the pulses to vary the amplitude of the ac voltage. The principal reason for doing so is to be able to vary the ac output voltage and to reduce the low-order harmonics, as will be explained here briefly. It goes without saying that more pulses means more switching losses, so that the gains from the use of PWM have to be sufficient to justify an increase in switching losses. There are also resonant PWM converter topologies that incorporate current-zero or voltage-zero type soft switching, in order to reduce the switching losses. Such converters are being increasingly utilized in some low power applications, but with the known topologies, they have not been justifiable at high power levels due to higher equipment cost.

PWM converters of low voltage and low power in the range of tens of watts. for, say, printed circuit boards' power supplies, may have internal pwM frequency in the hundreds of kilohertz. Industrial drives in tens of kilowatts may have inteinal PWM frequency in the tens of kilohertz. For converters in the 1 MW range, such as for Custom Power, the frequency may be in a few kilohertz range. For FACTS technology with high power in the tens of megawatts and converter voltage in kVs and tens of kVs, low frequencies in the few hundred Hertz or maybe the low kilohertz range may seem feasible and worth considering.





(a)



The following observations are worth noting with respect to the waveforms

1. The output voltage waveform contains a fundamental frequency component and harmonics.
2. The output voltage pulses are symmetrical about the zero crossings of the sine wave, because the sawtooth frequency is an odd integer multiple of the main frequency. Any even multiple will create asymmetry about the zero crossing, which will contain even harmonics. Non-integer multiples are even worse as they create sub- and supersynchronous harmonics as well. When the frequency is high, above a few kilohertz, this asymmetry becomes insignificant, but at the low PWM frequencies synchronization of the control signals is important.
3. With a fixed sawtooth wave, increasing the magnitude of the sine wave will increase the conduction time of device L, and decrease the conduction time of device 4 for the positive half-cycle and vice versa for the negative halfcycle. This means that the fundamental component of the ac voltage Voyl and hence the output ac voltage will increase with an increase in the magnitude of the control sine wave and decrease with a decrease in the magnitude of the control sine wave. For control sine wave peak less than the sawtoothwave peak, the output ac voltage varies linearly with variation of the control sine wave.
4. As the control sine-wave peak equals the peak of the sawtooth wave, the middle notch in the ac output voltage disappears. If the control sine wave is increased to a higher and higher magnitude, more and more notches will disappear and the output voltage will eventually become a single square wave per half-cycle.
5. It is clear that the ac output voltage can be controlled from zero to maximum.
6. The sine wave itself can be modified with notches, etc. to create other effects on the waveform.

BASIC CONCEPT OF CURRENT.SOURCED CONVERTERS

A current-sourced converter is characterized by the fact that the dc current flow is always in one direction and the power flow reverses with the reversal of dc voltage. In this respect, it differs from the voltage-sourced converter in which the dc voltage always has one polarity and the power reversal takes place with reversal of dc current. Figure 4.1 conveys this difference between the current sourced and the voltage sourced converters

Thus there are three principal types of current-sourced converters (Figure 4.2):

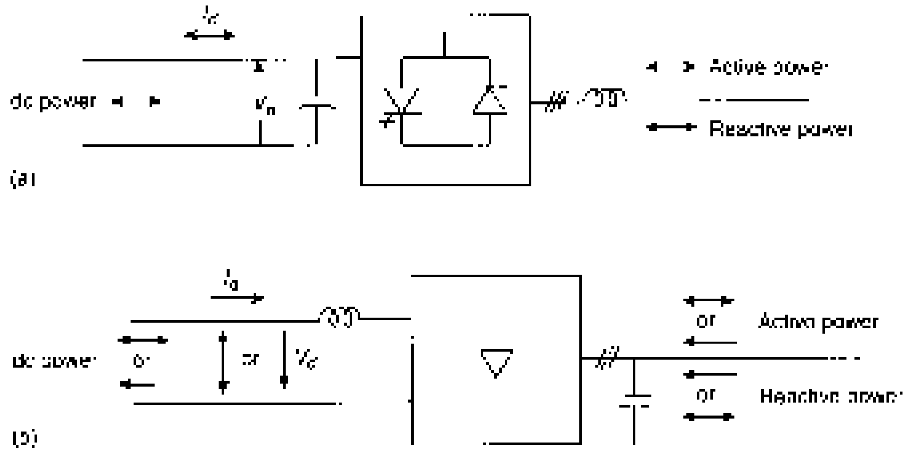


Figure 4.1 Voltage-sourced and current-sourced converter concepts: (a) voltage-sourced converter; (b) current-sourced converter.

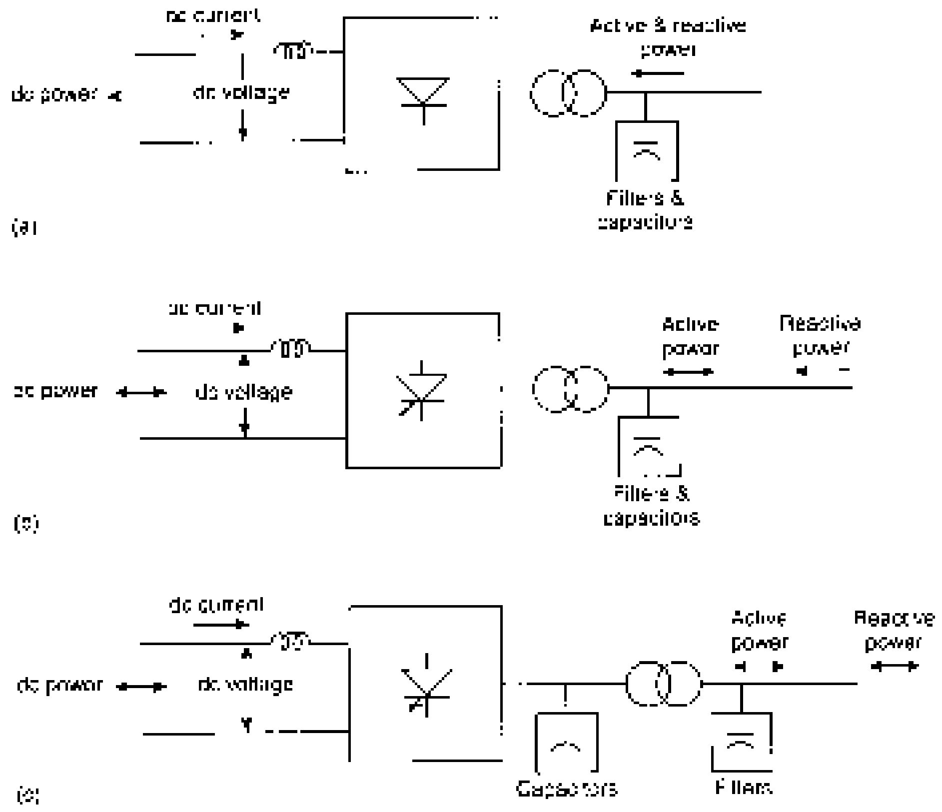


Figure 4.2 Types of current-sourced converters: (a) diode rectifier; (b) thyristor line-commutated converter; (c) self-commutated converters.

1 . Diode converter [Figure 4.2(a)], which simply converts ac voltage to dc voltage, and utilizes ac system voltage for commutation of dc current from one valve to another. obviously the diode-based, line-commutating converter

just converts ac power to dc power without any control and also in doing so consumes some reactive power on the ac side.

2. Line-commutated converter, based on conventional thyristors (with gate turnon but without gate turn-off capability), Figure 4.2(b), utilizes ac system voltage for commutation of current from one valve to another. This converter can convert and control active power in either direction, but in doing so consumes reactive power on the ac side. It can not supply reactive power to the ac system.

3. Self-commutated converter which is based on turn-off devices (GTOs, MTOs, IGCTs, IGBTs, etc.), in which commutation of current from valve to valve takes place with the device turn-off action and provision of ac capacitors, to facilitate transfer of current from valve to valve. whereas, in a voltage-sourced converter the commutation of current is supported by a stiff dc bus with a dc capacitor, in a self-commutated current-sourced converter, the ac capacitors provide a stiff ac bus for supplying the fast changing current pulses needed for the commutations. Apart from its capability of controlled power flow in either direction, this converter, like the voltage-sourced converter, can also supply or consume controlled reactive power. However, it is interesting to note that even though the converter can supply reactive power, sources of reactive power, i.e., capacitors and ac filters, are needed in any case. An advantage of the converters with turn-off devices (self-commutating converters) is that they offer greater flexibility including pwM mode of operation.

A ac side converter voltage will also have harmonics. Assuming sinusoidal voltage at the ac capacitor terminals, the dc voltage harmonics are defined by (4.22), but with $\gamma = 0$:

$$e_s = \sqrt{2}\, E \cos\left(\omega t + \frac{\pi}{6}\right) \quad \text{for} \quad 0 < \omega t < \alpha$$
$$e_a = \sqrt{2}\, E \cos\left(\omega t - \frac{\pi}{6}\right) \quad \text{for} \quad \alpha < \omega t < (\pi/3) \qquad (4.23)$$

CURRENT.SOURCED VERSUS VOLTAGE.SOURCED CONVERTERS

1. There are some advantages and disadvantages of current-sourced versus voltagesourced converters: Diode-based converters are the lowest cost converters, if control of active power by the converter is not required.
2. If the leading reactive power is not required, then a conventional thyristorbased converter provides a low-cost converter with active power control. It can also serve as a controlled lagging reactive power load (like a thyristorcontrolled reactor).
3. The curent-sourced converter does not have high short-circuit current, as does the voltage-sourced converter. For current-sourced converters, the rate of rise of fault current during external or internal faults is limited by the dc reactor. For the voltage-sourced converters, the capacitor discharge current would rise very rapidly and can damage the valves.
4. The six-pulse, current-sourced converter does not generate third harmonic voltage, and its transformer primaries for a 12-pulse converter do not have to be connected in series for harmonic cancellation. It is also relatively simple to obtain a 24-pulse operation with phase-shifting windings.
5. In a current-stiff converter, the valves are not subject to high durdt, due to the presence of the ac capacitors.
6. Ac capacitors required for the current-stiff converters can be quite large and expensive, although their size can be decreased by adoption of pWM topology. In general the problem of a satisfactory interface of current-sourced converters with the ac system is more complex.

7. continuous losses in the dc reactor of a current-sourced converter are much higher than the losses in the dc capacitor. These losses can represent a significant loss penalty. with the presence of capacitors, which are subjected to commutation charging and discharging, this converter will produce harmonic voltages at a frequency of resonance between the capacitors and the ac system inductances.
8. Adverse effects of this can be avoided by sizing the capacitors such that the resonance frequency does not coincide with characteristic harmonics.
9. These harmonics as well as the presence of a dc reactor can result in overvoltages on the valves and transformers. I Widespread adoption of asymmetrical devices, IGBTs and GTOs, as the devices of choice for lower on-state losses, has made voltage-sourced converters a favorable choice when turn-off capability is necessary.
10. The device market is generally driven by high-volume industrial applications, and as a result symmetrical turn-off devices of high-voltage ratings and required operating characteristics, in particular the switching characteristics, may not be readily available until the volume of the FACTS market increases.

UNIT-III

STATIC SHUNT COMPENSATION

OBJECTIVES OF SHUNT COMPENSATION

It has long been recognizedthat the steady-state transmittable power can be increased and the voltage profile along the line controlled by appropriate reactive shunt compensation. The purpose of, this reactive compensation is to chage the natural electrical characteristics of the transmission line to make it more compatible with the prevailing load demand. Thus, shunt connected, fixed or mechanically switched reactors are applied to minimize line overvoltage under light load conditions, and shunt connected, fixed or mechanically switched capacitors are applied to maintain voltage levels under heavy load conditions. In this section, basic considerations to increase the transmittable power by ideal shunt-connected var compensation will be reviewed in order to provide a foundation for power electronics-based compensation and control techniques to meet specific compensation objectives. The ultimate objective of applying reactive shunt compensation in a transmission system is to increase the transmittable power. This may be required to improve the steady-state transmission characteristics as well as the stability of the system. Var compensation is thus used for voltage regulation at the midpoint (or some intermediate) to segment the transmission line and at the end of the (radial) line to prevent voltage instability, as well as for dynamic voltage control to increase transient stability and damp power oscillations.

Midpoint Voltage Regulation for Line Segmentation

Consider the simple two-machine (two-bus) transmission model in which an ideal var compensator is shunt connected at the midpoint of the transmission line, as shown in Figure 5.1(a). For simplicity, the line is represented by the series line inductance. The compensator is represented by a sinusoidal ac voltage source (of the fundamental frequency), in-phase with the midpoint voltage, V., and with an amplitude identical to that of the sending- and receiving-end voltages (V^: V, : V, : V) The midpoint compensator in effect segments the transmission line into two independent parts: thefirst segment, with an impedance of Xl2, carries power from the sending end to the midpoint, and the second segment, also with an impedance of Xl2, carries power from the midpoint to the receiving end. The relationship between voltages, V,, V,, 7,, (together with Vr., V^,), and line segment currents .I", and 1," is shown by the phasor diagram in Figure 5.1(b). Note that the midpoint var compensator exchanges only reactive power with the transmission line in this process. For the lossless system assumed, the real power is the same at each terminal (sending end, midpoint, and receiving end) of the line, and it can be derived readily from the phasor diagram of Fig. 5.1(b). With

$$V_{sm} = V_{mr} = V\cos\frac{\delta}{4}; \qquad I_{sm} = I_{mr} = I = \frac{4V}{X}\sin\frac{\delta}{4}$$

the transmitted power is

$$P = V_{sm}I_{sm} = V_{mr}I_{mr} = V_mI_{sm}\cos\frac{\delta}{4} = VI\cos\frac{\delta}{4}$$

or

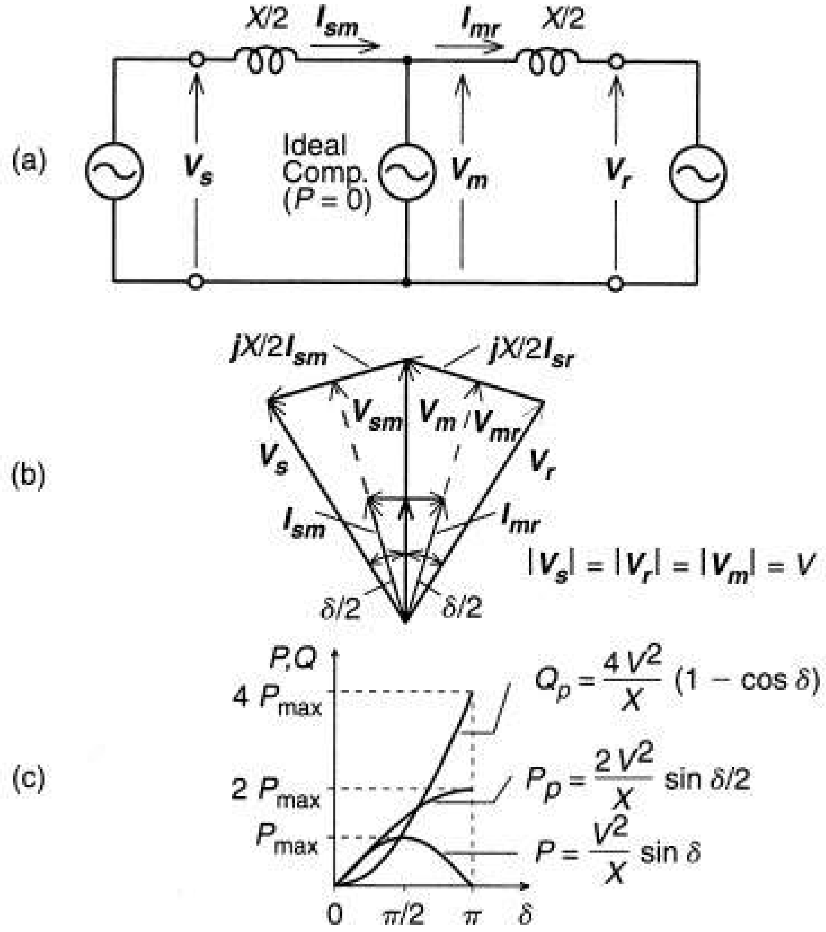


Figure 5.1 Two-machine power system with an ideal midpoint reactive compensator (a), corresponding phasor diagram (b), and power transmission vs. angle characteristic showing the variation of real power P_p and the reactive power output of the compensator Q_p with angle δ (c).

$$P = 2\frac{V^2}{X}\sin\frac{\delta}{2}$$

Similarly

$$Q = VI\sin\frac{\delta}{4} = \frac{4V^2}{X}\left(1 - \cos\frac{\delta}{2}\right)$$

The relationship between real power P, reactive power Q, and angle d'for the case of ideal shunt compensation is shown plotted in Figure 5.1(c). It can be observed that the midpoint shunt compensation can significantly increase the transmittable power (doubling its maximum value) at the expense of a rapidly increasing reactive power demand on the midpoint compensator (and also on the end-generators). It is also evident that for the single-line system of Figure 5.1 the midpoint of the transmission line is the best location for the compensator. This is because the voltage sag along the uncompensated transmission line is the largest at the midpoint. Also, the compensation at the midpoint breaks the transmission line into two equal segments for each of which the maximum transmittable power is the same. For unequal segments, the transmittable power of the longer segment would clearly determine the overall transmission limit.

would rapidly decrease, approaching the ideal case of constant voltage proflle. It is to be appreciated that such a distributed compensation hinges on the instantaneous response and unlimited var generation and absorption capability of the shunt compensators employed, which would have to stay in synchronism with the prevailing phase of the segment voltages and maintain the predefined amplitude of the transmission voltage, independently of load variation. Such a system, however, would tend to be too complex and probably too expensive, to be practical, particularly if stability and reliability requirements under appropriate contingency conditions are also considered. However, the practicability of limited line segmentation, using thyristor-controlled static var compensators, has been demonstrated by the major, 600 mile long,735 kV transmission line of the Hydro-Quebec power system built to transmit up to 12000 MW power from the James Bay hydro-complex to the City of Montreal and to neighboring U.S. utilities. More importantly, the transmission benefits of voltage support by controlled shunt compensation at strategic locations of the transmission system have been demonstrated by numerous installations in the world

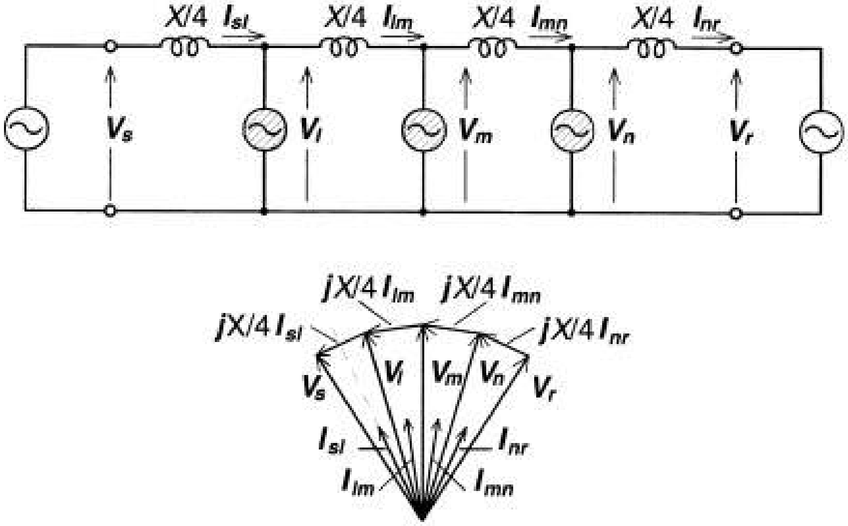


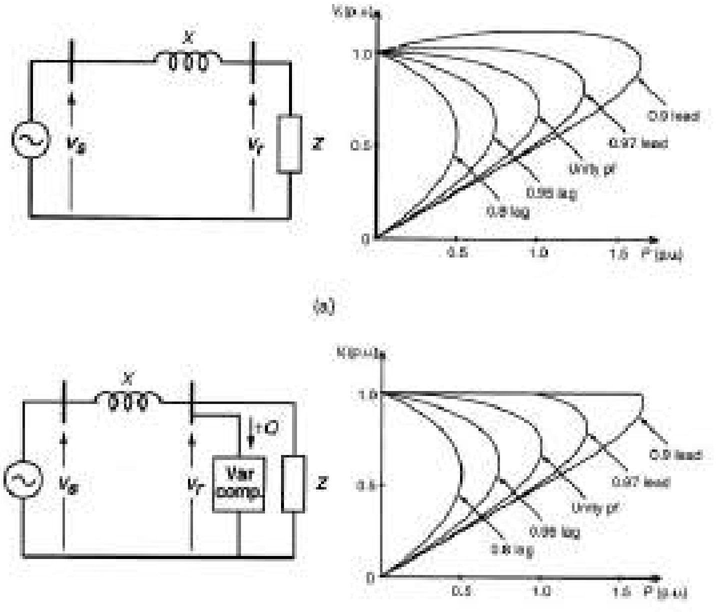
Figure 5.2 Two-machine system with ideal reactive compensators maintaining constant transmission voltage profile by line segmentation, and associated phasor diagram.

End of Line Voltage Support to Prevent Voltage Instability

The midpoint voltage support of a two-machine transmission power system discussed above can easily extend to the more special case of radial transmission. Indeed, if a passive load, consuming power P at voltage V, is connected to the midpoint in place of the receiving-end part of the system (which comprises the receiving-end generator and transmission link Xl2), the sending-end generator with the Xl2 impedance and load would represent a simple radial system. Clearly, without compensation the voltage at th-e midpoint (which is now the receiving end) would vary with the load (and load power factor). A simple radial system with feeder line reactance of X and load impedance Z, is shown in Figure 5.3(a) together with the normalized terminal voltage I/, versus power P plot at various load power factors, ranging from 0.8 lag and 0.9 lead. The "nose-point" at each plot given for a specific power factor represents the voltage instability corresponding to that system condition. It should be noted that the voltage stability limit decreases with inductive loads and increases with capacitive loads. The inherent circuit characteristics of the simple radial structure, and the V, versus P plots shown, clearly indicate that shunt reactive compensation can effectively increase the voltage stability limit by supplying the reactive load and regulating the terminal voltage (V - V,: 0) as illustrated in Figure 5.3(b). It is evident that for a radial line, the end of the line, where the largest voltage variation is experienced, is the best location for the compensator. (Recall that, by contrast, the midpoint is the most effective location for the line interconnecting two ac system buses.) Reactive shunt compensation is often used in practical applications to regulate the voltage at a given bus against load variations, or to provide voltage support for the load when, due to generation or line outages, the capacity of the sending-end system becomes impaired. A frequently encountered example is when a large load area is supplied from two or more generation plants with independent transmission lines. (This frequently happens when the locally generated power becomes inadequate to supply a growing load area and additional power is imported over a separate transmission link.) The loss of one of the power sources could suddenly increase the load demand on the remaining part of the system, causing severe voltage depression that could result in an ultimate voltage collapse.

lmprovement ol Transient Stability

As seen in the previous sections, reactive shunt compensation can significantly increase the maximum transmittable power. Thus, it is reasonable to expect that, with suitable and fast controls, shunt compensation will be able to change the power flow



(a)

(b)

Figure 5.3 Variation of voltage stability limit of a radial line with load and load power factor (a), and extension of this limit by reactive shunt compensation (b).

