Gokaraju Rangaraju Institute of Engineering and Technology (Autonomous)
Bachupally, Kukatpally, Hyderabad – 500 090, Telangana, India. (040) 6686 4440

VISION AND MISSION

Vision of the Institute

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

Mission of the Institute

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

Vision of the Department

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

Mission of the Department

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

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PEO'S AND PO'S MAPPINGS

Programme Educational Objectives (PEOs)	Programme Outcomes (POs)											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	M	M	-	-	H	-	-	H	H	-	H	H
2	-	-	M	M	H	H	H	-	-	-	-	H
3	-	-	-	-	H	H	M	M	M	M	H	H
4	-	-	-	M	M	H	M	H	H	-	M	H

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ACADEMIC CALENDER

Academic Year 2021-22

S.No	Event	Period	
1	I Spell of Instructions	11-04-2022 to 04-06-2022	9 Weeks
2	I Mid Examinations	06-06-2022 to 11-06-2022	1 Week
3	II Spell of Instructions	13-06-2022 to 06-08-2022	2 Weeks
4	II Mid Examinations	08-08-2022 to 13-08-2022	1 Week
5	Preparation/Break	15-08-2022 to 20-08-2022	1Week
6	End Semester Examinations	22-08-2022 to 03-09-2022	2 Weeks
7	Commencement of Second Year, F Semester, AY 2022-23	05-09-2022	

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Individual Time Table

	9:00 AM - 9:55 AM	9:55 AM - 10:50 AM	10:50 AM - 11:45 AM	11:45 AM - 12:25 PM	12:25 PM - 1:15 PM	1:15 PM - 2:05 PM	2:05 PM -2:55 PM
MON				BREAK			
TUE	DCPEDS						
WED							
THU			DCPEDS				
FRI							
SAT		DCPEDS					

DIGITAL CONTROL OF POWER ELECTRONICS AND DRIVE SYSTEMS

UNIT-I

Basic Mathematics of Digital Control Systems: Introduction, Digital Signals and Coding, Shannon's sampling theorem, Sample-and-hold devices, Analog-to-digital conversion, Digital-to-analog conversion, Energy quantization, The Laplace transform (the s-domain), The z-transform (the z-domain).

Mathematical Modeling of Digital Power Electronics: Introduction, A zero-order hold (ZOH) for AC/DC controlled rectifiers, A first-order transfer function for DC/AC pulse-width-modulation inverters, A second-order transfer function for DC/DC converters, A first-order transfer function for AC/AC (AC/DC/AC) converters.

UNIT-II

Digitally Controlled AC/DC Rectifiers: Mathematical modeling for AC/DC rectifiers, Single-phase full-wave AC/DC rectifier, Three-phase half-wave controlled AC/DC rectifier, Three-phase full-wave controlled AC/DC rectifier.

Digitally Controlled DC/AC Inverters: Mathematical modeling for DC/AC PWM inverters, Single-phase full bridge PWM VSI, Three-phase full-bridge PWM VSI, Three-phase full-bridge PWM CSI, Multistage PWM inverter, Multilevel PWM inverter.

UNIT-III

Digitally Controlled DC/DC Converters: Mathematical Modeling for power DC/DC converters, Fundamental DC/DC converter, Developed DC/DC converters, Soft-switching converters, Multi-element resonant power converters. Digitally Controlled AC/AC Converters: Traditional modeling for AC/AC (AC/DC/AC) converters, Single-phase AC/AC converter, Three-phase AC/AC voltage controllers, AC/DC/AC PWM converters.

UNIT-IV

Open-loop Control for Digital Power Electronics: Introduction, Stability analysis, Unit-step function responses, Impulse responses.

Closed-Loop Control for Digital Power Electronics: Introduction, PI control for AC/DC rectifiers, PI control for DC/AC inverters and AC/AC (AC/DC/AC) converters, PID control for DC/DC converters.

UNIT-V

Energy Factor Application in AC and DC Motor Drives: Introduction, Energy storage in motors, A DC/AC voltage source, An AC/DC current source, AC motor drives, DC motor drives.