The potential effectiveness of shunt (as well as other compensation and flow control techniques) on transient stability improvement can be conveniently evaluated by the equal area criterion. The meaning of the equal area criterion is explained with the aid of the simple two machine (the receiving end is an infinite bus), two line system shown in Figure 5.4(a) and the corresponding P versus 6 curves shown in Figure 5.4(b). Assume that the complete system is characterizedby the P versus 6 curve "a" and is operating at angle Q to transmit power P1 when a fault occurs at line segment "1.." During the fault the system is characterized by the P versus 6 curve "b" and thus, over this period, the transmitted electric power decreases significantly while mechanical input power to the sending-end generator remains substantially constant corresponding to P1. As a result, the generator 4gcelerates and the transmission angle increases from 4 to d'z at which the protective breakers disconnect the faulted line segment "1" and the sending-end generator absorbs accelerating energy, represented by area "4L." After fault clearing, without line segment "1" the degraded system is characterized

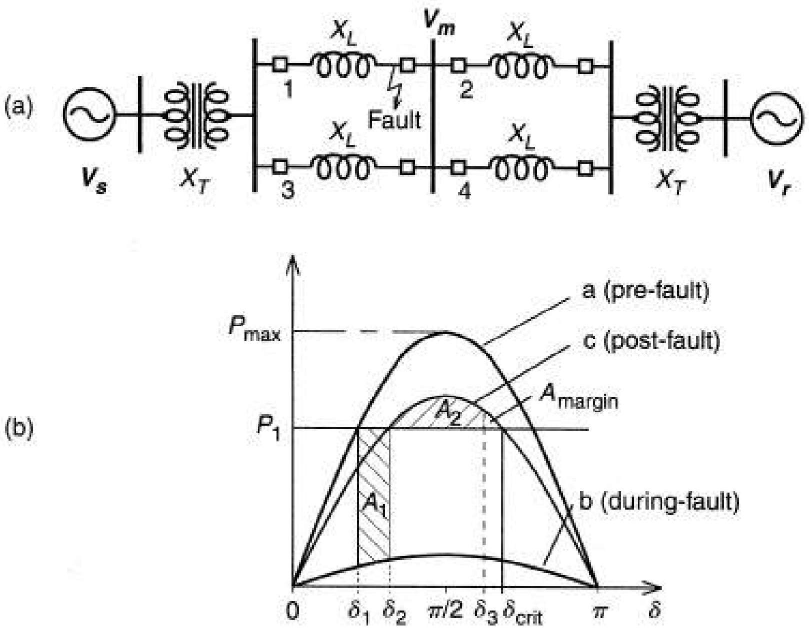


Figure 5.4 Illustration of the equal area criterion for transient stability of a two-machine, two-line power system.

Comparison of Figures 5.5(a) and (b) clearly shows a substantial increase in the transient stability margin the ideal midpoint compensation with unconstrained var output can provide by the effective segmentation of the transmission line. Alternatively, if the uncompensated system has a sufficient transient stability margin, shunt compensation can considerably increase the transmittable power without decreasing this margin. In the preceding discussion, the shunt compensator is assumed to be ideal. The adjective "ideal" here means that the amplitude of the midpoint voltage remains constant all the time, except possibly during faults, and its phase angle follows the generator angle swings so that the compensator would not be involved in real power exchange, but it would continuously provide the necessary reactive power. As Figure 5.1(c) shows, the reactive power demand on the midpoint compensator increases rapidly with increasing power transmission, reaching a maximum value equal to four per unit at the maximum steady-state real power transmission limit of two per unit. For

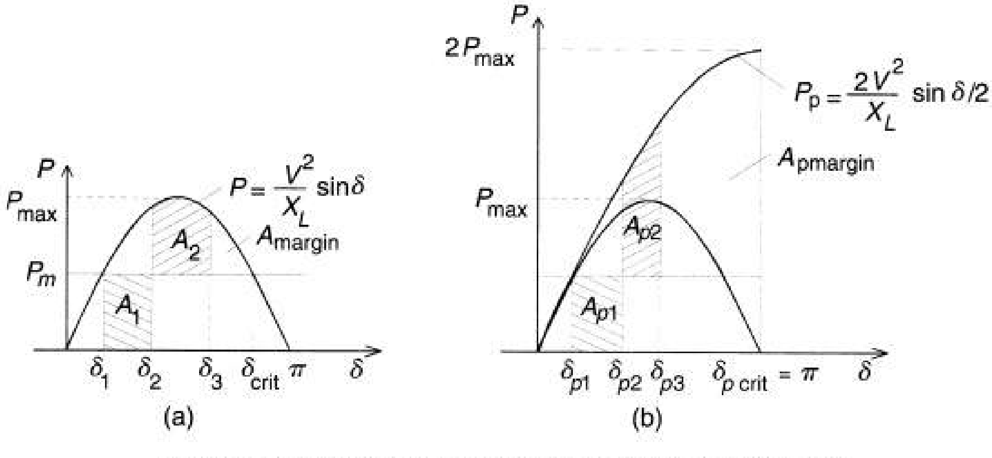


Figure 5.5 Equal area criterion to illustrate the transient stability margin for a simple two machine system without compensation (a), and with an ideal midpoint compensator (b).

Power Oscillation Damping

In the case of an under-damped power system, any minor disturbance can cause the machine angle to oscillate around its steady-state value at the natural frequency of the total electromechanical system. The angle oscillation, of course, results in a corresponding power oscillation around the steady-state power transmitted. The lack of sufficient damping can be a major problem in some power systems and, in some cases, it may be the limiting factor for the transmittable power. Since power oscillation is a sustained dynamic event, it is necessary to vary the applied shunt compensation, and thereby the (midpoint) voltage of the transmission line, to counteract the accelerating and decelerating swings of the disturbed machine(s). That is, when the rotationally oscillating generator accelerates and angle 6 increases (d6ldt > 0), the electric power transmitted must be increased to compensate for the excess mechanical input power. Conversely, when the generator decelerates and angle 6 decreases (d6l dt < 0), the electric power must be decreased to balance the insufficient mechanical input power. (The mechanical input power is assumed to be essentially constant in the time frame of an oscillation cycle.) The requirements of var output control, and the process of power oscillation damping, is illustrated by the waveforms in Figure 5.6. Waveforms in Figure 5.6(a) show the undamped and damped oscillations of angle 6 around the steady-state value fi. Waveforms in Figure 5.6(b) show the undamped and damped oscillations of the electric power P around the steady-state value P". (The momentary drop in power shown at the beginning of the waveform represents an assumed disturbance that initiated the oscillation.) Waveform c shows the reactive power output Qo of. the shunt-connected var compensator. The capacitive (positive) output of the compensator increases the midpoint voltage and hence the transmitted power when d6ldt) 0, and it decreases those when d6ldt < 0.

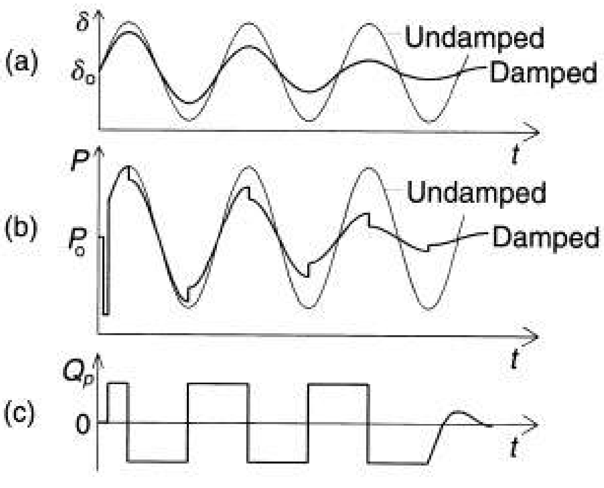


Figure 5.6 Waveforms illustrating power oscillation damping by reactive shunt compensation: (a) generator angle, (b) transmitted power, and (c) var output of the shunt compensator.

METHODS OF CONTROLLABLE VAR GENERATION

By definition, capacitors generate and reactors (inductors) absorb reactive power when connected to an ac power source. They have been used with mechanical switches for (coarsely) controlled var generation and absorption since the early days of ac power transmission. Continuously variable var generation or absorption for dynamic system compensation was originally provided by over- or under-excited rotating synchronous machines and, later, by saturating reactors in conjunction with fixed capacitors.

Modern static var generators are based on high-power semiconductor switching circuits. These switching circuits inherently determine some of the important operating characteristics, such as the applied voltage versus obtainable reactive output current, harmonic generation, loss versus var output, and attainable response time, setting limits for the achievable performance of the var generator and, independent of the external controls used, ultimately also that of the static var compensator. The followingtwo main sections describe the operating principles and characteristics of the two types of static var generator presently used: those which employ thyristor-controlled reactors with fixed and/or thyristor-switched capacitors to realize a variable reactive impedance and those which employ a switching power converter to realize a controllable synchronous voltage source. Subsequent sections deal with the application requirements, structure, and operation of the external control, applicable to both types of var generator, which define the functional capabilities and operating policies of the compensator under different system conditions.

Variable impedance Type Static Var Generators

The performance and operating characteristics of the impedance type var generators are determined by their major thyristor-controlled constituents: the thyristorcontrolled reactor and the thyristor-switched capacitor.

The Thyristor-Controlled and Thyristor-Switched Reactor (TCR and TSR)

An elementary single-phase thyristor-controlled reactor (TCR) is shown in Figure 5.7(a). It consists of a fixed (usually air-core) reactor of inductance L, and a bidirectional thyristor valve (or switch) sw. Currently available large thyristors can block voltage up to 4000 to 9000 volts and conduct current up to 3000 to 6000 amperes. Thus, in a practical valve many thyristors (typically 10 to 20) are connected in series to meet the required blocking voltage levels at a given power rating. A thyristor valve can be brought into conduction by simultaneous application of a gate pulse to all thyristors of the same polarity. The valve will automatically block immediately after the ac current crosses zero, unless the gate signal is reapplied' The current in the reactor can be controlled from maximum (thyristor valve closed) to zero (thyristor valve open) by the method of firing delay angle control. That is, the closure of the thyristor valve is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction intervals is controlled. This method of current control is illustrated separately for the positive and negative current half-cycles in Figure 5.7(b), where the applied voltage u and the reactor current iilot), at zero delay angle (switch fully closed) and at an arbitrary a delay angle, are shown. When d:0, the valve syy closes at the crest of the applied voltage and evidently the resulting current in the reactor will be the same as that obtained in steady state with a permanently closed switch. When the gating of the valve is delayed by an angle @ (0 = a < nl2) with respect to the crest of the voltage, the current in the reactor can be expressed with u(t) : V cos arl as follows:

$$i_L(t) = \frac{1}{L}\int_{\alpha}^{\omega t} v(t)\,dt = \frac{V}{\omega L}(\sin \omega t - \sin \alpha)$$

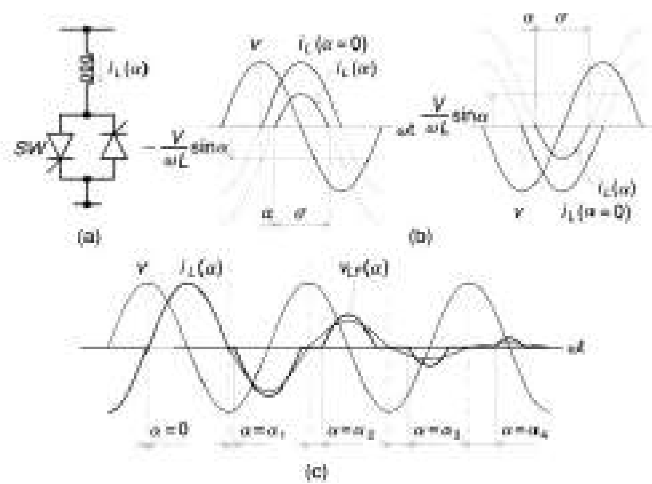


Figure 5.7 Basic thyristor-controlled reactor (a), firing delay angle control (b), and operating waveforms (c).

The TCR limits are established by design from actual operating requirements. If the TCR switching is restricted to a fixed delay angle, usually e : 0, then it becomes a thyristor-switched reactor (TSR). The TSR provides a fixed inductive admittance and thus, when connected to the ac system, the reactive current in it will be proportional to the applied voltage as the V-Iplot in Figure 5.9(b) indicates. Several

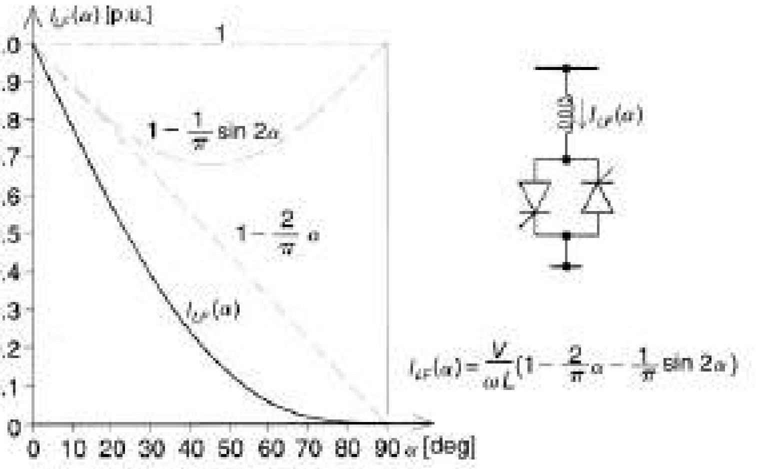


Figure 5.8 Amplitude variation of the fundamental TCR current with the delay angle α.

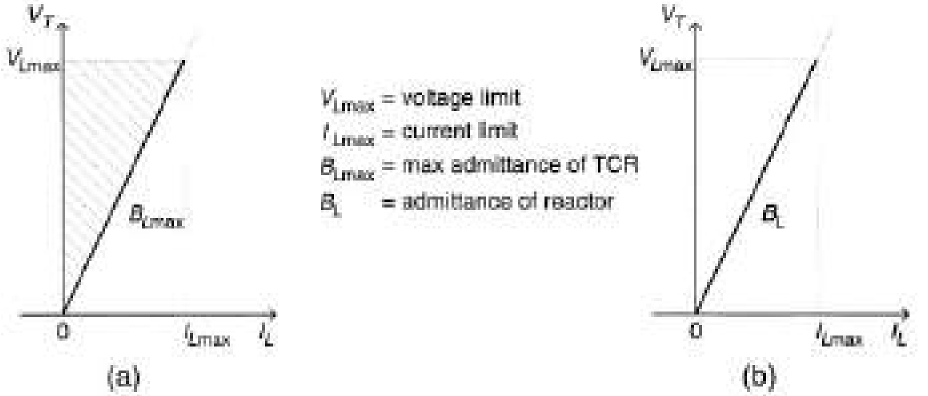


Figure 5.9 Operating V-I area of the TCR (a) and of the TSR (b).

Another method employs a L2-pulse TCR arrangement. In this, two identical three-phase delta connected thyristor-controlled reactors are used, one operated from wye-connected windings, the other from delta-connected windings of the secondary of a coupling transformer. (Other types of transformer arrangements providing two sets of three-phase voltages with 30-degree phase shift can, of course, also be used.) Because of the 30-degree phase shift between the related voltages of the two transformer windings, the 5th, 7th, 17th, 19th, generally the harmonic currents of order 6(2k- 1) - 1and6(2k - 1) + L,k:L,2,3,...cancel, resulting in an early sinusoidal output current, at all delay angles, as illustrated by the current waveforms in Figure 5.12. Further harmonic cancellation is possible by operating three or more delta connected TCRs from appropriately phase shifted voltage sets. In practice, however, these L8 and higher pulse circuit arrangements tend to be too complex and expensive. Also, it becomes increasingly difficult to meet the requirements for symmetry, due to possible unbalance in the ac system voltages, to achieve significant reduction in the amplitudes of higher order harmonics. For these reasons, higher than 12-pulse circuit configurations are seldom used. (The reader should note that this statement generally applies only to line commutated circuits employing conventional thyristors. The output voltage waveform construction of the self-commutated power circuits is largely independent of the ac system voltages and high, typically 48- or 24-pulse voltage-sourced converter structures have been used in all existing high-power compensator installations.)

Section 5.2 ■ Methods of Controllable VAR Generation

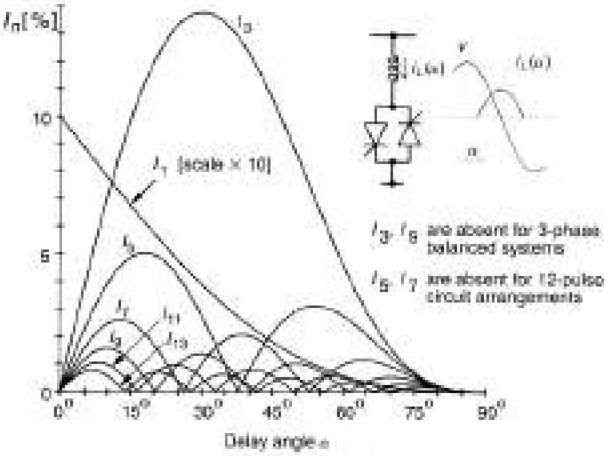


Figure 5.10 Amplitudes of the harmonic components in the current of the TCR versus the delay angle α.

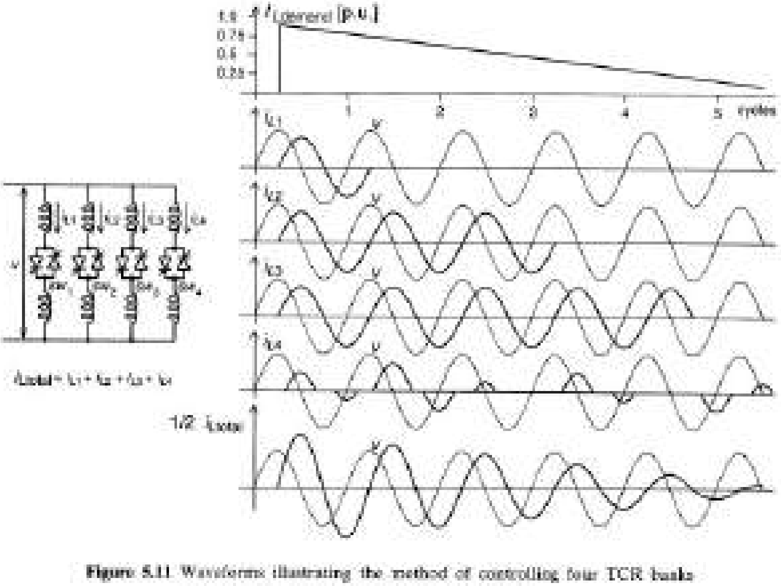


Figure 5.11 Waveforms illustrating the method of controlling four TCR banks "sequentially" to achieve harmonic reduction.

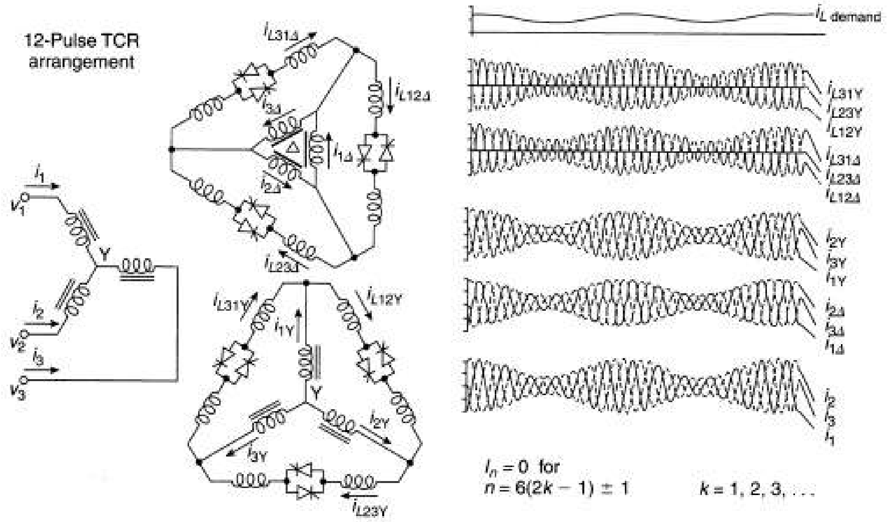


Figure 5.12 Twelve-pulse arrangement of two sets of thyristor-controlled reactors and associated current waveforms.

The Thyristor-Switched Capacitor (TSC)

A single-phase thyristorswitched capacitor (TSC) is shown in Figure 5.13(a). It consists of a capacitor, a bidirectional thyristor valve, and a relatively small surge current limiting reactor. This reactor is needed primarily to limit the surge current in the thyristor valve under abnormal operating conditions (e.g., control malfunction causing capacitor switching at a "wrong time," when transient free switching conditions are not satisfied); it may also be used to avoid resonances with the ac system impedance at particular frequencies. Under steady-state conditions, when the thyristor valve is closed and the TSC branch is connected to a sinusoidal ac voltase source. u : V sin orf. the current in the branch is given by

$$i(\omega t) = V\frac{n^2}{n^2-1}\omega C\cos\omega t$$

where

$$n = \frac{1}{\sqrt{\omega^2 LC}} = \sqrt{\frac{X_C}{X_L}}$$

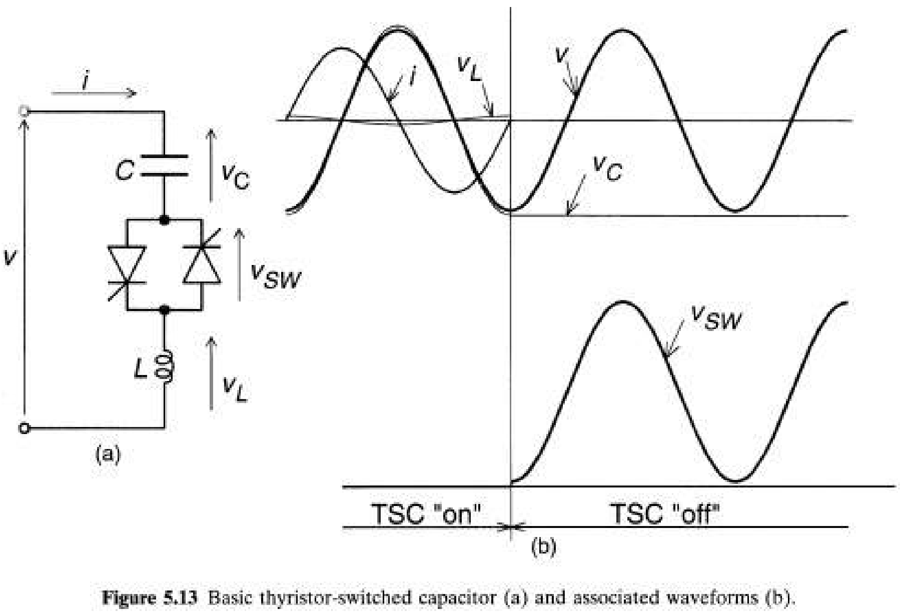


Figure 5.13 Basic thyristor-switched capacitor (a) and associated waveforms (b).

This can be accomplished with the minimum possible transient disturbance if the thyristor valve is turned on at those instants at which the capacitor residual voltage and the applied ac voltage are equal, that is, when the voltage across the thyristor valve is zero. Figure 5.15(a) and (b) illustrate the switching transients obtained with a fully and a partially discharged capacitor. These transients are caused by the nonzero du I dt at the instant of switching. which, without the series reactor, would result in an instantaneous current of i, : Cdu I dt in the capacitor. (This current represents the instantaneous value of the steady

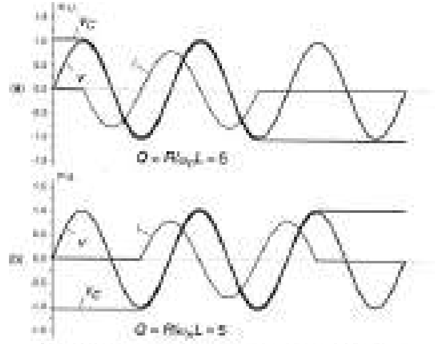
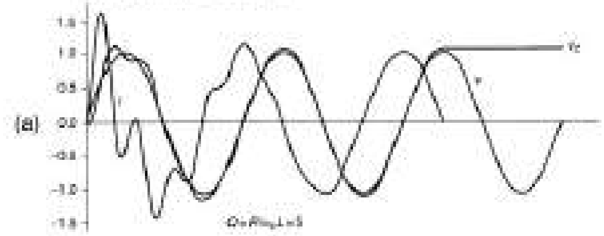


Figure 5.14 Waveforms illustrating transient-free switching by a thyristor-switched capacitor.

P.U. (a) Capacitor fully discharged



P.U. (b) Initial capacitor charge of 0.5 p.u.

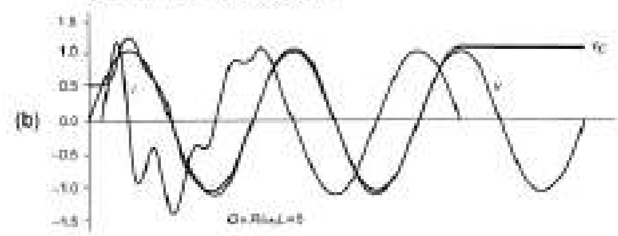


Figure 5.15 Waveforms illustrating the switching transients with the thyristor-switched capacitor fully (a) or partially discharged (b).

From the above, it follows that the maximum possible delay in switching in a capacitor bank is one full cycle of the applied ac voltage, that is, the interval from one positive (negative) peak to the next positive (negative) peak. It also follows that firing delay angle control is not applicable to capacitors; the capacitor switching must take place at that specific instant in each cycle at which the conditions for minimum transients are satisfied, that is, when the voltage across the thyristor valve is zero or minimum. For this reason, a TSC branch can provide only a stepJike change in the reactive current it draws (maximum or zero). In other words, the TSC branch represents

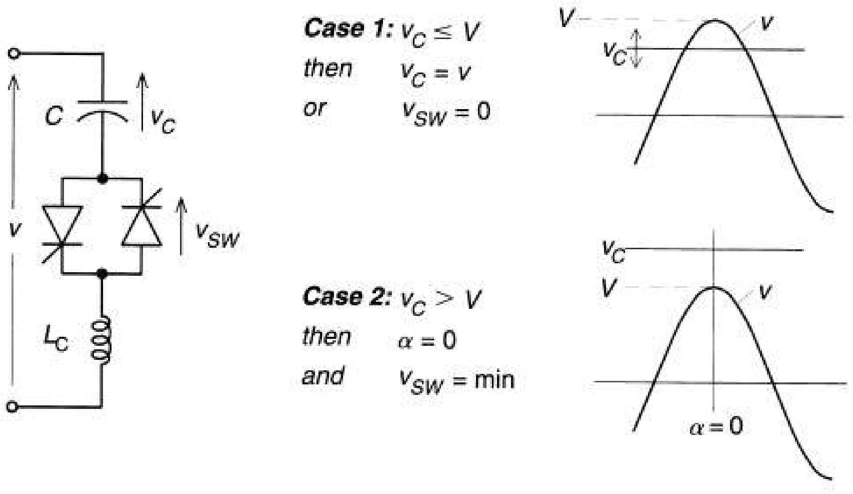


Figure 5.16 Conditions for "transient-free" switching for the thyristor-switched capacitor with different residual voltages.

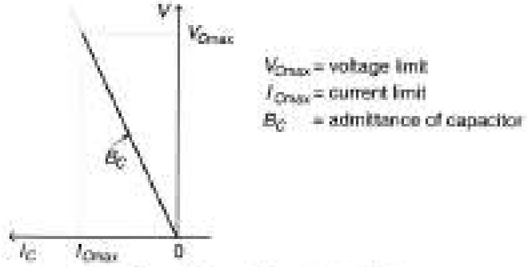


Figure 5.17 Operating V-I area of a single TSC.

Fixed Capacitor, Thyristor-Controlled Reactor Type Var Generator

A basic var generator arrangement using a fixed (permanently connected) capacitor with a thyristor-controlled reactor (FC-TCR) is shown functionally in Figure 5.1S(a). The current in the reactor is varied by the previously discussed method of firing delay angle control. The fixed capacitor in practice is usually substituted, fully or partially, by a fllter network that has the necessary capacitive impedance at the fundamental frequency to generate the reactive power required, but it provides a low impedance at selected frequencies to shunt the dominant harmonics produced by the TCR. The fixed capacitor, thyristor-controlled reactor type var generator may be considered essentially to consist of a variable reactor (controlled by delay angle a) and a fixed capacitor, with an overall var demand versus var output characteristic as shown in Figure 5.1S(b).

As seen , the constant capacitive var generation (Qc) of the fixed capacitor is opposed by the variable var absorption (Q) of the thyristor-controlled reactor, to yield the total var output (Q) required. At the maximum capacitive var output, the thyristor-controlled reactor is off (a : 90").To decrease the capacitive output, the current in the reactor is increased by decreasing delay angle a. At zero var output, the capacitive and inductive currents become equal and thus the capacitive and inductive vars cancel out. With a further decrease of angle o (assuming that the rating of the reactor is greater than that of the capacitor), the inductive current becomes larger than the capacitive current, resulting in a net inductive var output. At zero delay angle, the thyristor-controlled reactor conducts current over the full 180 degree interval, resulting in maximum inductive var output that is equal to the difference between the vars generated by the capacitor and those absorbed by the fullv conducting reactor.

The control of the thyristor-controlled reactor in the FC-TCR type var generator needs to provide four basic functions, as shown in Figure 5.19(a). One functionis synchronous timing. This function is usually provided by a phaselocked loop circuit that runs in synchronism with the ac system voltage and genirates appropriate timing pulses with respect to the peak of that voltage. (In a different approach, the ac voltage itself may be used for timing. However, this seemingly simple approach presents difflcult problems during system faults and major disturbances when the voltage exhibits wild fluctuations and large distortion.)

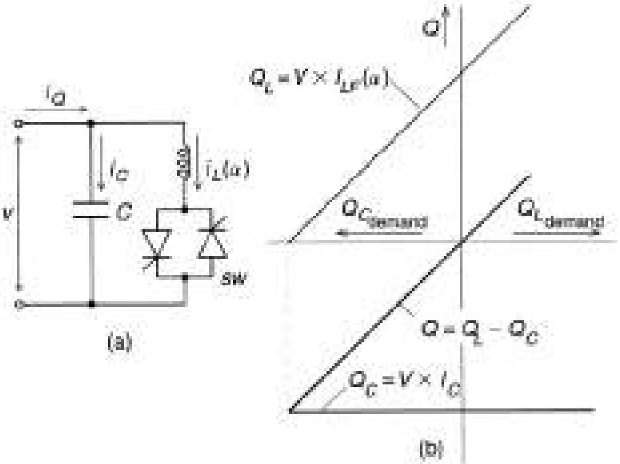


Figure 5.18 Basic FC-TCR type static var generator and its var demand versus var output characteristic.

The second function is the reactiue current (or admittance) to firing angle conuersion. This can be provided by a real time circuit implementation of the mathematical relationship between the amplitude of the fundamental TCR current lrr(o) and the delay angle a given by (5.5). Several circuit approaches are possible. One is an analog function generator producing in each half-cycle a scaled electrical signal that representi the [p(a) versus a relationship. [This approach is illustrated in Figure 5.19(6).] Another is a digital "look-up table" for the normalized lro(o) versus a function which is read at regular intervals (e.g., at each degree) starting from o : 0 (peak of the voltage) until the requested value is found, at which instant a firing pulse is initiated. A third approach is to use a microprocessor and compute, prior to the earliest firing angle (a : 0), the delay angle corresponding to the required lrr(o). The actual firing instant is then determined simply by a timing circuit (".g., u counter) "measuring" a from the peak of the voltage.

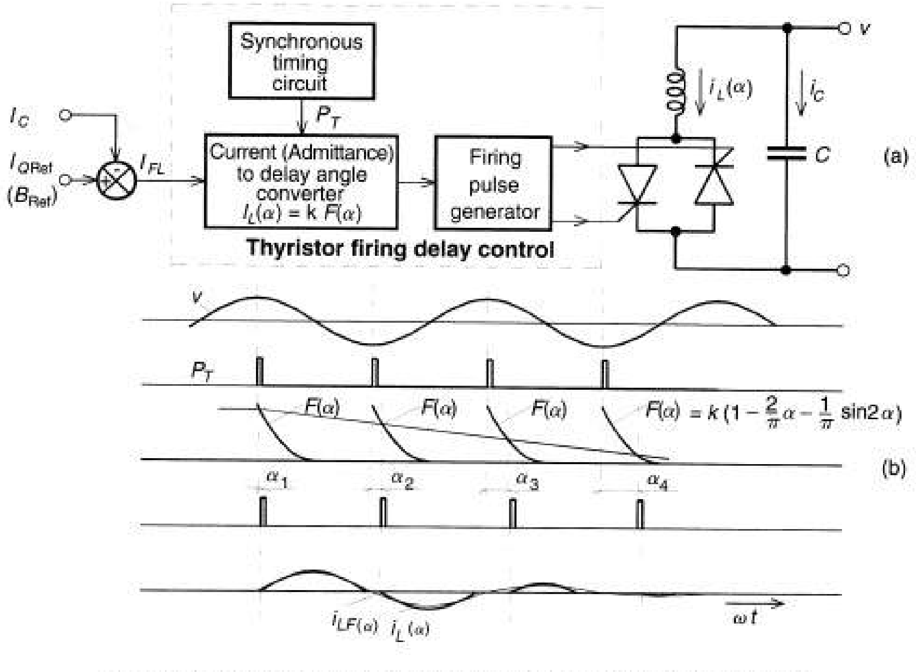


Figure 5.19 Functional control scheme for the FC-TCR type static var generator (a), and associated waveforms illustrating the basic operating principles (b).

Taking a "black box" viewpoint, the FC-TCR type var generator can be considered as a controllable reactive admittance which, when connected to the ac system, faithfully follows (within a given frequency band and within the specifled capacitive and inductive ratings) an arbitrary input (reactive admittance or current) reference signal. The V-l operating area of the FC-TCR var generator is defined by the maximum attainable capacitive and inductive admittances and by the voltage and current ratings of the major power components (capacitor, reactor, and thyristor valve), as illustrated in Figure 5.20. The ratings of the power components are derived from application requirements. The dynamic performance (e.g., the frequency band) of the var generator is limited by the firing angle delay control, which results in a time lag or transport lag with respect to the input reference signal. The actual transfer function of the FC-TCR type var generator can be expressed with the transport lag in the following form:

G(t) - ke-ra' (s.10)

where s is the Laplace transform operator, ft is a gain constant, and T6 is the transport lag corresponding to firing delay angle a.

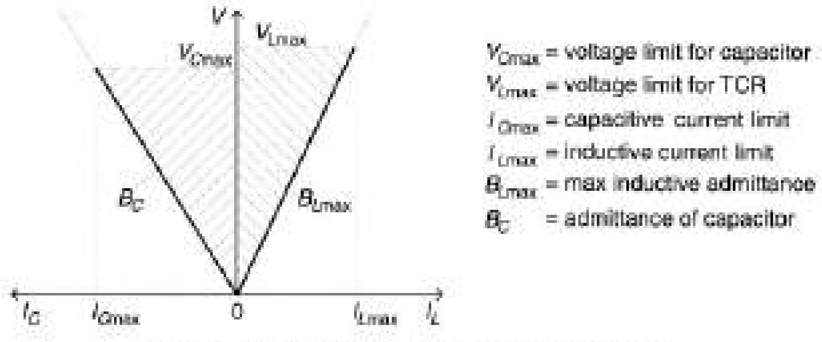


Figure 5.20 Operating V-I area of the FC-TCR type var generator.

Thyristor-Switched Capacitor, Thyristor-Controlled Reactor Type Var Generator

The thyristor-switched capacitor, thyristor-controlled reactor (TSC-TCR) type compensator was developed primarily for dynamic compensation of power transmission systems with the intention of minimizing standby losses and providing increased operating flexibility. A basic single-phase TSC-TCR arrangement is shown in Figure 5.22(a). For a given capacitive output range, it typically consists of n TSC branches and one TCR. The number of branches, n, is determined by practical considerations that include the operating voltage level, maximum var output, current rating of the thyristor valves, bus work and installation cost, etc. Of course, the inductive range also can be expanded to any maximum rating by employing additional TCR branches. The operation of the basic TSC-TCR var generator shown in Figure 5.22(a) can be described as follows:

The total capacitive output range is divided into n intervals. In the first interval, the output of the var generator is controllable in the zero to Qg^oln range, where O..- is the total rating provided by all TSC branches. In this interval, one capacitor bank is switched in (by firing, for example, thyristor valve SW1,) and, simultaneously, the current in the TCR is set by the appropriate firing delay angle so that the sum of the var output of the TSC (negative) and that of the TCR (positive) equals the capacitive output required. In the second, third, . . ., and nth intervals, the output is controllable in the Qs.*/ nto2Q6^-ln,2Qg^ lnto3Q6^*1n,. . ., and (n - L)Qr^*lnto Q6-urange by switching in the second, third, . .., and nth capacitor bank and using the TCR to absorb the surplus capacitive vars. By being able to switch the capacitor banks in and out within one cycle of the applied ac voltage, the maximum surplus capacitive var in the total output range can be restricted to that produced by one capacitor bank, and thus, theoretically, the TCR

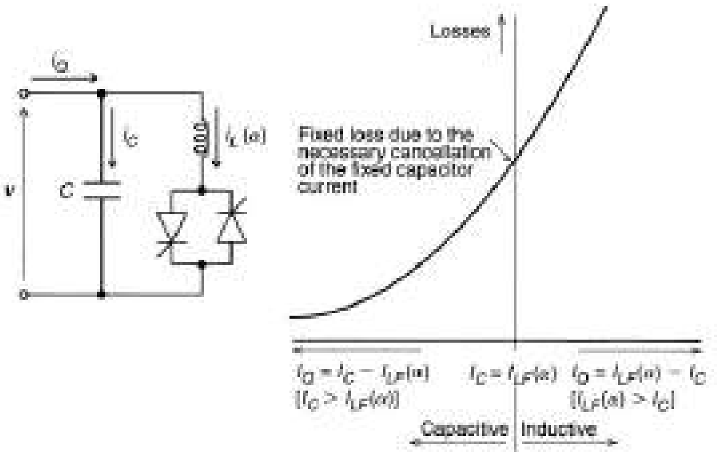
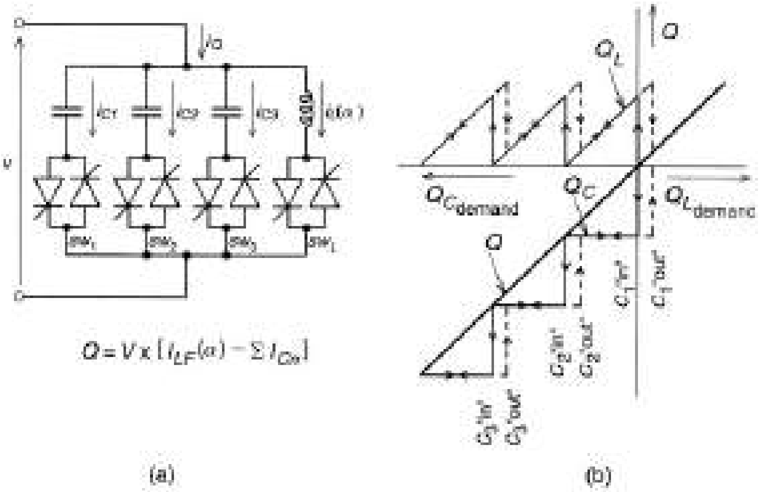


Figure 5.21 Loss versus var output characteristic of the FC-TCR type static var generator.

should have the same var rating as the TSC. However, to ensure that the switchins conditions at the endpoints of the intervals are not indeterminate, the var rating of the TCR has to be somewhat larger in practice than that of one TSC in order to provide enough overlap (hysteresis) between the "switching in" and "switching out" var levels. The var demand versus var output characteristic of the TSC-TCR type var generator is shown in Figure 5.22(b). As seen, the capacitive var output, Qr,is changed in a step-like manner by the TSCs to approximate the var demand with a net capacitive var surplus, and the relatively small inductive var output of the TCR, Q1, is used to cancel the surplus capacitive vars. In a way, this scheme could be considered as a special fixed capacitor, thyristorcontrolled reactor arrangement, in which the rating of the reactor is kept relativelr' small (1in times the maximum capacitive output), and the rating of the capacitor is changed in discrete steps so as to keep the operation of the TCR within its normal control range.

A functional control scheme for the TSC-TCR type var generator is shown in Figure 5.23.It provides three major functions: L. Determines the number of TSC branches needed to be switched in to approximate the required capacitive output current (with a positive surplus), and computes the amplitude of the inductive current needed to cancel the surplus capacitive current. 2. Controls the switching of the TSC branches in a "transient-free" manner. 3. Varies the current in the TCR by firing delay angle control. The first function is relatively simple. The input current reference /qn* representing the magnitude of the requested output current is divided by the (scaled) amplitude



(a) (b)

Figure 5.22 Basic TSC-TCR type static var generator and its var demand versus var output characteristic.

16 of the current that a TSC branch would draw at the given amplitude V of the ac voltage. The result, rounded to the next higher integer, gives the number of capacitor banks needed. The difference in magnitude between the sum of the activated capacitor currents, I16n, and the reference cunent, Ign"r, gives the amplitude, [p, of the fundamental reactor current required. The basic logic for the second function (switching of the TSC branches) is detailed in Figure 5.24. This follows the two simple rules for "transient-free" switching summarized in Figure 5.16. That is, either switch the capacitor bank when the voltage across the thyristor valve becomes zero or when the thyristor valve voltage is at a minimum. (The first condition can be met if the capacitor residual voltage is less than the peak ac voltage and the latter condition is satisfied at those peaks of the ac voltage which has the same polarity as the residual voltage of the capacitor.)

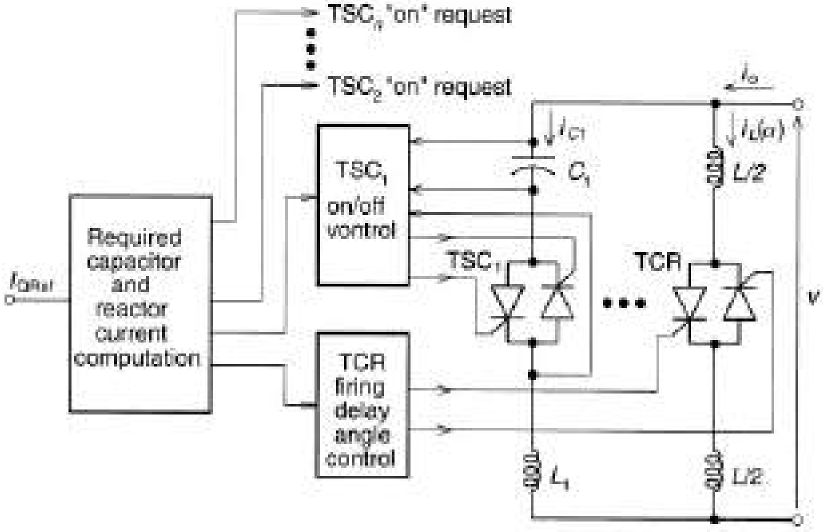


Figure 5.23 Functional control scheme for the TSC-TCR type static var generator.

The actual firing pulse generation for the thyristors in the TSC valve is similar to that used for the TCR with the exception that a continuous gate drive is usually provided to maintain continuity in conduction when the current is transferred from one thyristor string carrying current of one polarity (e.g., positive) to the other string carrying current of opposite polarity (e.g., negative). The third function (TCR firing delay angle control) is identical to that used in the fixed-capacitor, thyristor-controlled reactor scheme (refer to Figure 5.19). The operation of the TSC-TCR type var generator with three capacitor banks is illustrated by the oscillograms in Figure 5.25. The oscillograms show the reactive current reference signal Isn"i, the total output current iaF i, + lr), the curent 16, drawn by the thyristorswitched capacitor banks, and the current 11 drawn by the thyristor-controlled reactor. From the "black box" viewpoint, the TSC-TCR type var generator, similarly to its FC-TCR counterpart, can be considered as a controllable reactive admittance, which, when connected to the ac system, faithfully follows an arbitrary input reference (reactive admittance or current) signal. An external observer monitoring the output

UNIT-IV

SVC AND STATCOM

STATIC VAR COMPENSATORS: SVC AND STATCOM

Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are static var generators, whose output is varied so as to maintain or control specific parameters of the electric power system. It has been discussed in the previous sections that a static (var) generator may be of a controlled reactive impedance type, employing thyristor-controlled and switched reactors and capacitors, or synchronous voltage source type, employing a switching power converter, or a hybrid type, which employs a combination of these elements. Although the operating principles of these var generators are disparate and their V-I and loss versus var output characteristics, as well as their speed of response and attainable frequency bandwidth, are quite different, they all can provide the controllable reactive shunt compensation, exhibiting similar overall functional capabilities within their linear operating range. This means that the basic external control structure that defines the functional operation of the compensator, and to this end derives the necessary reference inputs for the var generator, is substantially the same independent of the type of var generator used.

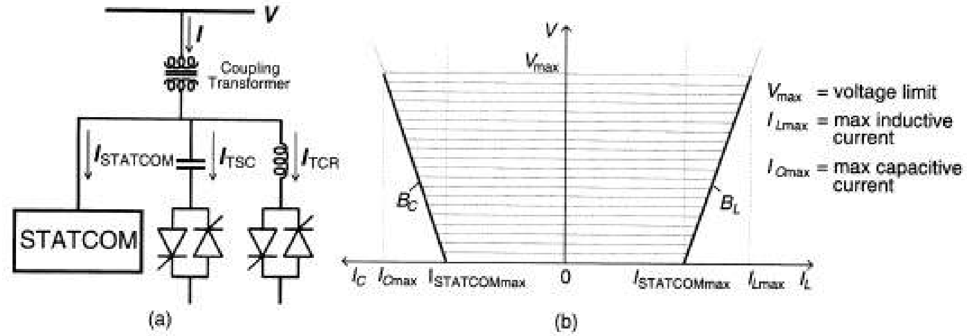


Figure 5.41 Combined converter-based and TSC-TCR type var generator (a), and associated operating V-I area (b).