Text Books

1. Digital Power Electronics and Applications- Fang Lin Luo Hong Ye Muhammad Rashid.

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CO'S AND PO'S MAPPINGS

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code.. GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**.........……………………………..Dept.: …**EEE**………

Designation: PROFESSOR

GR20D5036	Digital Control Of Power Electronics and Drive systems	Evaluate Mathematical Modeling of Digital Power Electronics	H	H	H	M	-	H	-	M	H	-	H	H
		Analyze AC/DC and DC/AC converters	-	H	H	M	-	H	M	M	H	-	H	H
		Design DC/DC converters and Compare Open-loop and Closed-Loop Control for Digital Power Electronics	H	H	H	M	-	H	-	M	H	-	H	H
		Design Multilevel PWM inverter	-	H	H	M	-	H	-	M	H	H	H	H
		Analyze AC/DC/AC PWM converters and List the Application in AC and DC Motor Drives	H	M	-	H	-	M	H	-	M	-	-	M

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COURSE OBJECTIVES

Academic **Y**ear : 2021-22

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Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

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The objective of this course is to provide the student:

S.No.	Course Objectives
1.	To know the Basic Mathematics of Digital Control Systems.
2.	To focus on Digitally Controlled AC/DC and DC/AC converters.
3.	To development of Digitally Controlled DC/DC and AC/AC Converters.
4.	To Information on Open-loop and Closed-Loop Control for Digital Power Electronics
5.	To analysis Application in AC and DC Motor Drives.

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COURSE OUTCOMES

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The expected outcomes of the Course/Subject are:

S.No	Outcomes
1.	Evaluate Mathematical Modeling of Digital Power Electronics.
2.	Analyze AC/DC and DC/AC converters.
3.	Design DC/DC converters and Compare Open-loop and Closed-Loop Control for Digital Power Electronics.
4.	Design Multilevel PWM inverter.
5.	Analyse AC/DC/AC PWM converters and List the Application in AC and DC Motor Drives.

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Date:

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Date:

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

GUIDELINES TO STUDY THE COURSE / SUBJECT

Academic **Y**ear : 2021-22

Semester : II

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Guidelines to study the Course/ Subject: Electrical Measurements & Instrumentation

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

Signature of HOD Signature of faculty

Date: Date:

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COURSE SCHEDULE

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

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Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

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The Schedule for the whole Course / Subject is:

S. No.	Description	Total No. Of Periods
1.	Basic Mathematics of Digital Control Systems	11
2.	Digitally Controlled AC/DC Rectifiers and DC/AC Inverters	10
3.	Digitally Controlled DC/DC Converters and AC/AC Converters	11
4.	Open-loop Control and Closed-loop Control for Digital Power Electronics	10
5.	Energy Factor Application in AC and DC Motor Drives	9

Total No. of Instructional periods available for the course: ..……51……. Hours / Periods

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SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

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Text Books:

B1: Digital Power Electronics and Applications- Fang Lin Luo Hong Ye Muhammad Rashid, Elsevier Academic Press

B2: Digital Control System Analysis and Design- Charles L Plilips, H Troy Nagle, Prentice Hall, 3rd Edition.

Unit No.	Lesson No.	No. of Periods	Topics / Sub-Topics	Objectives & Outcomes Nos.	References (Text Book, Journal…) Page Nos.: ____to ___
1	1	1	Introduction to digital control systems	Obj;- 1 Out;-1	Text Book B1 Page Nos: 85-89
	2	1	Digital Signals and Coding, Shannon's sampling theorem	Obj;- 1 Out;-1	Text Book B1 Page Nos: 91-94
	3	1	Sample-and-hold devices, Analog-to-digital conversion	Obj;- 1,3 Out;-1,2	Text Book B1 Page Nos: 95-99
	4	1	Digital-to-analog conversion, Energy quantization	Obj;- 1,3 Out;-1,2	Text Book B1 Page Nos: 101-104
	5	1	The Laplace transform (the s-domain), The z-transform (the z-domain).	Obj;- 1,3 Out;-1,2	Text Book B1 Page Nos: 118-121 Text Book B2 Page Nos: 27-31
	6	1	Numerical Problems	Obj;- 1,3 Out;-1,2	Text Book B2 Page Nos: 32-40
	7	1	Numerical Problems	Obj;- 2,4 Out;- 1,4	Text Book B2 Page Nos: 32-40