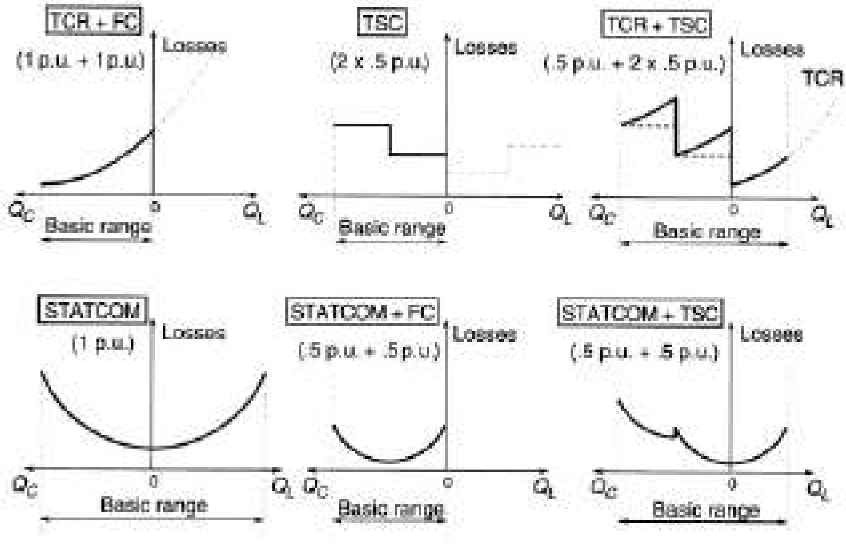


Figure 5.42 Summary of loss versus var output characteristics of different static var generator schemes.

The primary objective of applying a static compensator (this term or the shorter term compensator will be used in a general sense to refer to an SVC as well as to a STATCOM) in a power system is to increase the power transmission capability, with a given transmission network, from the generators to the loads. Since static compensators cannot generate or absorb real power (neglecting the relatively low internal losses of the SVC and assuming no energy storage for the STATCOM), the power transmission of the system is affected indirectly by voltage control. That is, the reactive output power (capacitive or inductive) of the compensator is varied to control the voltage at given terminals of the transmission network so as to maintain the desired power flow under possible system disturbances and contingencies. The control requirements for the compensator (which define the way the output of the var generator has to be varied to increase power flow and to stabilize specific parameters of the power system in face of network contingencies and dynamic disturbances) has been derived from the functional compensation considerations in Section 5.1 of this chapter. As shown there, the basic compensation needs usually fall into one of the following two main categories: (1) direct voltage support (to maintain sufficient line voltage for facilitating increased power flow under heavy loads and for preventing voltage instability) and (2) transient and dynamic-stability improvements (to increase the first swing stability margin and provide power oscillation damping). In that section it was shown that terminal voltage control can enhance significantly the power transmission capability of the power system. Specifically, the regulation of the voltage at particular intermediate points and selected load terminals of the

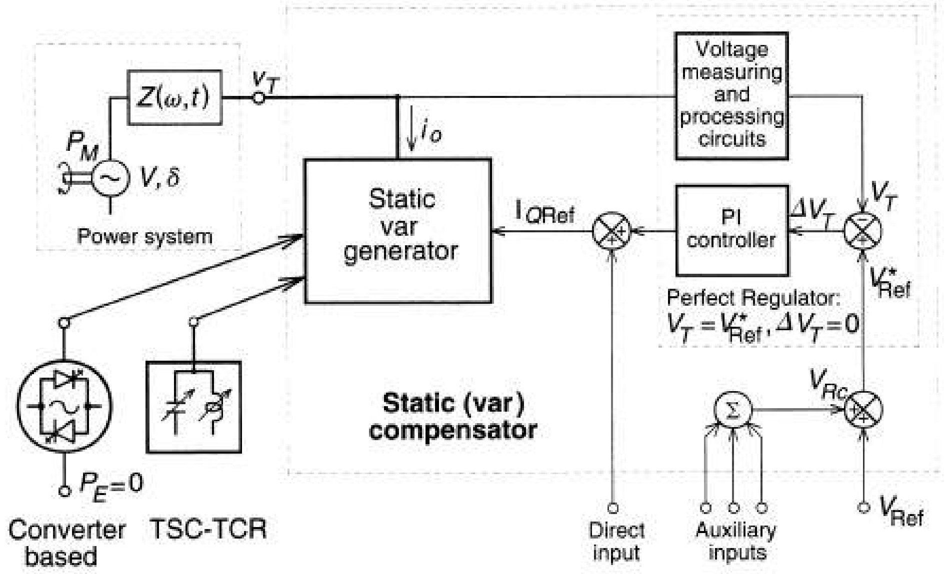


Figure 5.43 General control scheme of a static var generator.

The Regulation Slope

In many applications, the static compensator is not used as a perfect terminal voltage regulator, but rather the terminal voltage is allowed to vary in proportion with the compensating current. There are several reasons for this:

1. The linear operating range of a compensator with given maximum capacitive and inductive ratings can be extended if a regulation "droop" is allowed. Regulation "droop" means that the terminal voltage is allowed to be smaller than the nominal no load value at full capacitive compensation and, conversely, it is allowed to be higher than the nominal value at full inductive compensation.
2. Perfect regulation (zero droop or slope) could result in poorly defined operating point, and a tendency of oscillation, if the system impedance exhibited a "flat" region (low impedance) in the operating frequency range of interest.

3. A regulation "droop" or slope tends to enforce automatic load sharing between static compensators as well as other voltage regulating devices normally employed to control transmission voltage.

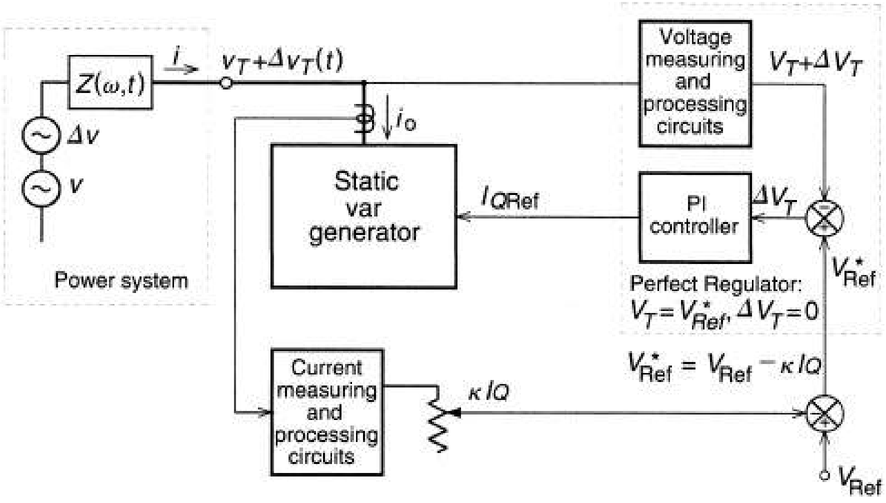


Figure 5.44 Implementation of the V-I slope by a minor control loop changing the reference voltage in proportion to the line current.

COMPARISON BETWEEN STATCOM AND SVC

On the basis of explanations provided in the previous sections it should be clear to the reader that, on the one hand, in the linear operating range the V-1 characteristic and functional compensation capability of the STATCOM and the SVC are similar. However, the basic operating principles of the STATCOM, which, with a converterbased var generator, functions as a shunt-connected synchronous voltage source, are fundamentally different from those of the SVC, which, with thyristor-co-ntrolled reactors and thyristor-switched capacitors, functions as a shunt-connected, controlled reactive admittance. This basic operational difference (voltage source versus reactive admittance) accounts for the STATCOM's overall superior functional characteristics, better performance, and greater application flexibility than those attainable with the SVC. These operational and performance characteristics are summarized here, with the underlying physical reasons behind them, and with the corresponding application benefits.

V-l and t/-O Characteristics

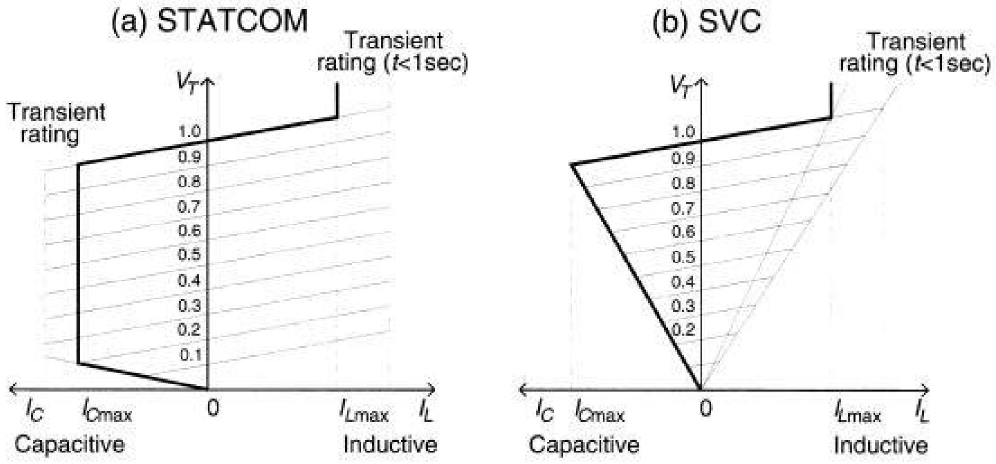


Figure 5.59 V-I characteristic of the STATCOM (a) and of the (SVC) (b).

The STATCOM is essentially an alternating voltage source behind a coupling reactance with the correspondingV-I andV-Q chancteristics shown in Figures S.Se1a) and 5.60(a), respectively. These show that the STATCOM can be operated ou", it. full output current range even at very low (theoretically zero), typicaliy about 0.2 p.u. system voltage levels. In other words, the maximum capacitive or inductive output current of the STATCOM can be maintained independently of the ac system voltage, and the maximum var generation or absorption changes linearly with the ac systJm voltage. In contrast to the STATCOM, the SVC, being composed of (thyristor-switched capacitors and reactors, becomes a fixed capacitive admittance at full output.

Thus the maximum attainable compensating current of the SVC decreases linearly with ac system voltage, and the maximum var output decreases with the square of this voltage, as shown in Figures 5.59(b) and 5.60(b), respectively. The STATCOM is, therefore, superior to the SVC in providing voltage support under large system disturbances during which the voltage excursions would be well outside of the linear operating range of the compensator. The capability of providing maximum compensating current at reduced system voltage enables the STATCOM to perform in a variety of applications the same dynamic compensation as an SVC of considerably higher rating.

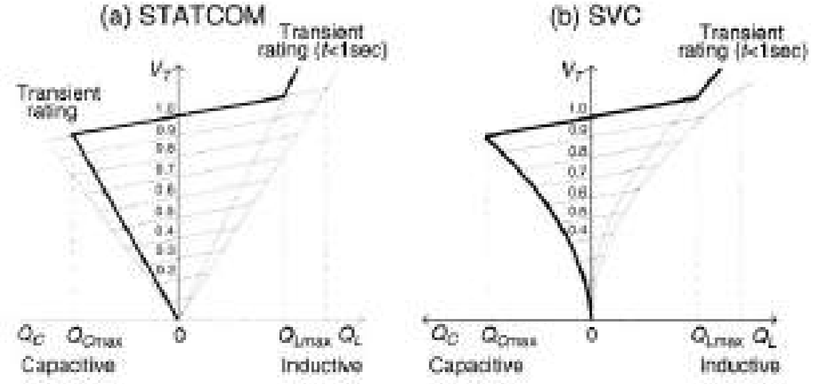


Figure 5.60 V-Q characteristic of the STATCOM (a) and of the (SVC) (b).

Transient Stability

The ability of the STATCOM to maintain full capacitive output current at low system voltage also makes it more effective than the SVC in improving the transient (first swing) stability. The effectiveness of the STATCOM in increasing the transmittable power is illustrated in Figure 5.61(a), where the transmitted power P is shown

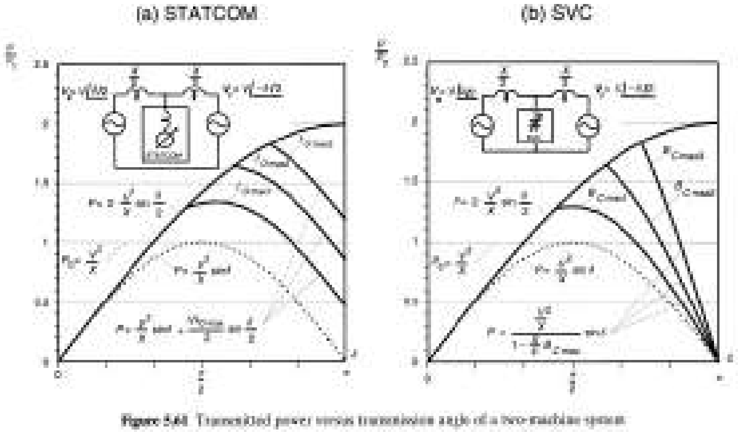


Figure 5.61 Transmitted power versus transmission angle of a two-machine system with a midpoint STATCOM (a) and a midpoint SVC (b) obtained with different var ratings.

improvement in stability margin is significantly increased. The increase in stability margin obtainable with a STATCOM over a conventional thyristor-controlled SVC of identical rating is clearly illustrated with the use of the previously explained equal-area criterium (Section 5.1.3) in Figures 5.62(a) and (b). The simple two-machine system, discussed at the review of the basic shunt compensation principles [Figure 5.1(a)], is compensated at the midpoint by a STATCOM and an SVC of the same var rating. For the sake of clarity, it is assumed that the system transmitting steady-state electric power Py at angle fi, is subjected to a fault for a period of time during which Pr becomes zero. During the fault, the sending-end machine accelerates (due to the constant mechanical input power), absorbing the kinetic energy represented by the shaded area below the constant P1 line, and increasing & to 6. (6. > 6,). Thus, when the original system is restored after fault clearing, the transmitted power becomes much higher than P1 due to the larger transmission angle 6". As a result, the sending-end machine starts to decelerate, but 6 increases further until the machine loses all the kinetic energy it gained during the fault.

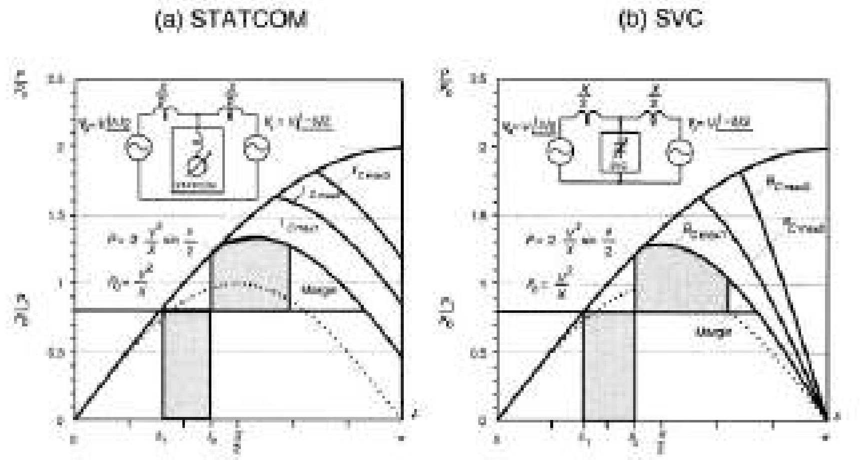


Figure 5.62 Improvement of transient stability obtained with a midpoint STATCOM (a) and a midpoint SVC (b) of a given var rating.

Response Time

As demonstrated in Section 5.3.2,the attainable response time and the bandwidth of the closed voltage regulation loop of the STATCOM are also significantly better than those of the SVC. Although the closedloop voltage regulation of both compensators can be expressed by the formula given in (5.17), i.e., LVTILV : ll(I + G1G2HX), the time constant Za in the transfer function G2 (which characterizes the inherent "transport lag" in the power circuits of the STATCoM and of the SVC) is about an order of magnitude smaller for the STATCOM than it is for the SVC, i.e., it is typically from less than 200 g,s to 350 g.s for the STATCoM and between 2.5 and 5.0 ms for the SVC. Considering the rapidly changing angle versus frequency characteristic of the e-ra'term, this improvement is important from the standpoint of attainable frequency bandwidth. The practical importance of wide frequency bandwidth cannot be overstated for applications requiring fast response, but even in typical transmission applications the STATCOM can provide stable operation with respectable response over a much wider variation of the transmission network impedance than is possible with an SVC.

Capability to Exchange Real Power

For applications requiring active (real) power compensation it is clear that the STATCOM, in contrast to the SVC, can interface a suitable energy storage with the ac system for real power exchange. That is, the STATCoM is capable of drawing controlled real power from an energy source (large capacitor, battery, fuel cell, superconducting magnetic storage, etc.) at its dc terminal and deliver it as ac power to the system. It can also control energy absorption from the ac system to keep the storage device charged. This potential capability provides a new tool for enhancing dynamic compensation, improving power system efficiency and, potentially, preventing power outages. The reactive and real power exchange between the STATCOM and the ac system can be controlled independently of each other and any combination of real power generation and absorption with var generation and absorption is achievable. Thus, by equipping the STATCOM with an energy storage device of suitable capacity, extremely effective control strategies for the modulation of the reactive and real output power can be executed for the improvement of transient stability and the damping of power oscillation. It should be noted that for short-term dynamic disturbances an energy consuming device (".g., a switched resistor) may be effectively used in place of the more expensive energy storage to absorb power from the ac system via the STATCOM. with this simple scheme, the STATCoM would transfer energy from the ac system to the dc terminals where it would be dissipated by the energy-consuming device that

Operation With Unbalanced AG System

The ac system voltages are normally balanced (maximum unbalance does not usually exceed 1.Vo) and therefore compensators normally control all three phases of their output current together. This for the SVC normally means that its control establishes three identical shunt admittances, one for each phase. Consequently, with unbalanced system voltages the compensating currents in each phase would become different. It is possible to control the three compensating admittances individually by adjusting the delay angle of the TCRs so as to make the three compensating currents identical. However, in this case the triple-n harmonic content would be different in each phase and their normal cancellation through delta connection would not take place. This operation mode thus would generally require the installation of the usually unneeded third harmonic fllters.

For this reason, individual phase control for SVCs in transmission line compensation is rarely employed. The operation of the STATCOM under unbalanced system conditions is different from that of the SVC, but the consequences of such operation are similar. The STATCOM operation is governed by the fundamental physical law requiring that the net instantaneous power at the ac and dc terminals of the voltage-sourced converter employed must always be equal. This is because the converter has no internal energy storage and thus energy transfer through it is absolutely direct, and consequently the net instantaneous power at its ac and dc terminals must be equal.

Assume that the dc terminal voltage of the STATCOM is supported entirely by an appropriately charged dc capacitor (i.e., there is no source or sink of power attached to this terminal), and that the losses of the converter are zero and its pulse number is infinite (ideal converter). With perfectly balanced sinusoidal ac terminal voltages (provided by the ac power system), the STATCOM will draw a set of balanced, sinusoidal currents in quadrature with the system voltages, but the dc capacitor will experience no charging current because no real power is exchanged with the ac system and, furthermore, because the net instantaneous power remains invariably zero at the ac terminals of the converter. However, if the ac system voltages become unbalanced, then an alternating power component at twice the fundamental frequency will appear at the ac terminals of the STATCOM converter and this will be matched by an alternating second harmonic charging current in the dc terminals, producing in turn an associated alternating voltage component of the same frequency across the capacitor shunting the dc terminals. If the converter control ignores this ac voltage component, that is, if it is operated to produce the ac output voltage as if the dc terminal voltage was constant, then the second harmonic voltage component from the dc terminal will be transformed (by the converter switching operation) as a negative sequence fundamental component and a positive sequence third harmonic component to the ac terminals. As a result, the STATCOM will, in general, draw a negative sequence fundamental current component (in proportion to the difference between its internally generated negative sequence voltage and the negative sequence component of the ac system voltage) as well as a (positive sequence) third harmonic current component. Out of the two voltage components, generated in the output of the STATCOM as a result of system unbalance, the third harmonic is clearly "unwanted." Whereas the negative sequence fundamental voltage, generated "naturally" by the converter with properly sized dc capacitor, reduces significantly the negative sequence current ul function. The "natural" behavior of the STATCOM is illustrated in Figure 5.63 where relevant voltage and current waveforms records, representing a TNA simulated power system with precisely scaled 48-pulse STATCOM hardware model that was subjected to a severe line to ground fault. The traces in the figure show (from top to bottom): line to line voltages up6 zr.d u"6 (phase a is faulted to ground); the three currents drawn by the STATCOM, io, ib, l.; the dc capacitor voltage u6; and the reactive current reference 1pn.r (limited to 2 p.u.). In steady state, the STATCOM was producing 1.0 p.u. capacitive current, when it was subjected to a line to ground fault lasting for about five cycles. It can be observed that, due to the internally generated negative sequence converter voltage (that largely matched the negative sequence voltage of the unbalanced ac system), the STATCOM was providing during the fault substantially balanced, capacitive compensating currents with the maximum magnitude of 2.0 p.u., but with considerable third harmonic distortion. Flowever, the harmonics, present only during the five cycle fault period are, arguably, of no significant consequence (since, presumably, under this condition significantly more distortion is generated by various static

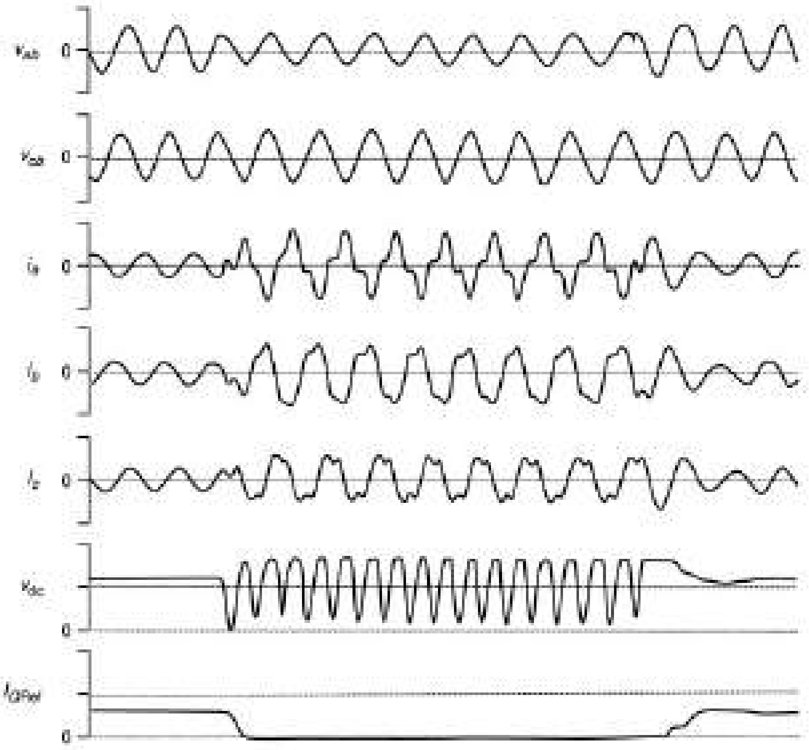


Figure 5.63 Waveforms illustrating the operation of a STATCOM (without individual phase voltage control) during and following a line to ground fault at the regulated bus.

Loss Versus Var Output Gharacteristic

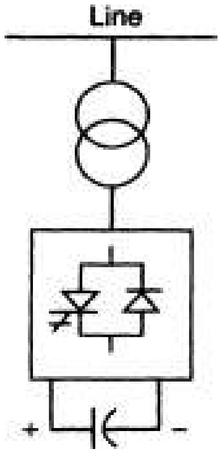
As shown in Figures 5.38 and 5.27 the overall loss versus reactive output characteristic, as well as the actual operating losses, of the srATCoM are comparable to those of the SVC using both thyristor-controlled reactors and thyristor-switched capacitors. Both types of compensator have relatively low losses (about 0.1to 0.27o) at and in the vicinity of zero var output. On the average, the losses in both cases increase with increasing var output reaching about 1.0Vo at rated output. This type of loss versus output characteristic is generally considered favorable for transmission applications where the average var output demand is normally low and the compensator is primarily applied to handle dynamic events, system contingencies, and possibly the coordination of the overall area var control. The loss contribution of power semiconductors and related components to the total compensator losses is higher for the STATCOM than for the SVC. This is because presently available power semiconductor devices with internal turn-off capability have higher conduction losses than conventional thyristors. Also switching losses with forced current interruption tend to involve more losses than natural commutation. However, it is reasonable to expect that the historically rapid semiconductor developments will reduce the device losses in the coming years, whereas the losses of conventional power components, such as reactors, are not likely to change significantly. Thus, the technological advances probably will have help to reduce the overall losses of the STATCOM more than those of the SVC.

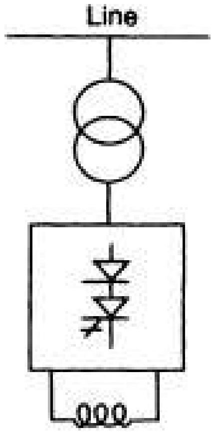
Shunt connected controllers

- *Static Synchronous Generator (SSG)*
- *Static Synchronous Compensator (STATCOM)*
- Battery *Energy* Storage *System (BESS)*
- *Superconducting Magnetic Energy* Storage (SMES)
- *Static Var Compensator (SVC)*
- *Thyristor Controlled Reactor (TCR)*
- *Thyrlstor Swltched Reactor (TSR)*
- *Thyristor Switched Capacitor (TSC)*
- *Static Var Generator or Absorber (SVG)*
  Thyristor Controlled Braking Resistor (TCBR

Static Synchronous Compensator (STATCOM):

A Static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage



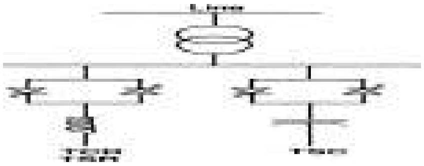


STATCOM based on voltage-sourced converters

STATCOM based on current-sourced converters

Static Var Compensator (SVC):

- ❖ A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).



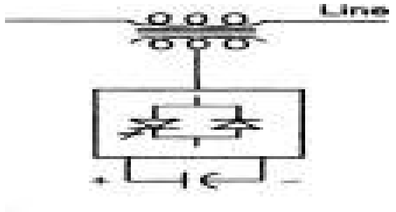
- ✓ The thyristor-controlled reactor (TCR) or thyristor-switched reactor (TSR) for absorbing reactive power and thyristor-switched capacitor (TCS) for supplying the reactive power.
- ✓ SVC is considered by some as a lower cost alternative to STATCOM**.**

Series connected controllers

- Static Synchronous Series Compensator (SSSC)
- Interline Power Flow Controller (IPFC)
- Thyristor Controlled Series Capacitor (TCSC)
- Thyristor-Switched Series Capacitor (TSSC)
- Thyristor-Controlled Series Reactor (TCSR)
- Thyristor-Switched Series Reactor (TSSR)

Static Synchronous Series Compensator (SSSC):

- ➢ *In a Static Synchronous Series Compensator, output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line*

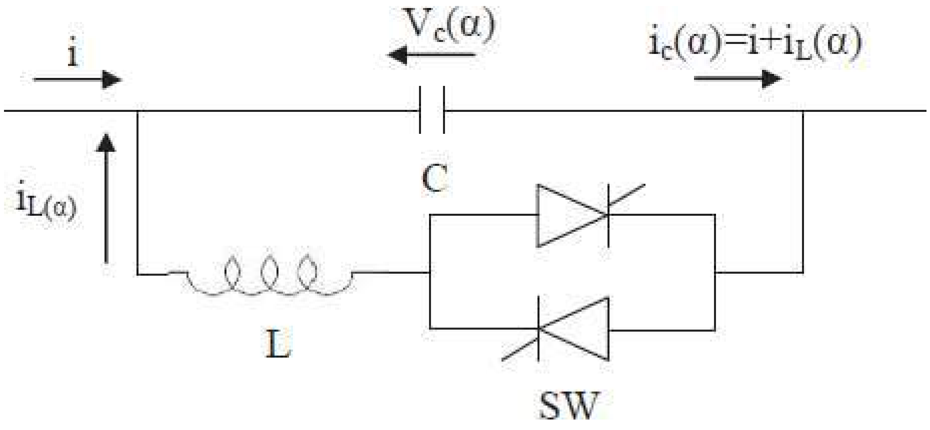


It is like a STATCOM, except that the output ac voltage is in series with the line.

TCSC

- ➢ TCSC is a series compensating FACTS device using to control power flow in transmission lines and improves transient stability in power system.
- ➢ It controls the effective line reactance by connecting a variable reactance in series with line.

- It is a capacitive/ inductive reactance compensator which consists of a series capacitor bank shunted by a thyristor controlled reactor in order to provide a smoothly variable series capacitive/ inductive reactance.
- TCSC controls the power flow in transmission lines by varying the impedance of TCSC by controlling the delay angle of thyristor valves.
- The basic scheme of TCSC is shown in Fig.



- A TCSC is typically made up of the following major components:
  - A series compensating capacitor (C)
  - Bypass inductor (L)
  - Back to back thyristors (SW)
- The degree of TCSC compensation is controlled by the size of capacitor C. Thyristors are used to transform the equivalent impedance of TCSC which fulfills the need in improving the stability increasing the transmission capability, restraining hypo-synchronization resonance etc.
- The basic idea behind power flow control with the TCSC is to decrease or increase the overall lines effective series transmission impedance, by adding a capacitive or inductive reactive correspondingly. In capacitive mode TCSC reduces the transfer reactance between the buses at which the line is connected and increases the maximum power that can be transmitted.
- TCSC is that of a parallel LC circuit, consisting of a fixed capacitive impedance, Xc,and a variable inductive impedance, $X_L(\alpha)$, that is,

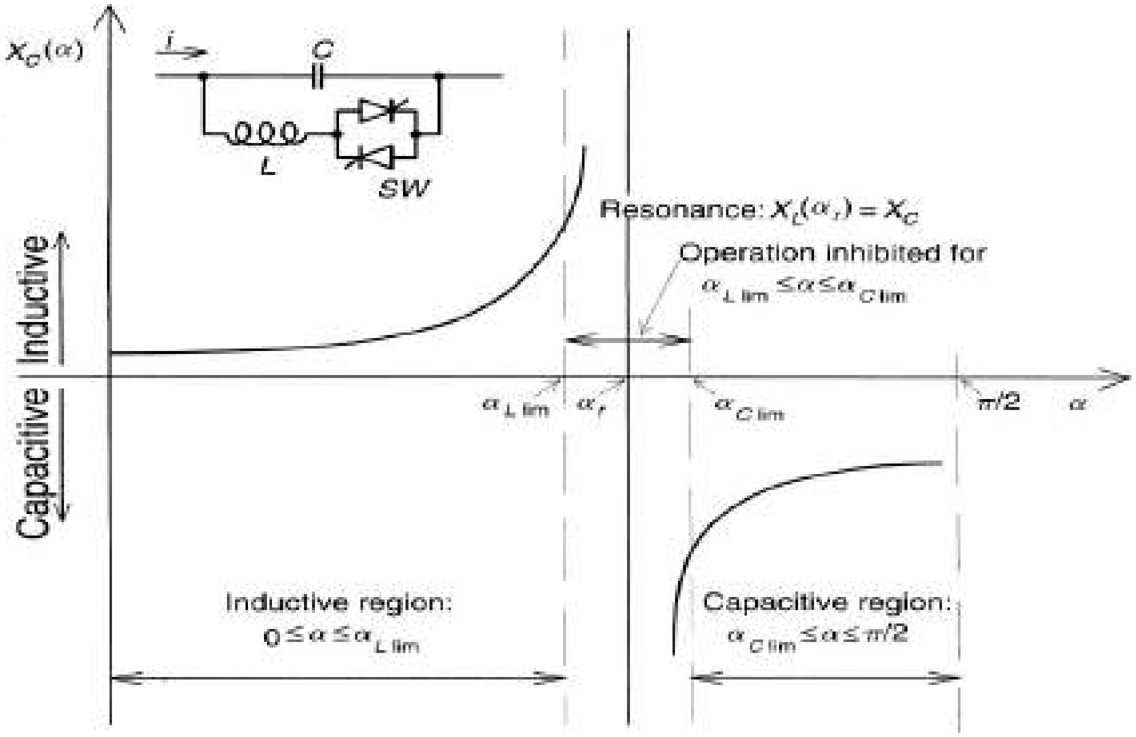
$$X_{TCSC}(\alpha)=\frac{X_C X_L(\alpha)}{X_L(\alpha)-X_C}$$

Where

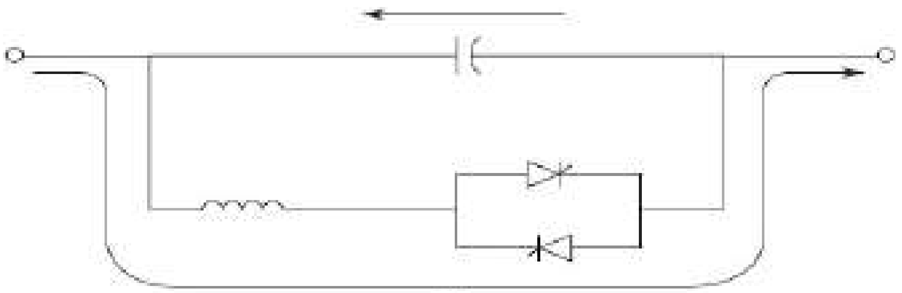
$$X_L(\alpha)=X_L\frac{\pi}{\pi-2\alpha-\sin 2\alpha}, X_L\le X_L(\alpha)\le\infty$$

- $X_L = \omega L$, and α is the delay angle measured from the crest of the capacitor voltage (or, equivalently, the zero crossing of the line current).
- The TCSC thus presents a tunable parallel LC circuit to the line current that is substantially a constant alternating current source.
- As the impedance of the controlled reactor, $X_L(\alpha)$, is varied from its maximum (infinity) toward its minimum (ωL), the TCSC increases its minimum capacitive impedance, $X_{TCSC}=X_c=1/(\omega c)$ and thereby the degree of series capacitive compensation) until parallel resonance at $X_c=X_L(\alpha)$is established and $X_{TCSC\ max}$ theoretically becomes infinite.
- Decreasing $X_L(\alpha)$ further,the impedance of the TCSC, $X_{TCSC}(\alpha)$ becomes inductive, reaching its minimum value of $X_LXc/(X_L - X_c)$ at α =0, where the capacitor is in effect bypassed by the TCR.
- Therefore, with the usual TCSC arrangement in which the impedance of the TCR reactor, X_L is smaller than that of the capacitor, Xs, the TCSC has two operating ranges around its internal circuit resonance

1. $\alpha clim \le a \le \pi/2$ range where $X_{TCSC}(\alpha)$ is capacitive
2. $0 \le a \le a\ L_{lim}$ range where $X_{TCSC}(\alpha)$ is inductive as shown in Figure



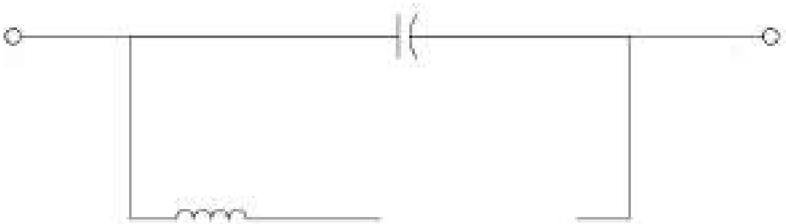
1. ***Thyristor valve bypass mode (inductive region operation:* $0\ L \le \alpha \le \alpha_{Llim}$ *)***



(a)

In the bypass mode thyristors are gated for full conduction and the current flow in the reactor is continuous and sinusoidal. In this case the net reactance is slightly inductive because the susceptance of reactor is larger than that of the capacitor. This mode is mainly used for protecting the capacitor against the overvoltage (during transient over currents in the line).

2. *Thyristor valve blocked mode (resonance region for inhibited operation:* L_{lim} C_{lim} $\alpha \le \alpha \le \alpha$ *):*



- In this mode, also known as the *waiting* mode, the firing pulses to the thyristor valves are blocked. If the thyristors are conducting and a blocking command is given, the thyristors turn off as soon as the current through them reaches a zero crossing.
- The TCSC module is thus reduced to a fixed-series capacitor, and the net TCSC reactance is capacitive.
- In this mode, the dc-offset voltages of the capacitors are monitored and quickly discharged using a dc-offset control without causing any harm to the transmissionsystem transformers.

3. Partially Conducting Thyristor or Vernier Mode

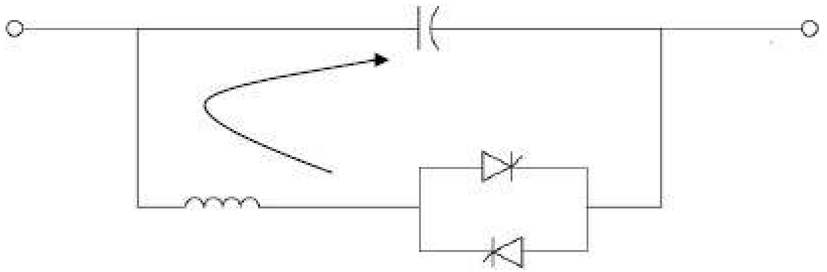
This mode allows the TCSC to behave either as a continuously controllable capacitive reactance or as a continuously controllable inductive reactance. It is achieved by varying the thyristor-pair firing angle in an appropriate range. A smooth transition from the capacitive to inductive mode is not permitted because of the resonant region between the two modes.

Capacitive-vernier-control mode
inductive-vernier mode

***(i) Capacitive-vernier-control* mode,**

In this, the thyristors are fired when the capacitor voltage and capacitor current have opposite polarity.

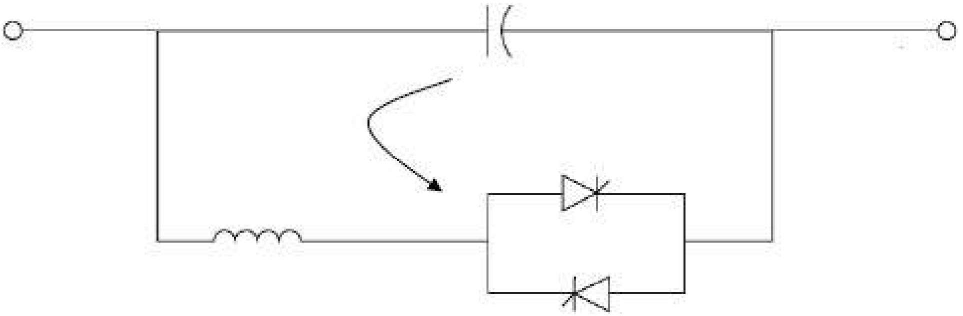
- This condition causes a TCR current that has a direction opposite that of the capacitor current, thereby resulting in a loop-current flow in the TCSC controller.
- This loop current increases the voltage across the FC, effectively enhancing the series compensation level.



- The maximum TCSC reactance permissible with α=αmin is typically two-and-a half to three times the capacitor reactance at fundamental frequency.

(ii) Inductive-vernier mode

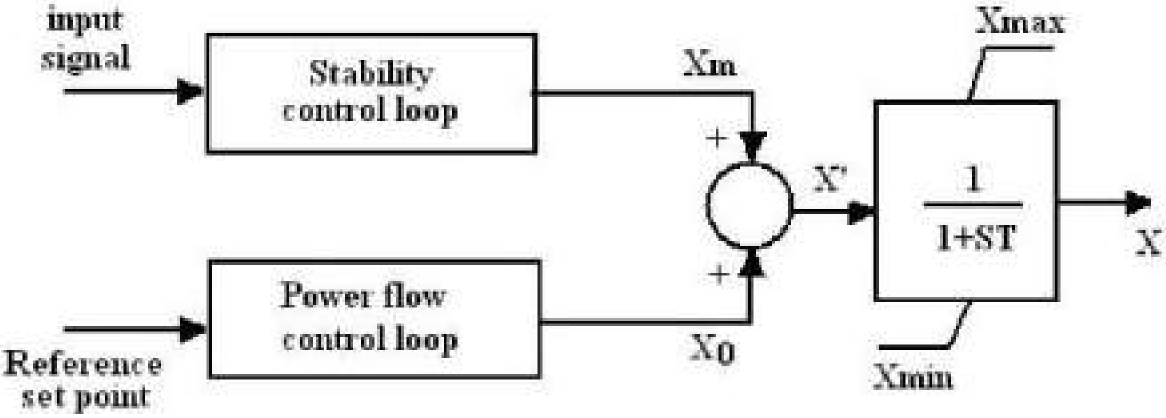
- In which the TCSC can be operated by having a high level of thyristor conduction. In this mode,the direction of the circulating current is reversed and the controller presents a net inductive impedance.



UNIT-V
STATIC SERIES COMPENSATORS

MODELING OF THE TCSC

The Fig.(a) shows the general block diagram of the TCSC controller for dynamic and steady state stability studies . It consists of Power flow controller and stability controller.



(a)General block diagram of TCSC controller model for stability studies

Power flow controller is used to control power flow in the transmission line under steady state condition by comparing power flow in transmission line with reference power set point.

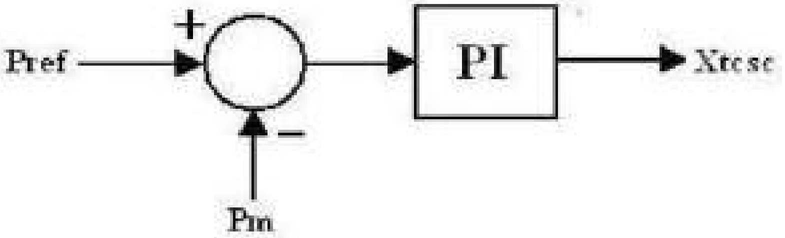


Fig b Power flow controller diagram for TCSC

If this controller is slow due to the large time constant of PI controller or if it is manually operated, the output (X0) of power flow controller is to be constant during large disturbances, because of this power oscillations increase. To reduce power oscillations the TCSC must be in a position to provide maximum compensation level immediately after the fault is cleared. This is achieved by adding the stability control loop to power flow control loop as shown in Fig.(a).

The stability controller gives modulation reactance (Xm) during transient or dynamic periods. The sum of two outputs (X0) of power flow controller and (Xm) of the stability controller yields the X“ which is the final value of reactance required to the system during transient and dynamic periods.

Variable-reactance model of TCSC

The variable-reactance model of TCSC shown in Fig is widely used for transient- and oscillatory-stability studies.

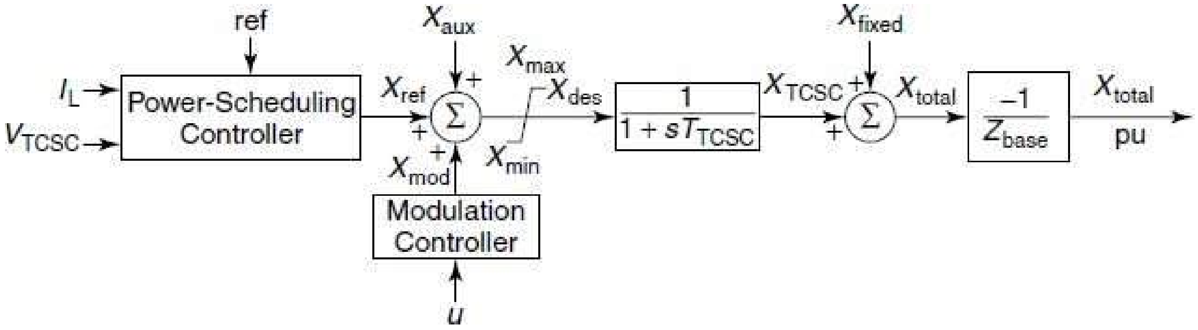


Fig.(c) A block diagram of the variable-reactance model of the TCSC

Xref - Power scheduling controller based on power flow specification

Xmod – Modulation controller for damping enhancement

Xaux – External power flow controller

Xdes – Desired magnitude of TCSC

TTcsc – Time constant

Xfixed – reactance of TCSC installation's FC component

Where

$$Zbase = \frac{(kV[TCSC])^2}{MVA_{sys}}$$

kV_{TCSC}=the rms line-line voltage of the TCSC in kilovolts(kV)

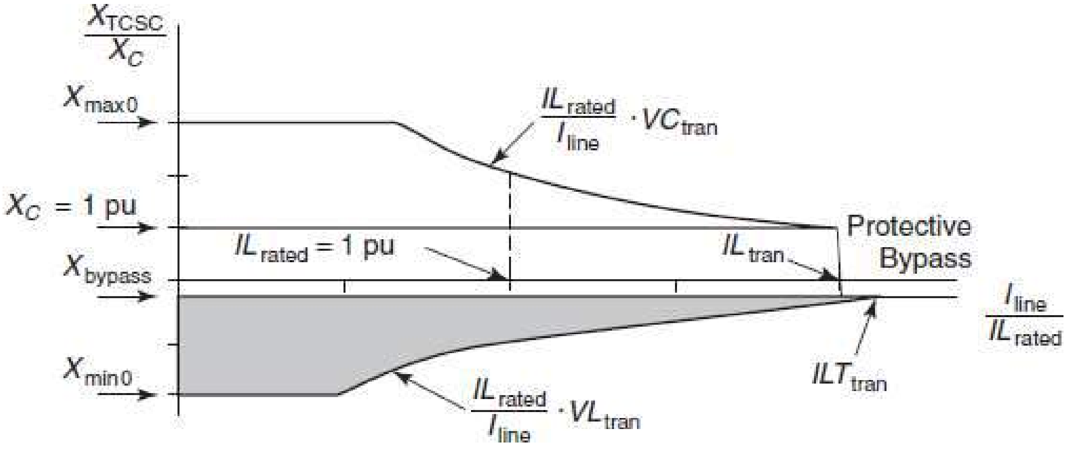
MVA_{sys}=the 3-phase MVA base of the power system

- *X*ref, is generated from a power-scheduling controller based on the power-flow specification in the transmission line. The reference *X*ref value may also be set directly by manual control in response to an order from an energy-control center, and it essentially represents the initial operating point of the TCSC; it does not include the reactance of FCs (if any).