	8	1	A zero-order hold (ZOH) for AC/DC controlled rectifiers	Obj;- 2,4 Out;- 1,4	Text Book B1 Page Nos:121-125
	9	1	A first-order transfer function for DC/AC pulse-width-modulation inverters	Obj;- 1,3 Out;-1,3	Text Book B1 Page Nos:128-131
	10	1	A second-order transfer function for DC/DC converters	Obj;- 1,3,4 Out;-1,3	Text Book B1 Page Nos:132-135
	11	1	A first-order transfer function for AC/AC (AC/DC/AC) converters	Obj;- 1,3,4 Out;-1,3	Text Book B1 Page Nos:136-140
2	1	1	Mathematical modeling for AC/DC rectifiers	Obj;- 1,3,4 Out;-1,3	Text Book B1 Page Nos:142-151
	2	1	Single-phase full-wave AC/DC rectifier	Obj;- 1,2,3,4 Out;-1,3,5	Text Book B1 Page Nos:153-154
	3	1	Three-phase half-wave controlled AC/DC rectifier, Three-phase full-wave controlled AC/DC rectifier	Obj;- 1,2,3,4 Out;-1,5	Text Book B1 Page Nos:155-156
	4	1	Mathematical modeling for DC/AC PWM inverters	Obj;- 1,2,3,4 Out;-1,5	Text Book B1 Page Nos:162-172
	5	1	Single-phase fullbridge PWM VSI, Three-phase full-bridge PWM VSI	Obj;- 1,2,3,4 Out;-1,5	Text Book B1 Page Nos:174-175
	6	1	Three-phase full-bridge PWM CSI	Obj;- 1,2,3,4 Out;-1,5	Text Book B1 Page Nos:175-176
	7	1	Multistage PWM inverter, Multilevel PWM inverter	Obj;- 1,2,3,4 Out;-1,3	Text Book B1 Page Nos:176-177
3	1	1	Mathematical Modeling for power DC/DC converters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos:179-202
	2	1	Fundamental DC/DC converter	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos: 205-207
	3	1	Developed DC/DC converters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos:208-209
	4	1	Soft-switching converters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos:209-210
	5	1	Multi-element resonant power converters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos:213-217
	6	1	Traditional modeling for AC/AC (AC/DC/AC) converters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos:241-244

	7	1	Single-phase AC/AC converter	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos:245-245
	8	1	Three-phase AC/AC voltage controllers	Obj;- 1,2,3,4 Out;-1,4	Text Book B1 Page Nos:245-246
	9	1	AC/DC/AC PWM converters	Obj;- 1,2,3,4 Out;-1,3	Text Book B1 Page Nos:246-247
4	1	1	Introduction to open loop control	Obj;- 1,2,3,4 Out;-4	Text Book B1, B2 Page Nos: 249-255
	2	1	Stability analysis	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos: 256-268
	3	1	Unit-step function responses	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:269-279
	4	1	Unit-step function responses	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:280-281
	5	1	Impulse responses	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:281-281
	6	1	Introduction to closed loop control	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:283-287
	7	1	PI control for AC/DC rectifiers	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:288-297
	8	1	PI control for DC/AC inverters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:298-300
	9	1	PI control for AC/AC (AC/DC/AC) converters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:301-304
	10	1	PID control for DC/DC converters	Obj;- 1,2,3,4 Out;-1,4	Text Book B1, B2 Page Nos:305-310
5	1	1	Introduction to energy factor application	Obj;- 4, 5 Out;-1,5	Text Book B1, B2 Page Nos:314-315
	2	1	Energy storage in motors	Obj;- 4, 5 Out;-1,5	Text Book B1, B2 Page Nos:315-316
	3	1	DC/AC voltage source	Obj;- 4, 5 Out;-1,5	Text Book B1, B2 Page Nos:317-331
	4	1	AC/DC current source	Obj;- 4, 5 Out;-1,5	Text Book B1, B2 Page Nos:333-337
	5	1	AC motor drives	Obj;- 4, 5 Out;-1,5	Text Book B1, B2 Page Nos:338-341
	6	1	DC motor drives	Obj;- 4, 5 Out;-1,5	Text Book B1, B2 Page Nos:342-345

Signature of HOD Signature of faculty

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SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic Year : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……I………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Introduction to digital control systems	1	1	Text Book B1 Page Nos: 85-89
2	1	Digital Signals and Coding, Shannon's sampling theorem	1	1	Text Book B1 Page Nos: 91-94
3	1	Sample-and-hold devices, Analog-to-digital conversion	1,3	1,2	Text Book B1 Page Nos: 95-99
4	1	Digital-to-analog conversion, Energy quantization	1,3	1,2	Text Book B1 Page Nos: 101-104
5	1	The Laplace transform (the s-domain), The z-transform (the z-domain).	1,3	1,2	Text Book B1 Page Nos: 118-121 Text Book B2 Page Nos: 27-31
6	1	Numerical Problems	1,3	1,2	Text Book B2 Page Nos: 32-40
7	1	Numerical Problems	1,3	1,2	Text Book B2 Page Nos: 32-40
8	1	A zero-order hold (ZOH) for AC/DC controlled rectifiers	1,3	1,2	Text Book B1 Page Nos:121-125

9	1	A first-order transfer function for DC/AC pulse-width-modulation inverters	1,3	1,2	Text Book B1 Page Nos:128-131
10	1	A second-order transfer function for DC/DC converters	1,3	1,2	Text Book B1 Page Nos:132-135
11	1	A first-order transfer function for AC/AC (AC/DC/AC) converters	1,3	1,2	Text Book B1 Page Nos:136-140

Signature of HOD
Date:

Signature of faculty
Date:

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 OUT COME NUMBERS AGAINST EACH TOPIC.

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Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Mathematical modeling for AC/DC rectifiers	2,4	1,4	Text Book B1 Page Nos:142-151
2	1	Single-phase full-wave AC/DC rectifier	2,4	1,4	Text Book B1 Page Nos:153-154
3	1	Three-phase half-wave controlled AC/DC rectifier, Three-phase full-wave controlled AC/DC rectifier	2,4	1,4	Text Book B1 Page Nos:155-156
4	1	Mathematical modeling for DC/AC PWM inverters	2,4	1,4	Text Book B1 Page Nos:162-172
5	1	Single-phase fullbridge PWM VSI, Three-phase full-bridge PWM VSI	2,4	1,4	Text Book B1 Page Nos:174-175
6	1	Three-phase full-bridge PWM CSI	2,4	1,4	Text Book B1 Page Nos:175-176
7	1	Multistage PWM inverter, Multilevel PWM inverter	2,4	1,4	Text Book B1 Page Nos:176-177

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Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Mathematical Modeling for power DC/DC converters	1,2,3,4	1,3,5	Text Book B1 Page Nos:179-202
2	1	Fundamental DC/DC converter	1,2,3,4	1,3,5	Text Book B1 Page Nos: 205-207
3	1	Developed DC/DC converters	1,2,3,4	1,3,5	Text Book B1 Page Nos:208-209
4	1	Soft-switching converters	1,2,3,4	1,3,5	Text Book B1 Page Nos:209-210
5	1	Multi-element resonant power converters	1,2,3,4	1,3,5	Text Book B1 Page Nos:213-217
6	1	Traditional modeling for AC/AC (AC/DC/AC) converters	1,2,3,4	1,3,5	Text Book B1 Page Nos:241-244
7	1	Single-phase AC/AC converter	1,2,3,4	1,3,5	Text Book B1 Page Nos:245-245

8	1	Three-phase AC/AC voltage controllers	1,2,3,4	1,3,5	Text Book B1 Page Nos:245-246
9	1	AC/DC/AC PWM converters	1,2,3,4	1,3,5	Text Book B1 Page Nos:246-247

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Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Introduction to open loop control	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos: 249-255
2	1	Stability analysis	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos: 256-268
3	1	Unit-step function responses	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:269-279
4	1	Unit-step function responses	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:280-281
5	1	Impulse responses	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:281-281
6	1	Introduction to closed loop control	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:283-287
7	1	PI control for AC/DC rectifiers	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:288-297

8	1	PI control for DC/AC inverters	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:298-300
9	1	PI control for AC/AC (AC/DC/AC) converters	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:301-304
10	1	PID control for DC/DC converters	1,2,3,4	1,2,5	Text Book B1, B2 Page Nos:305-310

Signature of HOD

Date:

Signature of faculty

Date:

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Gokaraju Rangaraju Institute of Engineering and Technology
(Autonomous)
Bachupally, Kukatpally, Hyderabad – 500 090, Telangana, India. (040) 6686 4440

SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Introduction to energy factor application	1,2,3,5	1,5	Text Book B1, B2 Page Nos:314-315
2	1	Energy storage in motors	1,2,3,5	1,5	Text Book B1 Page Nos:315-316
3	1	DC/AC voltage source	1,2,3,5	1,5	Text Book B1 Page Nos:317-331
4	1	AC/DC current source	1,2,3,5	1,5	Text Book B1 Page Nos:333-337
5	1	AC motor drives	1,2,3,5	1,5	Text Book B1 Page Nos:338-341
6	1	DC motor drives	1,2,3,5	1,5	Text Book B1 Page Nos:342-345

Signature of HOD   Signature of faculty

Date: Date:

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 OUT COME NUMBERS AGAINST EACH TOPIC.