- The reference value is modified by an additional input, *X*mod, from a modulation controller for such purposes as damping enhancement.
- *X*aux, which can be obtained from an external power-flow controller.
- A desired magnitude of TCSC reactance, *X*des, is obtained that is implemented after a finite delay caused by the firing controls and the natural response of the TCSC. This delay is modeled by a lag circuit having a time constant, *T*TCSC, of typically 15–20 ms.
- The resulting *X*TCSC is added to the *X*fixed, which is the reactance of the TCSC installation's FC component.
- To obtain per-unit values, the TCSC reactance is divided by the TCSC base reactance, *Z*base, given as
- $Zbase = \frac{(kV\,[TCSC])^2}{MVA_{sys}}$

kV_{TCSC}=the rms line-line voltage of the TCSC in kilovolts(kV)
MVA_{sys}=the 3-phase MVA base of the power system

The reactance capability curve of the multimodal TCSC is shown in Fig. 7.23.



A simplified reactance-capability curve of a multimodule TCSC

In the Capacitive region, there are three different TCSC reactance constraints which are given below

☐ The limit of TCSC firing angle,represented by constant reactance limit Xmax 0
☐ The limit on the TCSC voltageVCtran. The corresponding reactance constraint is given by

$$X_{\max VC} = (VC_{\text{tran}})\ \frac{IL_{\text{rated}}}{I_{\text{line}}}$$

□ Limit on the line current (ILtrans), beyond which the TCSC enter in to protective bypass mode.

$$\begin{aligned} X_{\max\, I_{\text{line}}} &= \infty \qquad \text{for } I_{\text{line}} < IL_{\text{tran}} \cdot IL_{\text{rated}} \\ &= X_{\text{bypass}} \qquad \text{for } I_{\text{line}} > IL_{\text{tran}} \cdot IL_{\text{rated}} \end{aligned}$$

The effective capacitive-reactance limit is finally obtained as a minimum of the following limits:

$$X_{\max\ \text{limit}} = \min(X_{\max\ 0}, X_{\max\ VC}, X_{\max\ I_{\text{line}}})$$

In the inductive region, the TCSC operation is restricted by the following limits:

□ The limit on the firing angle, represented by a constant-reactance limit, Xmin 0
□ The harmonics-imposed limit, represented by a constant-TCSC-voltage limit *VL*tran.
The equivalent-reactance constraint is given by

$$X_{\min\ VL} = (VL_{\text{tran}})\ \frac{IL_{\text{rated}}}{I_{\text{line}}}$$

□ The limit on the fundamental component of current that is permitted to flow through the thyristors in the bypassed-thyristor mode during a transient. This current limit is also expressed as a minimum-reactance limit:

$$X_{\min\ ILT} = \left[1 - \frac{ILT_{\text{tran}} \cdot IL_{\text{rated}} \cdot (1 - X_{\text{bypass}})}{I_{\text{line}}}\right]$$

The final inductive-reactance limit in the inductive-vernier operation is obtained as a maximum of the foregoing constraints:

$$X_{\min\ \text{limit}} = \max(X_{\min\ 0}, X_{\min\ VL}, X_{\min\ ILT})$$

TCSC is used for the improvement of the stability of a system.

- During the outage of a critical line in a meshed system, a large volume of power tends to flow in parallel transmission paths, which may become severely loaded.
- Providing fixed-series compensation on the parallel path to augment the power-transfer capability appears to be a feasible solution, but it may increase the total system losses.
- Therefore, it is advantageous to install a TCSC in key transmission paths, which can adapt its series-compensation level to the instantaneous system requirements and provide a lower loss alternative to fixed-series compensation.
- The series compensation provided by the TCSC can be adjusted rapidly to ensure specified magnitudes of power flow along designated transmission lines.
- This condition is evident from the TCSC's efficiency, that is, ability to change its power flow as a function of its capacitive-reactance setting:

$$P_{12} = \frac{V_1 V_2}{(X_L - X_C)} \sin \delta$$

where P_{12} = the power flow from bus 1 to bus 2

V_1, V_2 = the voltage magnitudes of buses 1 and 2, respectively

X_L = the line-inductive reactance

X_C = the controlled TCSC reactance combined with fixed-series-capacitor reactance

δ = the difference in the voltage angles of buses 1 and 2

- This change in transmitted power is further accomplished with minimal influnece on the voltage of interconnecting buses, as it introduces voltage in quadrature.
- In contrast, the SVC improves power transfer by substantially modifying the interconnecting bus voltage, which may change the power into any connected passive loads.
- The freedom to locate a TCSC almost anywhere in a line is a significant advantage. Power-flow control does not necessitate the high-speed operation of power flow control devices.
- Hence discrete control through a TSSC may also be adequate in certain situations.

- However, the TCSC cannot reverse the power flow in a line, unlike HVDC controllers and phase shifters.

Enhancement of System Damping

Introduction

- The TCSC can be made to vary the series-compensation level dynamically in response to controller-input signals so that the resulting changes in the power flow enhance the system damping .The power modulation results in a corresponding variation in the torques of the connected synchronous generators particularly if the generators operate on constant torque and if passive bus loads are not installed.
- The damping control of a TCSC or any other FACTS controller should generally do the following:
- 1. Stabilize both post disturbance oscillations and spontaneously growing
- oscillations during normal operation;
- 2. Obviate the adverse interaction with high-frequency phenomena in power systems, such as network resonances; and
- 3. Preclude local instabilities within the controller bandwidth.
- In addition, the damping control should
- 1. be robust in that it imparts the desired damping over a wide range of system operating conditions, and
- 2. be reliable.

\

Principle of Damping

□ □ The concept of damping enhancement by line-power modulation can be illustrated with the two-machine system depicted in Fig.

□ □ The machine *SM*1 supplies power to the other machine, *SM*2, over a lossless transmission line. Let the speed and rotor angle of machine *SM*1 be denoted by $\eta 1$ and $\varphi 1$, respectively; of machine *SM*2, denoted by $\eta 2$ and $\varphi 2$, respectively.

□ □ During a power swing, the machines oscillate at a relative angle

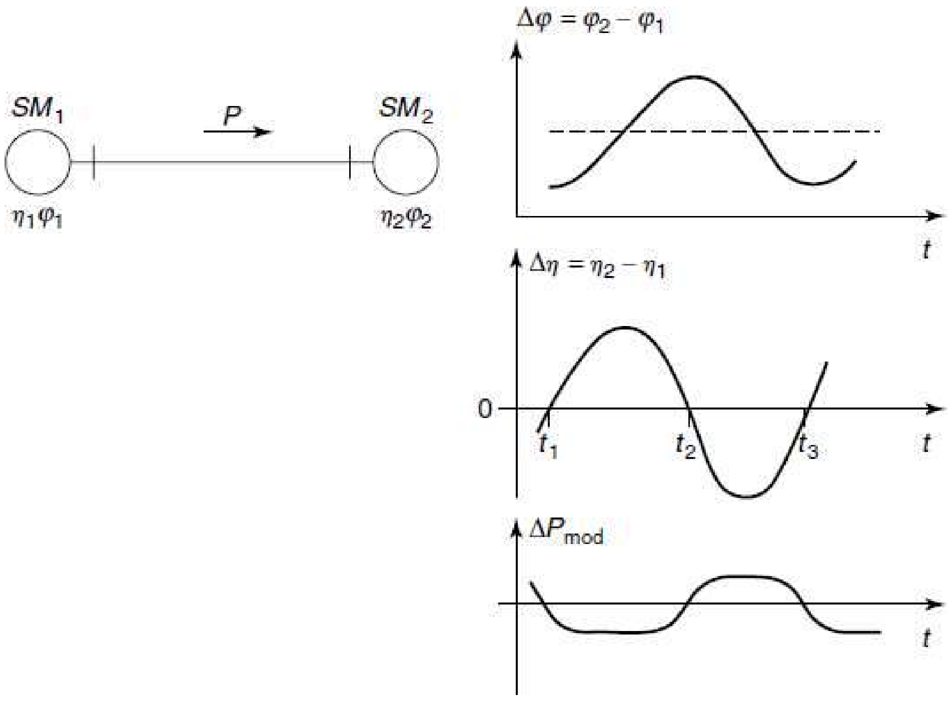
$\Delta \varphi = (\varphi 2 - \varphi 1)$.

□ □ If the line power is modulated by the TCSC to create an additional machine torque that is opposite in sign to the derivative of the rotor-angle deviation, the oscillations will get damped. This control strategy translates into the following actions: When the receiving end–machine speed is lower than the sending end–machine speed, that is, $\Delta h = (\eta 2 - \eta 1)$ is negative, the TCSC should increase power flow in the line.

- In other words, while the sending-end machine accelerates, the TCSC control should attempt to draw more power from the machine, thereby reducing the kinetic energy responsible for its acceleration.
- On the other hand, when Δη is positive, the TCSC must decrease the power transmission in the line.
- This damping control strategy is depicted in Fig. through plots of the relative machine angle Δφ, the relative machine speed Δη, and the incremental power variation Δ*P*mod.
- The incremental variation of the line-power flow D*P*, given in megawatts (MW), with respect to D*Q*TCSC, given in MVAR, is as follows

$$\frac{\Delta P}{\Delta Q_{\mathrm{TCSC}}} = \frac{1}{2\tan\delta/2}\left(\frac{I}{I_N}\right)^2$$

where δ = the angular difference between the line-terminal voltages
I = the operating-point steady-state current
I_N = the rated current of the TCSC



The TCSC line power modulation for damping enhancement

- Thus the TCSC action is based on the variation of line current magnitude and is irrespective of its location.
- Typically, the change in line power transfer caused by the introduction of the full TCSC is in the range of 1–2, corresponding to an angular difference (d) of 308–408 across the line.
- The influence of any bus load on the torque/ power control of the synchronous generator is derived for the case of a resistive load and completely inductive generator impedance.
- The ratio of change in generator power to the ratio of change in the power injected from the line into the generator bus is expressed as

$$\frac{\Delta P_m}{\Delta P} = \frac{\cos(\delta/2 \pm \alpha)}{\cos(\delta/2)}$$

where the + sign corresponds to the sending end; the − sign, the receiving end. Also,

where ΔP_m = the variation in generator power

ΔP = the variation in power injected from the transmission line into the machine bus

$\alpha = \tan^{-1}(X_{\text{source}}/R_{\text{load}})$ (it is assumed that $R_{\text{load}} \gg X_{\text{source}}$)

- The effect of all practical passive loads is generally moderate, and the sign of generator power is not changed. In the absence of any bus load,

$\Delta Pm = \Delta P$.

- The controlled-to-fixed ratio of capacitive reactance in most applications is in the 0.05–0.2 range, the exact value determined by the requirements of the specific application.

The operation of STATCOM with its V-I characteristics.

STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

- The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating and/ or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system.
- It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals.
- Specifically, the STATCOM considered is a voltage-source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance (which is provided by either an interface reactor or the leakage inductance of a coupling transformer).

PRINCIPLE OF OPERATION

□ □ A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC).

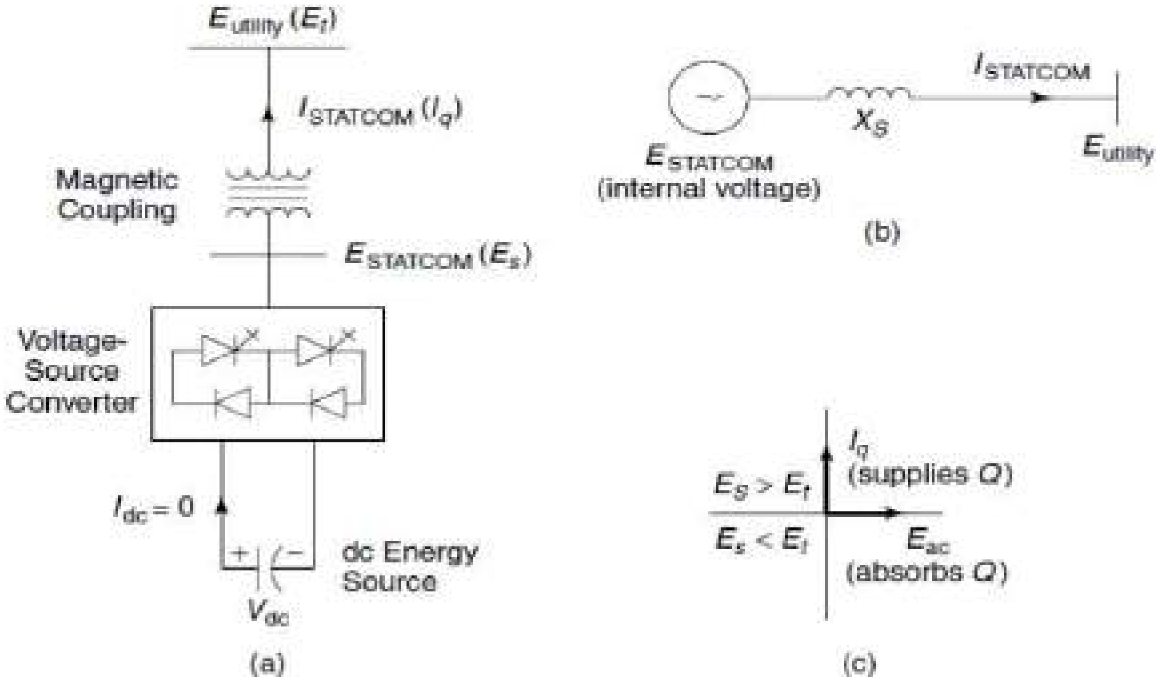
□ □ A single-line STATCOM power circuit is shown in Fig.(a),where a VSC is connected to a utility bus through magnetic coupling.

□ □ In Fig. (b), a STATCOM is seen as an adjustable voltage source behind a reactance meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact.

□ □ The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, *Es*, of the converter, as illustrated in Fig. (c).

□ □ If the amplitude of the output voltage is increased above that of the utility bus voltage, E_t, then a current flows through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system.

□ □ If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-reactive power from the ac system.



The STATCOM principle diagram: (a) a power circuit;(b) an equivalent circuit;(c) a power exchange

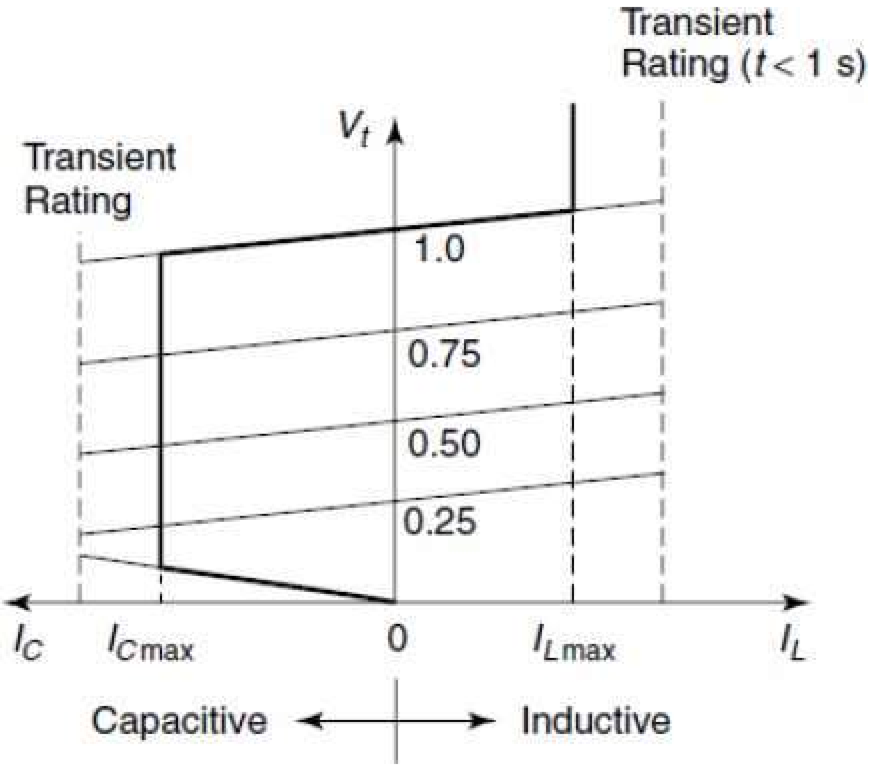
□ □ If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state.

- Adjusting the phase shift between the converte-routput voltage and the acsystem voltage can similarly control real-power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter-output voltage is made to lead the ac-system voltage.
- On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage.
- A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system.
- The mechanism by which the converter internally generates and/ or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter. The converter switches connect the dc-input circuit directly to the ac-output circuit. Thus the net instantaneous power at the acoutput terminals must always be equal to the net instantaneous power at the dc-input terminals (neglecting losses).
- Assume that the converter is operated to supply reactive-output power. In this case, the real power provided by the dc source as input to the converter must be zero.
- Furthermore, because the reactive power at zero frequency(dc) is by definition zero, the dc source supplies no reactive ower as input to the converter and thus clearly plays no part in the generation of reactive-output power by the converter.
- In other words, the converter simply interconnects the three outputterminals so that the reactive-output currents can flow freely among them. If the terminals of the ac system are regarded in this context, the converter establishes a circulating reactive-power exchange among the phases. However, the real power that the converter exchanges at its ac terminals with the ac system must, of course, be supplied to or absorbed from its dc terminals by the dc capacitor.
- Although reactive power is generated internally by the action of converter switches, a dc capacitor must still be connected across the input terminals of the converter.
- The primary need for the capacitor is to provide a circulating-current path as well as a voltage source.
- The magnitude of the capacitor is chosen so that the dc voltage across its terminalsremains fairly constant to prevent it from contributing to the ripples in the dc current. The VSC-output voltage is in the form of a staircase wave into which smooth sinusoidal current from the ac system is drawn, resulting in slight fluctuations in the output power of the converter.
- However, to not violate the instantaneous powe-requality constraint at its input and output terminals, the converter must draw a fluctuating current from its dc source.
- Depending on the converter configuration employed,it is possible to calculate the minimum capacitance required to meet the system requirements, such as ripple limits on the dc voltage and the rated-reactivepower support needed by the ac system.
- The VSC has the same rated-current capability when it operates with the capacitive- or inductive-reactive current.
- Therefore, a VSC having a certain MVA rating gives the STATCOM twice the dynamic range in MVAR (this also contributes to a compact design). A dc capacitor bank is used to support (stabilize) the controlled dc voltage needed for the operation of the VSC.
- The reactive power of a STATCOM is produced by means of powe-relectronic equipment of the voltage-source-converter type.

- The VSC may be a 2 level or 3-level type, depending on the required output power and voltage . A number of VSCs are combined in a multi-pulse connection to form the STATCOM.
- In the steady state, the VSCs operate with fundamenta-lfrequency switching to minimize converter losses. However, during transient conditions caused by line faults, a pulse width–modulated (PWM) mode is used to prevent the fault current from entering the VSCs . In this way, the STATCOM is able to withstand transients on the ac side without blocking.

V-I CHARACTERISTICS OF STATCOM

- A typical *V-I* characteristic of a STATCOM is depicted in Fig.
- The STATCOM can supply both the capacitive and the inductive compensation and is able to independently control its output current over the rated maximum capacitive or inductive range irrespective of the amount of ac-system voltage.
- The STATCOM can provide full capacitive reactive power at any system voltage—even as low as 0.15 pu.



- The characteristic of a STATCOM reveals another strength of this technology: that it is capable of yielding the full output of capacitive generation almost independently of the system voltage (constant-current output at lower voltages). This capability is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor.
- Figure illustrates that the STATCOM has an increased transient rating in both the capacitive- and the nductive-operating regions.

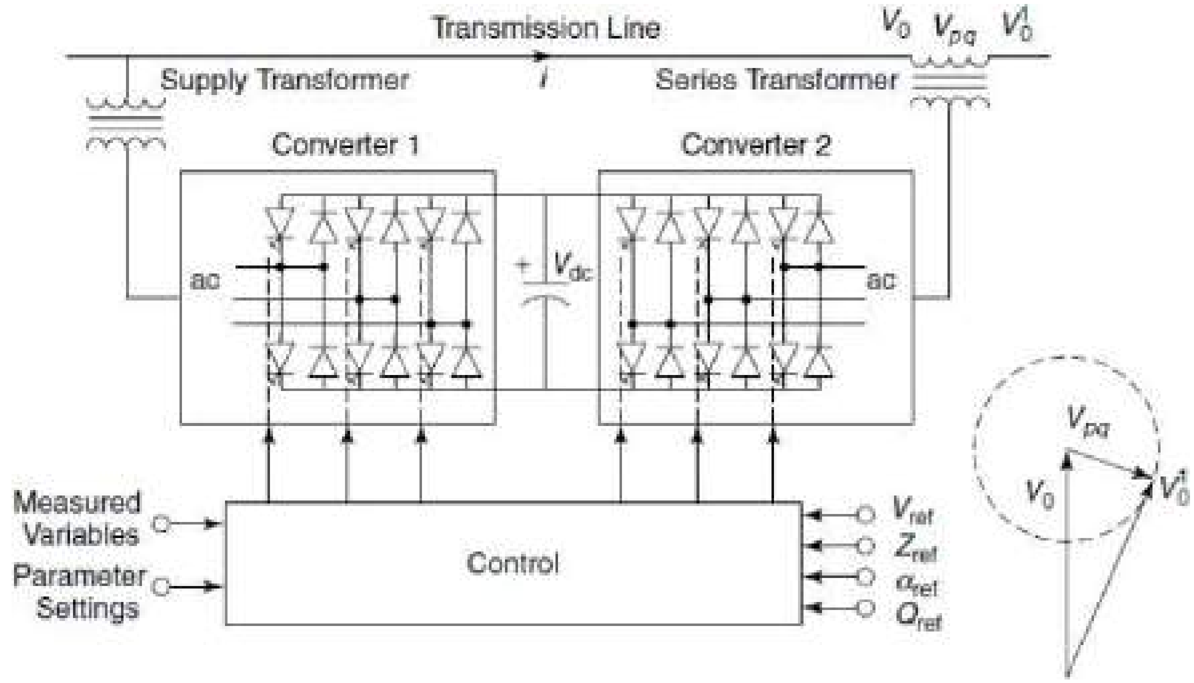
- The maximum attainable transient overcurrent in the capacitive region is determined by the maximum current turn-off capability of the converter switches.
- In the inductive region, the converter switches are naturally commutated; therefore, the transient-current rating of the STATCOM is limited by the maximum allowable junction temperature of the converter switches.

UNIFIED POWER FLOW CONTROLLER (UPFC)

UPFC is a combination of STATCOM and SSSC coupled via a common DC voltage link.

Principle of Operation

- The UPFC is the most versatile FACTS controller developed so far, with all encompassing capabilities of voltage regulation, series compensation, and phase shifting.
- It can independently and very rapidly control both rea-l and reactive power flows ina transmission.
- It is configured as shown in Fig. and comprises two VSCs coupled through a common dc terminal.

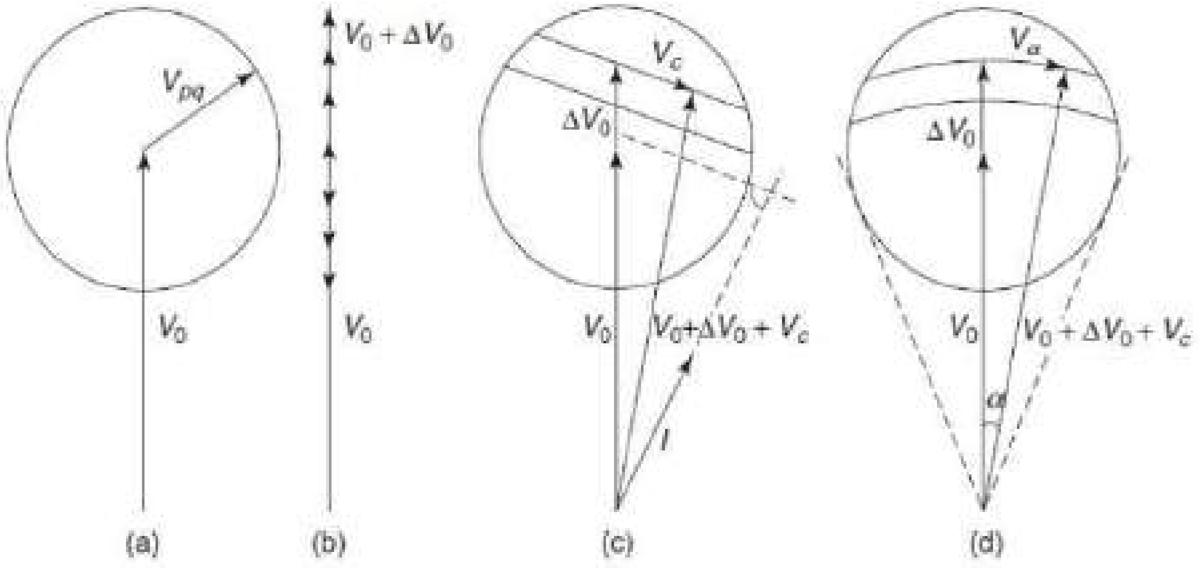


The implementation of the UPFC using two –back – to –back‖ VSCs with a common DC-terminal capacitor

- One VSC converter 1 is connected in shunt with the line through a coupling transformer; the other VSC converter 2 is inserted in series with the transmission line through an interface transformer.
- The dc voltage for both converters is provided by a common capacitor bank.
- The series converter is controlled to inject a voltage phasor, Vpq, in series with the line, which can be varied from 0 to Vpq max. Moreover, the phase angle of Vpq can be independently varied from 0^0 to 360^0.

- In this process, the series converter exchanges both real and reactive power with the transmission line.
- Although the reactive power is internally generated/ absorbed by the series converter, the real-power generation/ absorption is made feasible by the dc-energy–storage device that is, the capacitor.
- The shun-tconnected converter 1 is used mainly to supply the real-power demand of converter 2, which it derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus.
- Thus the net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers.
- In addition, the shunt converter functions like a STATCOM and independently regulates the terminal voltage of the interconnected bus by generating/ absorbing a requisite amount of reactive power.

Modes of Operation

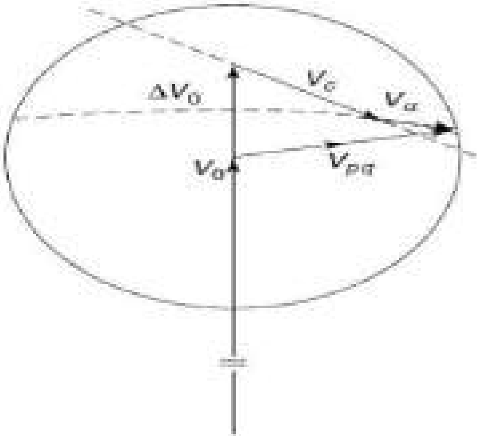


The phasor diagram illustrating the general concept of sries-voltage injection and attainable power flow control functions a) Series-voltage injection;(b)terminal-voltage regulation;(c)terminal-voltage and line-impedance regulation and (d) terminal-voltage and phse-angle regulation

The concepts of various power-flow control functions by use of the UPFC are illustrated in Figs. (a)–(d). Part (a) depicts the addition of the general voltage phasor Vpq to the existing bus voltage, $V0$, at an angle that varies from 0^0 to 360^0.

- Voltage regulation is effected if $Vpq = \Delta V0$ is generated in phase with $V0$, as shown in part (b). A combination of voltage regulation and series compensation is implemented in part (c), where Vpq is the sum of a voltageregulating component $\Delta V0$ and a series compensation providing voltage component Vc that lags behind the line current by 900. In the phase-shifting process shown in part (d), the UPFC-generated voltage Vpq is a combination of voltage- regulating component $\Delta V0$ and phase-shifting voltage component Va.
- The function of Va is to change the phase angle of the regulated voltage phasor, $V0 + \Delta V$, by an angle α. A simultaneous attainment of all three foregoing power-flow control functions is depicted in Fig.
- The controller of the UPFC can select either one or a combination of the three functions as its control objective, depending on the system requirements.
- The UPFC operates with constraints on the following variables :

1. The series-injected voltage magnitude;
2. The line current through series converter;
3. The shunt-converter current;
4. The minimum line-side voltage of the UPFC;
5. The maximum line-side voltage of the UPFC; and
6. The real-power transfer between the series converter and the shunt converter



A phasor diagram illustrating the simultaneous regulaiton of the terminal voltage, line impedance, and phase angle by appropriate series-voltage injection

Static Synchronous Series Compensator (SSSC)

Configuration and operation

The basic scheme of SSSC is shown in Fig.4.9. The SSSC is a series compensation device of the FACTS family using power electronics based on the voltage source converter (VSC) to control power flow in transmission lines and improve transient stability in power system [33]. The SSSC controls the power flow in transmission lines by controlling the magnitude and phase angle of injected voltage (Vse) in series with the transmission line where SSSC is connected. The exchange of real and reactive power between SSSC and power system depends on the magnitude and phase displacement with respect to transmission line current.

The Fig. 4.10 shows the four-quadrant operation of SSSC. The line current I, is taken as reference phasor while the series injected voltage phasor Vse of SSSC is allowed to rotate around the center of the circle defined by the maximum inserted voltage Vse-max. In Capacitive mode of operation, the series injected voltage Vse of SSSC is made lag by 900 with transmission line current. In this case the SSSC operates like series capacitor with variable capacitance kXC, i.e., Vse = - kXC*I, where k is variable. By this action the total reactance of transmission line is reduced while the voltage across the line is increased. This leads to increase in the line current and hence the transmitted power. In the case of inductive mode of operation, the series injected voltage Vse of SSSC is made to lead by 900 with transmission line current, i.e., Vse = kXC*I. This leads to increase in the transmission line reactance, which results in a decrease in line current and hence the transmitted power. The above equation shows that the magnitude of Vse is directly proportional to the line current (I) magnitude, this is true for series capacitance, but not for SSSC. Actually the series inserted voltage Vse is set by the SSSC control is independent of the line reactance. The SSSC can control the power flow through the transmission line by controlling the magnitude of Vse and injecting in qudarture with transmission line current I as mentioned in the following equation

Vse=V2-V1=Vd+jVq

Vd~ 0

Vq>0: SSSC is Capacitive

Vq<0: SSSC is Inductive

The magnitude of Vse is controlled through the changes in the amplitude modulation ratio mse, as the output voltage magnitude is directly proportional to mse according to the following equation mse = √ (8*Vse/Vdc) ------------------ (4.7) **Fig.**

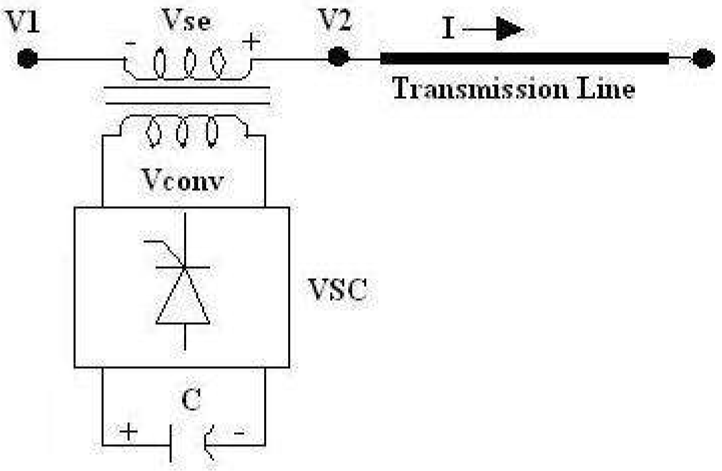


Fig.4.9. The basic scheme of SSSC

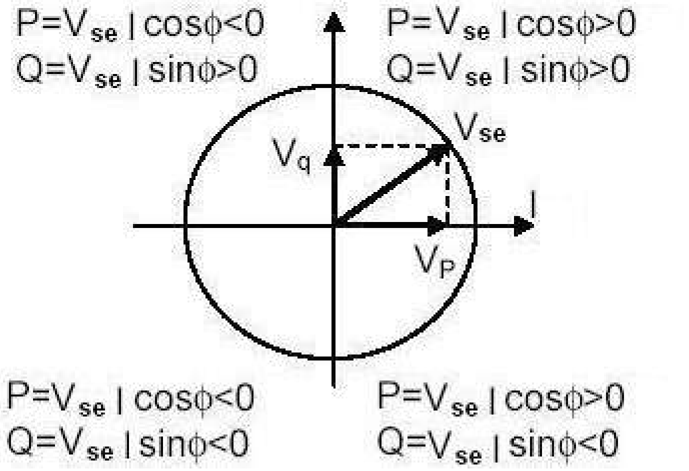


Fig. 4.10 four-quadrant operation of SSSC

V-I Characteristics of SSSC

The fig.4.11 shows the V-I Characteristic of SSSC. The SSSC can provide capacitive voltage and inductive voltage up to its specified maximum current rating. The SSSC can generate a controllable compensating capacitive or inductive voltage, which implies that the amount of transmittable power can be increased as well as decreased from natural power.

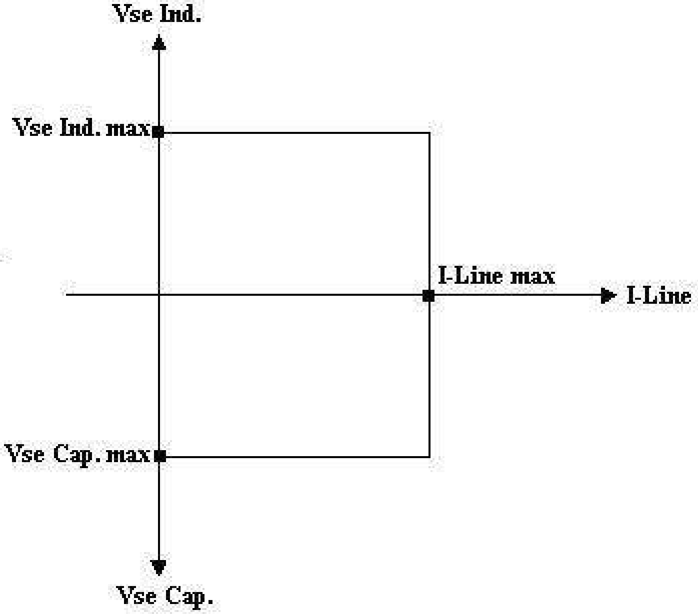


Fig.4.11 V-I Characteristics of SSSC

Basic Two-Converter Scheme For IPFC

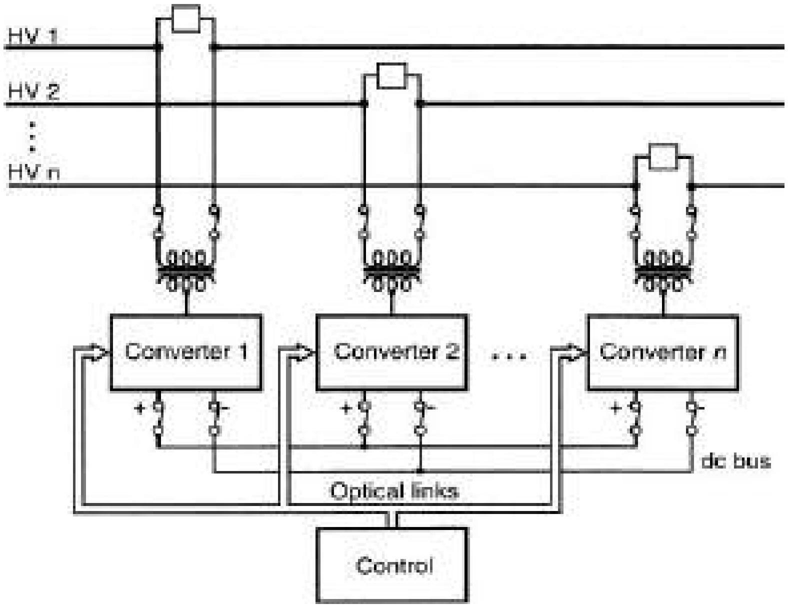


Figure : Interline Power Flow Controller comprising /n converters

The schematic representation of an IPFC shown in Figure 1.There are two back-to-back voltage-source converters (VSCs), based on the use of gate-turnoff (GTO) thyristor valves. The VSCs produce voltages of variable magnitude and phase angle. These voltages are injected in series with the managed transmission lines via series transformers. The injected voltages are

represented by the voltage phasors .The converters labeled VSC1 and VSC2 are coupled together through a common dc link. Illustrates the IPFC phasor diagram. With respect to the transmission-line current, in phase and quadrature phase components of injected voltage, respectively, determine the negotiated real and reactive powers of the respective transmission lines. The real power exchanged at the ac terminal is converted by the corresponding VSC into dc power which appears at the dc link as a negative or a positive demand. Consequently, the real power negotiated by each VSC must be equal to the real power negotiated by the other VSC through the dc lines.VSC1 is
operated at point A. Therefore, VSC2 must be operated along the complementary voltage compensation line, such as point B, to satisfy the real power demand of VSC1. This is given by
Psc1+Psc2=V1pI1+V2pI2=0 (5.1)
In the IPFC structure, each converter has the capability to operate as a stand-alone SSSC under contingency conditions, such as the outage of another ac line, other converter, or opening the dc link between the two converters. The protective actions can be divided into two levels in each converter station. In case a failure occurs and affects all components, the protection system The IPFC has the in-built capacity to bypass the rest of the componentsin that, when a failure occurs at a series transformer, the associated SSSC is bypasses using the bypass breaker. For instance, when a failure takes place in a valve of the VSC, built within the GTO thyristor module, the GTO module is bypassed. This means that, where a number of failures occur affecting a single component, the protective actions is specifically employed on that particular component, bypassing the failure and setting it right.

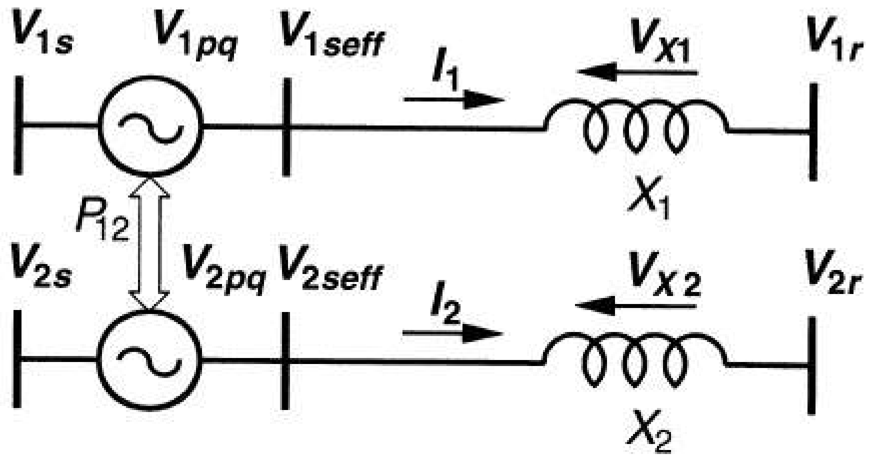


Figure Basic two-converter Interline Power Flow Controller scheme.

- Consider an elementary IPFC scheme consisting of two back-to-back dc-to-ac converters, each compensating a transmission line by series voltage injection. This arrangement is shown functionally in Figure, where two synchronous voltage sources, with phasors V_{1pq} and V_{2pq} in series with transmission Lines 1 and 2, represent the two back-to-back dc- to-ac converters.
- The common dc link is represented by a bidirectional link for real power exchange between the two voltage sources.

- Transmission Line 1, represented by reactance X_1 has a sending-end bus with voltage phasor V_{1s} and a receiving-end bus with voltage phasor V_{1r}. The sending-end voltage phasor of Line 2, represented by reactance X2, is V_{2s}" and the receiving-end voltage phasor is V_{2r}.

- all the sending-end and receiving-end voltages are assumed to be constant with fixed amplitudes,
- V1s= V1r= V2s= V2r=1.0 p.u and with fixed angles resulting in identical transmission angles, δ1= δ2=30o for the two systems.

- In order to establish the transmission relationships between the two systems,

  System 1 is arbitrarily selected to be the prime system for which free controllability of both real and reactive line power flow is stipulated.

  The reason for this stipulation is to derive the constraints which the free controllability of System 1 imposes upon the power flow control of System

generalize IPFC which can be operated as a STATCOM , SSSC, UPFC OR IPFC.

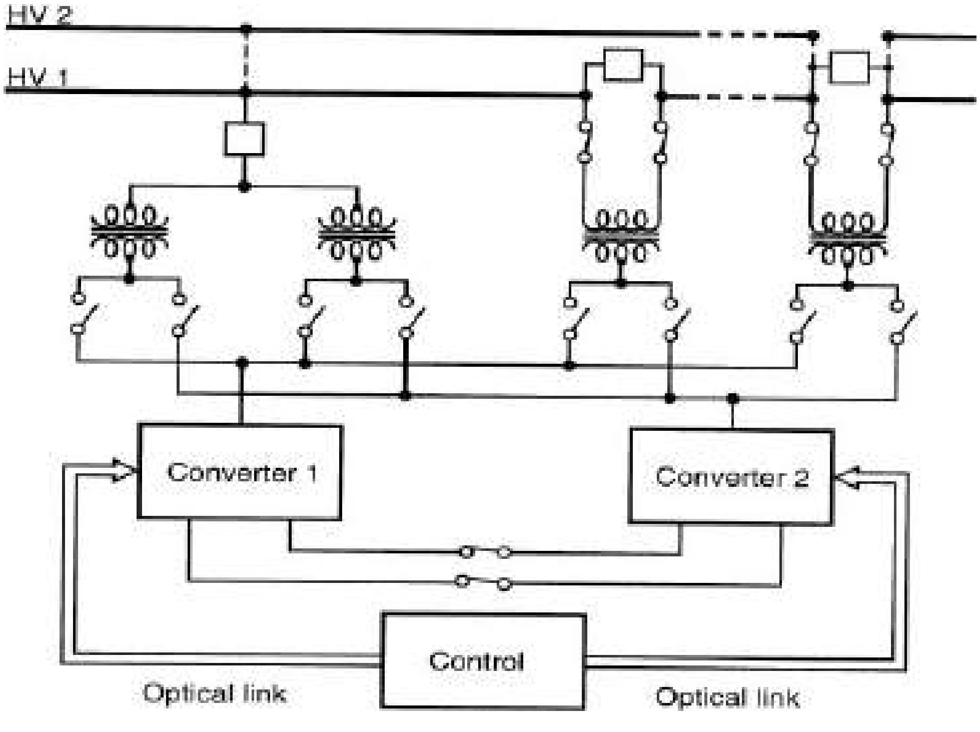


Figure -1 Illustration of the functional convertibility of a compensator scheme comprising two voltage-sourced converters.

Figure 1 shows the two converter, two-line arrangement, which could be expanded to any number of converters and lines. The inspection of this figure shows that with the appropriate closing and opening of the circuit switches connecting the converter outputs to the coupling transformers, the two converters, each with 1..0 p.u. VA rating, could be configured to function as:

- STATCOM (1.0 p.u. and 2.0 p.u. rating)
- SSSC (1.0 p.u. and 2.0 p.u. rating)
- STATCOM and SSSC (each L.0 p.u. rating)
- UPFC (1.0 p.u. series and L.0 p.u. shunt converter rating)
- IPFC (1.0 p.u. for each line)

Note that the per unit ratings shown are not the throughput ratings of the lines.
Generally, the FACTS Controller ratings are smaller than the throughput ratings.
They are more related to the per unit series inductance of the lines. The power electronic-based Controller ratings are defined by the product of the maximum voltage and maximum current the equipment handles, even if the maximum voltage and current do not occur simultaneously.
This approach may be economically savvy for the short term, it may not have the capability for broader optimization of the transmission assets, or the flexibility to handle changing transmission conditions, and ultimately it may result in a 'stranded asset.,,

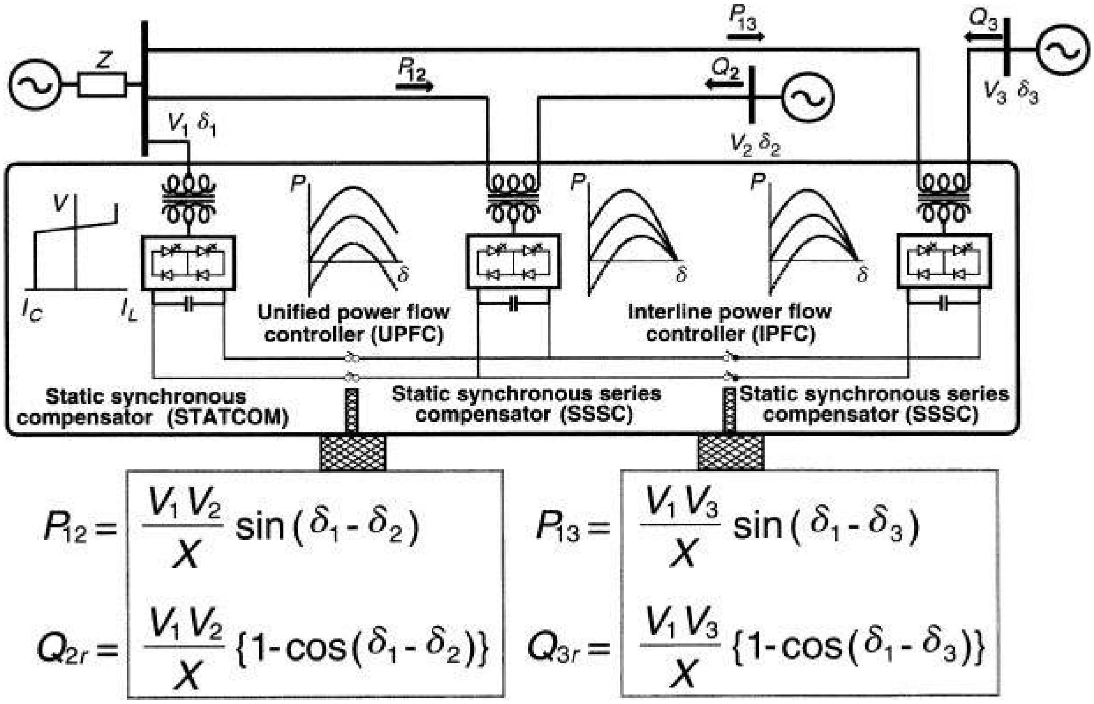


Figure 2 Illustration of a generalized IPFC concept for comprehensive real and reactive power flow control of a multiline transmission system.