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LESSON PLAN

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Lesson No: …………………….1&2……………Duration of Lesson: ……... 55 min……………….

Lesson Title: Basic Mathematics of Digital Control Systems

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Recollect the basic mathematics required for digital control systems.
2. Understand Digital Signals and Coding, Shannon's sampling theorem

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 2 min.: Taking attendance
- 8 min.: Importance of the subject and introduction
- 45 min.: Basic Mathematics of Digital Control Systems, Digital Signals and Coding, Shannon's sampling theorem
- 5 min.: Doubts clarification and Review of the class.

- Assignment / Questions: What are the various test signals and their Laplace & Z transforms? State and explain Shannon's sampling theorem (Obj;- 1,2 Out;-1,3)

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Designation: PROFESSOR

Lesson No: ……………….3 &4…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Sample-and-hold devices, Analog-to-digital conversion, Digital-to-analog conversion, Energy quantization

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Understand Sample-and-hold devices
2. Apply Analog-to-digital conversion,
3. Apply Digital-to-analog conversion,
4. Understand Energy quantization

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re collecting the contents of previous class.
- 48 min.: Sample-and-hold devices, Analog-to-digital conversion, Digital-to-analog conversion, Energy quantization
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: What is an ADC? What are the main advantages of integrating type ADCs? What is quantisation of energy?

(Obj;- 1,2Out;-1,3)

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Designation: PROFESSOR

Lesson No: …………5 …………….Duration of Lesson: ……………. 55 min ……………….

Lesson Title: The Laplace transform (the s-domain)

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Find Laplace transform of a given function

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re collecting the contents of previous class.
- 45 min.: The Laplace transform (the s-domain)
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: What is Laplace transform? What are the limitations? (Obj;- 1,2Out;-1,3)

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Designation: PROFESSOR

Lesson No: ………………….6&7…………….Duration of Lesson: ……………. 55 min ……………….

Lesson Title: The z-transform (the z-domain), Numerical Problems

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Find Z-transform of a given function

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re collecting the contents of previous class.
- 45 min.: The Z-transform (the z-domain).
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: What is Z-transform and find Z transform of standard test signals.
(Obj;- 1,2Out;-1,3)

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Designation: PROFESSOR

Lesson No: ……………….8 & 9…………….Duration of Lesson: ……….. 55 min ……………….

Lesson Title: A zero-order hold (ZOH) for AC/DC controlled rectifiers, A first-order transfer function for DC/AC pulse-width-modulation inverters

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Apply A zero-order hold (ZOH) for AC/DC controlled rectifiers,
2. Find A first-order transfer function for DC/AC pulse-width-modulation inverters

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER

TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re collecting the contents of previous class.
- 45 min.: A zero-order hold (ZOH) for AC/DC controlled rectifiers, A first-order transfer function for DC/AC pulse-width-modulation inverters
- 5 min.: Doubts clarification and Review of the class.

- Assignment / Questions: Determine transfer function for DC/AC pulse-width-modulation inverters (Obj;- 1,2Out;-1,3)

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Designation: PROFESSOR

Lesson No: …………………….10…………….Duration of Lesson: …………… 55 min ……………….

Lesson Title: A second-order transfer function for DC/DC converters

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

Understand a second-order transfer function for DC/DC converters

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: A second-order transfer function for DC/DC converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the transfer function for DC/DC converters (Obj;- 1,2Out;-1,3)

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Designation: PROFESSOR

Lesson No: …………….11…………….Duration of Lesson: …………… 55 min ……………….

Lesson Title: A first-order transfer function for AC/AC (AC/DC/AC) converters.

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Find a first-order transfer function for AC/AC (AC/DC/AC) converters

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: A first-order transfer function for AC/AC (AC/DC/AC) converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the transfer function for AC/AC converters (Obj;- 2,4 Out;-1,4)

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Designation: PROFESSOR

Lesson No: ………….12 …………….Duration of Lesson: …………… 55 min ……………….