Figure 2 illustrates which can function individually as conventional (voltage, impedance or angle) Controllers, but can also be converted from one functional

use to another, and, more importantly, can be connected to a common dc link
to provide comprehensive transmission control capabilities. As can be observed two voltage-sourced converter modules, used to control the power flow between bus 1 and bus 2, can be used individually as a STATCOM and an SSSC, or can be combined to function as a UPFC for the comprehensive control of both real and reactive power flow between bus 1 and bus 2. With the addition of the third converter module, the second line receives an independent series reactive compensator (SSSC). However,by connecting this converter to the common dc bus, a genlralized IPFC is established which can control and optimize under the prevailing system condition the real and reactive power in both lines, from bus L to bus 2, and also from bus 1 to bus 3. This simple example shows the capability of the voltage-sourced converter-based approach to maintain full convertibility and individual functionality while also providing a powerful potential for an integrated transmission management system with capacity of real and reactive power flow control and handling of dynamic disturbances In the multifunctional FACTS Controller arrangements discussed above, each Controller in a line can independently carry out limited compensation and control functions and thus the common dc connection does not represent a significant single
point failure.

Various kinds of control interactions occurring between different FACTs controllers using their frequency response characteristics

- **FACTS Controller Interactions**
- Controller interactions can occur in the following combinations:
  - Multiple FACTS controllers of a similar kind.
  - Multiple FACTS controllers of a dissimilar kind.
  - Multiple FACTS controllers and HVDC converter controllers.
- Because of the many combinations that are possible, an urgent need arises for power systems to have the ontrols of their various dynamic devices coordinated.The term *coordinated* implies that the controllers have been tuned simultaneously to effect an overall positive improvement of the control scheme.
- The frequency ranges of the different control interactions have been classified as follows:
  - 0 Hz for steady-state interactions
  - 0–3/ 5 Hz for electromechanical oscillations
  - 2–15 Hz for small-signal or control oscillations
  - 10–50/ 60 Hz for subsynchronous resonance (SSR) interactions
  - >15 Hz for electromagnetic transients, high-frequency resonance or harmonic resonance interactions, and network-resonance interactions
- **1 Steady – State Interactions**
- Steady-state interactions between different controllers (FACTS–FACTS or FACTS–HVDC) occur between their system-related controls.
- They are steady state in nature and do not involve any controller dynamics. These interactions are related to issues such as the stability limits of steady-state voltage and steady-state power; included are evaluations of the adequacy of reactive-power support at

buses, system strength, and so on.

- An example of such control coordination may be that which occurs between the steady-state voltage control of FACTS equipment and the HVDC supplementary control for ac voltage regulation.
- Load-flow and stability programs with appropriate models of FACTS equipment and HVDC links are generally employed to investigate the foregoing control interactions.

- Steady-state indices, such as voltage-stability factors (VSF),are commonly used. Centralized controls and a combination of local and centralized controls of participating controllers are recommended for ensuring the desired coordinated performance.
- **2 Electromechanical – Oscillation Interactions**
- Electromechanical-oscillation interactions between FACTS controllers also involve synchronous generators, compensator machines, and associated powersystem stabilizer controls .
- The oscillations include *local mode* oscillations, typically in the range of 0.8–2 Hz, and *inter-area mode* oscillations, typically in the range of 0.2–0.8 Hz.

- The local mode is contributed by synchronous generators in a plant or several generators located in close vicinity; the inter-area mode results from the power exchange between tightly coupled generators in two areas linked by weak transmission lines.
- Although FACTS controllers are used primarily for other objectives, such as voltage regulation, they can be used gainfully for the damping of electromechanical oscillations.
- In a coordinated operation of different FACTS controllers, the task of damping different electromechanical modes may be assumed by separate controllers.
- Alternatively, the FACTS controllers can act concertedly to damp the critical modes without any adverse interaction.
- Eigenvalue analysis programs are employed for determining the frequency and damping of sensitive modes.
- **3 Control or Small – Signal oscillations**
- Control interactions between individual FACTS controllers and the network or between FACTS controllers and HVDC links may lead to the onset of oscillations in the range of 2–15 Hz (the range may even extend to 30 Hz).
- These oscillations are largely dependent on the network strength and the choice of FACTS controller parameters, and they are known to result from the interaction between voltage controllers of multiple SVCs, the resonance between series capacitors and shunt reactors in the frequency range of 4–15 Hz ,and so forth. The emergence of these oscillations significantly influences the tuning of controller gains.
- Analysis of these relatively higher frequency oscillations is made possible by frequency-scanning programs, electromagnetic-transient programs (EMTPs), and physical simulators (analog or digital).
- Eigenvalue analysis programs with modeling capabilities extended to analyze higher-frequency modes as well may be used .

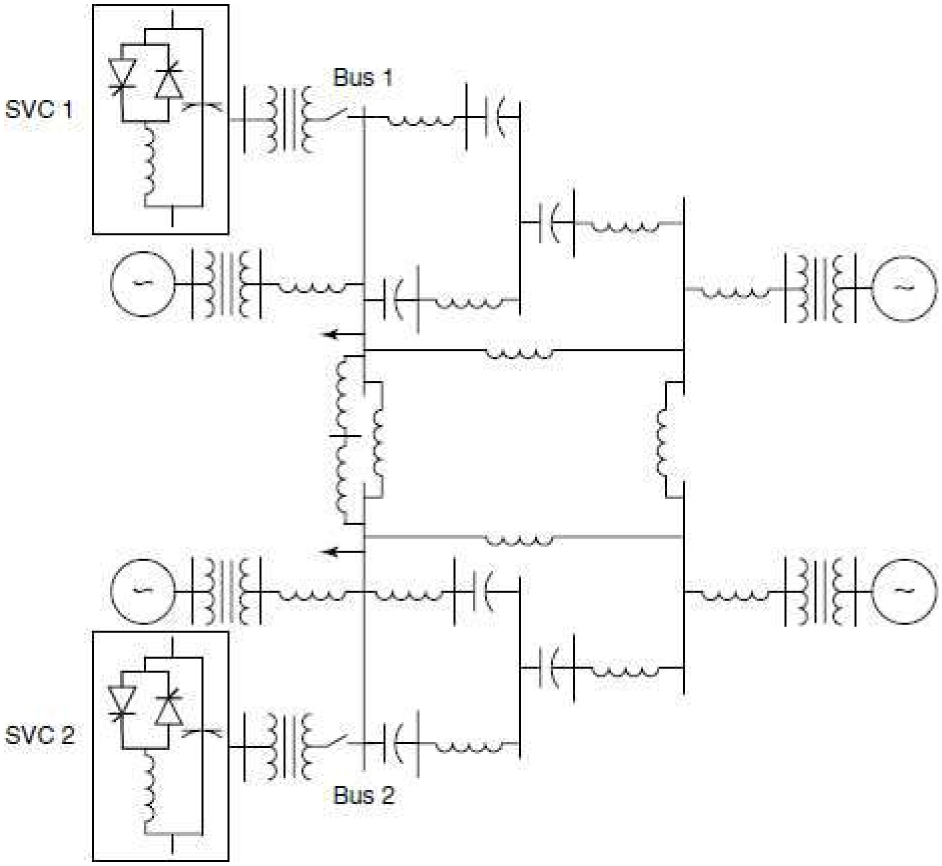
4 Sub Synchronous resonance (SSr) Interactions

- Subsynchronous oscillations may be caused by the interaction between the generator torsional system and the series-compensated-transmission lines, the HVDC converter controls, the generator excitation controls, or even the SVCs.These oscillations, usually in the frequency range of 10–50/ 60 Hz, can potentially damage generator shafts.
- Subsynchronous damping controls have been designed for individual SVCs and HVDC links.
- In power systems with multiple FACTS controllers together with HVDC converters, a coordinated control can be more effective in curbing these torsional oscillations.
- **5 High – Frequency Interactions**
- High-frequency oscillations in excess of 15 Hz are caused by large nonlinear disturbances, such as the switching of capacitors, reactors, or transformers, for which reason they are classified as electromagnetic transients.
- Control coordination for obviating such interactions may be necessary if the FACTS and HVDC controllers are located within a distance of about three major buses. Instabilities of harmonics (those ranging from the 2nd to the 5th) are likely to occur in power systems because of the amplification of harmonics in FACTS controller loops.
- Harmonic instabilities may also occur from synchronization or voltage-measurement systems, transformer energization, or transformer saturation caused by geomagnetically induced currents (GICs).

- ✓ **The controller interactions between multiple SVCs (SVC-SVC) in a large power system.**

- **SVC – SVC Interactions**
- **1 The Effect of Electrical Coupling and Short-Circuit Levels**

- The interaction phenomena are investigated as functions of electrical distance (electrical coupling) between the SVCs and the short-circuit level at the SVC buses.



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- SVC interaction – analysis network

  - **Uncoupled SVC Buses**

- A simplified test system shown in Fig. is considered for the interaction analysis performed through eigenvalue analyses and root-loci plots.
- All the generating units are represented by infinite buses. If the transfer reactance between buses 1 and 2 is high, making the buses electrically uncoupled, then the SVCs connected to those buses do not interact adversely.
- Increasing the proportional gain of SVC 1 connected to bus 1, even to the extent of making the SVC unstable, does not affect the eigenvalues of SVC 2—implying that the controller designs of SVCs can be done independently for multiple SVCs in a power system if the transfer reactance between their connecting buses is high.

  - **Coupled SVC Buses**

- If the reactance between the two SVC buses is low, it constitutes a case of high electrical coupling between the SVCs.

- Here again, two ossibilities exist with respect to short-circuit capacity of the region where the SVCs are installed: the SVC region with a high shortcircuit capacity and the SVC region with a low short-circuit capacity.
- For high short-circuit capacity conditions in the same system as Fig. reveal that by increasing the proportional gain of one SVC, the eigenvalues of the other SVC are impacted very slightly. Almost no control interaction exists between the two SVCs irrespective of their electrical coupling, as long as they are in a high short-circuit-level region, that is, when the ac system is stiff.
- The reason for this condition is that the interlinking variable between the two SVCs is the bus voltage.
- Thus the controls of both SVCs can be independently designed and optimized, but if the short-circuit capacity of the SVC region is low, varying the proportional gain of SVC 1 will strongly influence the eigenvalues associated with SVC 2.
- Therefore imperative that a coordinated control design be undertaken for both SVCs.
- Despite simplifications in the study system and in the analysis approach, the aforementioned interaction results are general, for the phenomena investigated are independent of the number of buses, transmission lines, or generators.

the co-ordination of multiple controllers Using linear control techniques,

Co-Ordination of Multiple Controllers using Linear – Control Techniques

- **1 Introduction**
- The term *coordination* does not imply centralized control; rather, it implies the simultaneous tuning of the controllers to attain an effective, positive improvement of the overall control scheme.
- It is understood that each controller relies primarily on measurements of locally available quantities and acts independently on the local FACTS equipment.

- **The Basic Procedure for Controller Design**
  - The controller-design procedure involves the following steps:
  - Derivation of the system model;
  - Enumeration of the system-performance specifications;
  - Selection of the measurement and control signals;
  - Coordination of the controller design; and
  - Validation of the design and performance evaluation.
- **Step 1: Derivation of System Model**
- First, a reduced-order nonlinearsystem model must be derived for the original power system and this model should retain the essential steady-state and dynamic characteristics of the power system .

- Then, the model is linearized around an operating point to make it amenable to the application of linear-control design techniques. If a controllermust be designed for damping electromechanical oscillations, a further reducedlinear model is selected that exhibits the same modal characteristics over the relevant narrow range of frequencies as the original system.
- In situations where linearized-system models may not be easily obtainable, identification techniques are employed to derive simple linear models from time-response information.
- **Step 2: Enumeration of the System – performance Specifications**
- The damping controller is expected to satisfy the following criteria.
- It should help the system survive the first few oscillations after a severe system disturbance with an adequate safety margin. This safety factor is usually specified in terms of bus-voltage levels that should not be violated after a disturbance.
- A minimum level of damping must be ensured in the steady state after a disturbance.
- Potentially deleterious interactions with other installed controls should be avoided or
- minimized.
- Desired objectives over a wide range of system-operating conditions should be met (i.e., it should be robust).
- **Step 3: Selection of the Measurement and Control Signals**
- The choice of appropriate measurement and control signals is crucial to controller design.
- The signals must have high observability and controllability of the relevant modes to be damped, and furthermore, the signals should only minimally affect the other system modes.
- The selection of these signals is usually based on system-modal magnitudes, shapes, and sensitivties—all of which can be obtained from small-signal-stability analysis.
- **Step 4: Controller Design and Coordination**
- The FACTS controller structures are usually chosen from industry practice. Typically, the controller transfer function, *Hj*(*s*), of controller *j* is assumed to be

$$H_j(s) = k_j G_j(s) = k_j \, \frac{sT_W}{1 + sT_W} \left(\frac{1 + s\tau_1}{1 + s\tau_2} \right)^p \frac{1}{(1 + sT_1)(1 + sT_2)\cdots(1 + sT_n)}$$

- This transfer function consists of a gain, a washout stage, and a *p*th-order leadlag block, as well as low-pass filters. Alternatively, it can be expressed as

$$H_j(s) = k_j G_j(s) = k_j \left[k_0 \, \frac{(s + \cdots + b_m s^m}{1 + a_1 s + \cdots + a_n s^n} \right], \qquad m \leq n$$

- Although the basic structure of different controllers is assumed as from the preceding text, the coordination of controllers involves the simultaneous selection of gains and time constants through different techniques.
- Doing so permits the system-operating constraints and damping criteria to be satisfied over a wide range of operating conditions.
- The coordination techniques may use linearized models of the power system and other embedded equipments, capitalizing on the existing sparsity in system representation.
- This model may be further reduced by eliminating certain algebraic variables yet still retaining the essential system behavior in the frequency range of interest.
- Eigenvalue analysis–based controller-optimization and -coordination techniques are applicable to power systems typically with a thousand states occurring when full modal analysis must be performed. However, sometimes a limited number of electromechanical modes must be damped; hence the eigenvalue analysis of a selected region can be performed even for relatively larger power systems.
- **Step 5: Validation of the Design and performance Evaluation**
- Even though the controller design is performed on the simplified system model, the performance of the controller must still be established by using the most detailed system model.
- The controller should meet the specifications over a wide range of operating conditions and consider all credible contingencies.This validation is generally performed with nonlinear time-domain
- simulations of the system.

Linear control techniques used for coordination of control of different FACTS controllers

- ***(i)Global coordination using nonlinear-constrained optimization***
- In the global-coordination technique, the parameters (both gain and time constants) of the damping controllers of multiple FACTS controllers are coordinated globally by using nonlinear-constrained optimization.
- It is usually observed in power systems that if the FACTS controllers have large ratings, their damping action on the real-power oscillations causes substantial reactive power oscillations.
- To restrict oscillations—in both the real and the reactive power—the optimization problem is stated as follows:
- Minimize

$$F = \int_0^{\infty} [\Delta P^{\mathrm{T}} I \Delta P + K_Q \Delta Q^{\mathrm{T}} I \Delta Q]\, dt$$

subject to

$$V_{\min} \le V_{\mathrm{bus}\,k} \le V_{\max}, \qquad k = 1, 2, m$$

where for n FACTS controllers,

$\Delta P = [\Delta P_1, \Delta P_2, \ldots, \Delta P_n]^{\mathrm{T}}$
= the n locally measured real-power-flow oscillations
$\Delta Q = [\Delta Q_1, \Delta Q_2, \ldots, \Delta Q_n]^{\mathrm{T}}$
= the n locally measured reactive-power oscillations
$V_{\mathrm{bus}\,k}$ = the voltage magnitude of the kth bus
$V_{\max}, V_{\min}$ = the upper and lower limits of the bus-voltage magnitude respectively
K_Q = the weighting factor

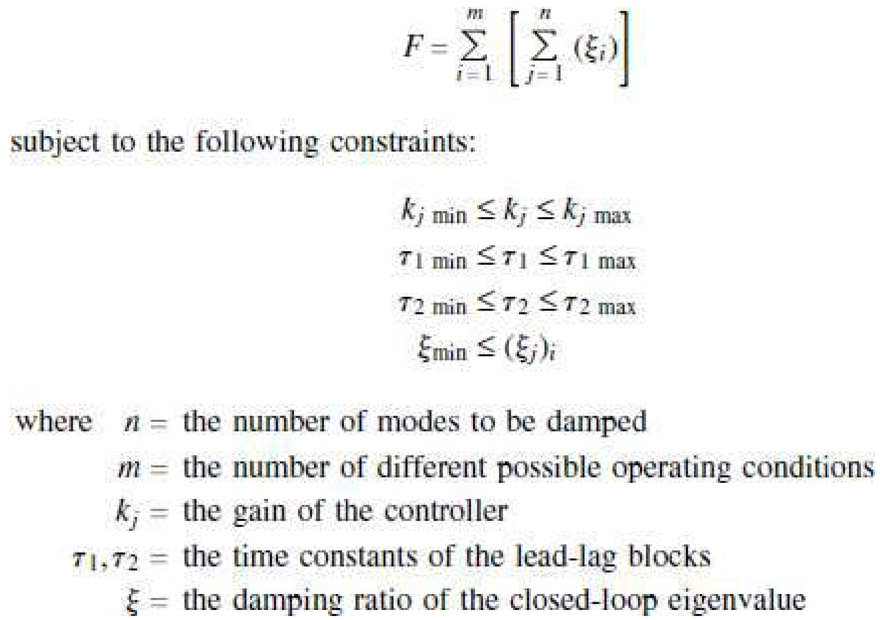
- If the primary control objective is to damp active-power oscillations, the
    - weighting factor *KQ* is assigned a small value, typically 0.2. However, if reactive-power swings must also be restricted, *KQ* is assigned a higher magnitude.
- The foregoing optimization scheme results in robust controllers having a significant damping influence on both large and small disturbances.
- An example of the global coordination of damping controllers of an SVC and a TCSC is presented in ref. [2]. The transfer function, *FD*(*s*), of both damping controllers is assumed to be of the form

$$F_D(s) = K \cdot \frac{sT_1}{1 + sT_2} \cdot \frac{1 + sT_3}{1 + sT_4}$$

☐

- Although *T*2 and *T*4 are chosen a priori, parameters *K*, *T*1, and *T*3 are determined for both controllers through the optimization procedure.
- ***(ii) Control coordination using Genetics algorithm***
- Genetic algorithms are optimization techniques based on the laws of natural
    - selection and natural genetics that recently have been applied to the control
    - design of power systems .

- These techniques provide robust, decentralized control design and are not restricted by problems of nondifferentiability, nonlinearity, and nonconvexity, all of which are often limiting in optimization exercises.
- Genetic-algorithm techniques use the linearized state-space model of the power system.
- The objective function is defined as the sum of the damping ratios of all the modes of interest.
- This sum is evaluated over several likely operating conditions to introduce robustness.
- A minimum damping level is specified for all the modes; the other constraints include limits on the gain and time constants of the damping controllers assumed to be from a fixed structure, as given in Eq. (9.3).
- The optimization problem is therefore stated as follows:
    - Maximize



$$F = \sum_{i=1}^{m} \left[\sum_{j=1}^{n} (\xi_i) \right]$$

subject to the following constraints:

$$k_{j\,\min} \le k_j \le k_{j\,\max}$$
$$\tau_{1\,\min} \le \tau_1 \le \tau_{1\,\max}$$
$$\tau_{2\,\min} \le \tau_2 \le \tau_{2\,\max}$$
$$\xi_{\min} \le (\xi_j)_i$$

where n = the number of modes to be damped
m = the number of different possible operating conditions
k_j = the gain of the controller
τ_1, τ_2 = the time constants of the lead-lag blocks
ξ = the damping ratio of the closed-loop eigenvalue

- This maximization yields the gain *kj* and the time constants τ1, τ 2 for all the controllers for a prespecified order *p* of the lead-lag blocks. The time constant T_W of the washout filter is assumed to be adequately large and known a priori.
- Likewise, the time constants *T*1, *T*2, . . . , *Tn* of the low-pass filters are selected beforehand.
- The foregoing optimization problem involves a computation of eigen values
- of a large system matrix, which is usually difficult to solve with conventional techniques.
- An advantage of genetic-algorithm techniques is that the parameter limits can be varied during the optimization, making the techniques computationally efficient. An application of these techniques to two large power systems

Control techniques used for coordination of multiple FACTS controllers

(1)Linear Quadratic Regular (LQR) –based technique

- The LQR technique is one of optimal control that can be used to coordinate the controllers with the overall objective of damping low-frequency inter-area modes during highly stressed power-system operations.
- The system model is first linearized and later reduced to retain the modal features of the main system over the frequency range of interest.
- The control-system specifications are laid out as described previously. Appropriate measurement and control signals are selected, based on observability and controllability considerations, to have only a minimal interaction with other system modes.
- Using a projective-controls approach , the control-coordination method involves formulating an LQR problem to determine a full-state-feedback controller in which a quadratic performance index is minimized.
- An output-feedback controller is then obtained, based on the reduced eigen space of the full-state solution.
- The dominant modes of the full-state-feedback system are retained in the closed-loop system with output feedback.
- The order of the controller and the number of independent measurements influence the number of modes to be retained.
- The output-feedback solution results in the desired coordinated control.
- The performance of coordinated controls is later tested and evaluated through time-domain simulation of the most detailed model of the nonlinear system.

- ***(ii)Non Linear – Control Techniques***
- Several nonlinear-control techniques have been applied for the design of FACTS controllers.
- These techniques are likely to yield greatly improved controllers, as they include the effects of system nonlinearities.
- Some of these methods are described briefly in the following text.
- One nonlinear-control technique in which the system nonlinearities are expressed as system changes constituting a function of time is the *adaptive*
    - *control* .
- If the number of controller parameters to be optimized is not too large, a *cost-penalty function* technique can be used, which is based on nonlinear simulation .
- An effective technique commonly used for enhancing transient stability during large disturbances is the *discontinuous control* or *bang-bang control*.

- Another nonlinear-control technique is the *normal forms*, which includes the effects of higher-order terms in Taylor's series to represent power systems—especially during high-power transfers .
- For damping low-frequency oscillations, FACTS controllers can be designed using the *dissipation* technique, which is based on the concept that passive systems always absorb energy .
- For designing the controls of FACTS controllers in large power systems, the *energy*, or *Lyapunov*, technique can be used.

- For stability enhancement, *nonlinear fuzzy* and *neural net* techniques are
    - presently being researched .
- In the future, these techniques may be extended for coordination of FACTS
- controllers.
- One possible approach could be to first do a ―coarse‖ coordination using linear-control techniques, followed by a ―fine‖ coordination employing
    - the nonlinear-control methods.