Lesson Title: Single-phase full-wave AC/DC rectifier

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

Find Mathematical model for AC/DC rectifiers

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Mathematical modeling for AC/DC rectifiers
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the model for AC/DC rectifiers (Obj;- 2,4Out;-1,4)

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Designation: PROFESSOR

Lesson No: …………….13…………….Duration of Lesson: …………… 55 min ………………

Lesson Title: Three-phase half-wave controlled AC/DC rectifier, Three-phase full-wave controlled AC/DC rectifier

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Analyse Three-phase half-wave controlled AC/DC rectifier
2. Analyse Three-phase full-wave controlled AC/DC rectifier

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Three-phase half-wave controlled AC/DC rectifier, Three-phase full-wave controlled AC/DC rectifier
- 5 min.: Doubts clarification and Review of the class.

1. Assignment / Questions: Analyse Three-phase half-wave controlled AC/DC rectifier (Obj;- 1,3 Out;-1,3)

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Designation: PROFESSOR

Lesson No: ……………….14…………Duration of Lesson: ………… 55 min ……………….

Lesson Title: Mathematical modeling for DC/AC PWM inverters

.

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Mathematical modeling for DC/AC PWM inverters

TEACHING AIDS :OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER

TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Mathematical modeling for DC/AC PWM inverters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Mathematical modeling for DC/AC PWM inverters (Obj;- 1,3,4 Out;-1,3)

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Designation: PROFESSOR

Lesson No: ………………15 ……….Duration of Lesson: …………… 55 min……………….

Lesson Title: Single-phase fullbridge PWM VSI, Three-phase full-bridge PWM VSI
.

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Single-phase fullbridge PWM VSI, Three-phase full-bridge PWM VSI

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Single-phase full bridge PWM VSI, Three-phase full-bridge PWM VSI
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Single-phase full bridge PWM VSI, Three-phase full-bridge PWM VSI. (Obj;-1,3,4Out;-1,3)

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Lesson No: ………………16……….. ……….Duration of Lesson: …………… 55 min……………….

Lesson Title: Three-phase full-bridge PWM CSI

.

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Three-phase full-bridge PWM CSI

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER

TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Three-phase full-bridge PWM CSI
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Three-phase full-bridge PWM CSI. (Obj;- 1,3,4Out;-1,3)

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Lesson No: ……………….17…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Multistage PWM inverter, Multilevel PWM inverter

.

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Multistage PWM inverter, Multilevel PWM inverter

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER

TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Multistage PWM inverter, Multilevel PWM inverter
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Multistage PWM inverter, Multilevel PWM inverter (Obj;- 1,2,3,4Out;-1,3,5)

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Designation: PROFESSOR

Lesson No: …………….18…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Mathematical Modeling for power DC/DC converters

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

Mathematical Modeling for power DC/DC converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Mathematical Modeling for power DC/DC converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Mathematical Modeling for power DC/DC converters (Obj;- 1,2,3,4Out;-1,5)

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Designation: PROFESSOR

Lesson No: ………………19…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Fundamental DC/DC converter

.

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Fundamental DC/DC converter

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER

TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Fundamental DC/DC converter
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Fundamental DC/DC converter (Obj;- 1,2,3,4Out;-1,5)

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Lesson No: ………20 …………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Developed DC/DC converters
.
INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Developed DC/DC converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Developed DC/DC converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Developed DC/DC converters (Obj;- 1,2,3,4Out;-1,5)

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Designation: PROFESSOR

Lesson No: ……….21……………Duration of Lesson: …………… 55 min……………….

Lesson Title: Soft-switching converters

.

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Soft-switching converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER

TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Soft-switching converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Soft-switching converters (Obj;- 1,2,3,4Out;-1,5)

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Lesson No: ……………. 22……………Duration of Lesson: …………… 55 min……………….

Lesson Title: Multi-element resonant power converters

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Multi-element resonant power converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Multi-element resonant power converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: . Multi-element resonant power converters (Obj;- 1,2,3,4Out;-1,5)

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Designation: PROFESSOR

Lesson No: ………………. 23 ………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Traditional modeling for AC/AC (AC/DC/AC) converters

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

Traditional modeling for AC/AC (AC/DC/AC) converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER

TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Traditional modeling for AC/AC (AC/DC/AC) converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: . Traditional modeling for AC/AC (AC/DC/AC) converters (Obj;- 1,2,3,4Out;-1,5)

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Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………….24…………….Duration of Lesson: ………… 55 min……………….

Lesson Title: Single-phase AC/AC converter

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Single-phase AC/AC converter

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Single-phase AC/AC converter
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Single-phase AC/AC converter (Obj;- 1,2,3,4Out;-1,4,5)

Signature of faculty

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Bachupally, Kukatpally, Hyderabad – 500 090, Telangana, India. (040) 6686 4440

LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………25…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Three-phase AC/AC voltage controllers

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Three-phase AC/AC voltage controllers

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Three-phase AC/AC voltage controllers
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Three-phase AC/AC voltage controllers (Obj;- 1,2,3,4Out;-1,4,5)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**………..…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………. 26…………….Duration of Lesson: ………… 55 min……………….

Lesson Title: AC/DC/AC PWM converters

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

AC/DC/AC PWM converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: AC/DC/AC PWM converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: AC/DC/AC PWM converters (Obj;- 1,2,3,4Out;-1,4,5)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………….27…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Introduction to open loop control

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Introduction to open loop control

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Introduction to open loop control
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Introduction to open loop control. (Obj;- 1,2,3,4Out;-1,5)

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: ……………….28…………….Duration of Lesson: …………… 55 min………………

Lesson Title: Stability analysis

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Stability analysis

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Stability analysis
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Stability analysis (Obj;- 1,2,3,4Out;-1,2,4)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………………29…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Unit-step function responses

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Unit-step function responses

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Unit-step function responses
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Unit-step function responses (Obj;- 1,2,3,4 Out;-1,2)

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: ……………30…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Impulse responses

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Impulse responses

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Impulse responses
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Impulse responses (Obj;- 1,2,3,4Out;-1,5)

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………….31…………….Duration of Lesson: ………… 55 min……………….

Lesson Title: Introduction to closed loop control

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Introduction to closed loop control

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Introduction to closed loop control
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Introduction to closed loop control (Obj;- 1,2,3,4Out;-1,5)

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: ………….32………….Duration of Lesson: …………… 55 min……………….

Lesson Title: PI control for AC/DC rectifiers

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

PI control for AC/DC rectifiers

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: PI control for AC/DC rectifiers
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: PI control for AC/DC rectifiers (Obj;- 1,2,3,4Out;-1,5)

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: ………….33………….Duration of Lesson: …………… 55 min……………….

Lesson Title: PI control for DC/AC inverters

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

PI control for DC/AC inverters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: PI control for DC/AC inverters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: PI control for DC/AC inverters (Obj;- 1,2,3,4Out;-1,5)

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………34…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: PI control for AC/AC (AC/DC/AC) converters

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

PI control for AC/AC (AC/DC/AC) converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: PI control for AC/AC (AC/DC/AC) converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: PI control for AC/AC (AC/DC/AC) converters (Obj;- 1,2,3,4 Out;-1,2,4)

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………35…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: PID control for DC/DC converters

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

PID control for DC/DC converters

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: PID control for DC/DC converters
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: PID control for DC/DC converters (Obj;- 1,2,3,4Out;-1,2,4)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………36…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Introduction to energy factor application

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Introduction to energy factor application

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Introduction to energy factor application
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Introduction to energy factor application (Obj;- 1,2,3,4Out;-1,2,4)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………37…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: Energy storage in motors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

Energy storage in motors

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: Energy storage in motors
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: Energy storage in motors (Obj;- 1,2,3,4Out;-1,2,5)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………38…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: DC/AC voltage source

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

DC/AC voltage source

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: DC/AC voltage source
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: DC/AC voltage source (Obj;- 1,2,3,4Out;-1,2,4)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………39…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: AC/DC current source

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

AC/DC current source

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: AC/DC current source
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: AC/DC current source (Obj;- 1,2,3,4 Out;-1,2,4)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………40…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: AC motor drives

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

AC motor drives

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: AC motor drives
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: AC motor drives (Obj;- 1,2,3,4 Out;-1,2,4)

Signature of faculty

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LESSON PLAN

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

Lesson No: …………41…………….Duration of Lesson: …………… 55 min……………….

Lesson Title: DC motor drives

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

DC motor drives

TEACHING AIDS : LCD PROJECTOR, WHITEBOARD, MARKER, DUSTER
TEACHING POINTS :

- 2 min.: Taking attendance
- 3 min.: Re-collecting the contents of previous class.
- 45 min.: DC motor drives
- 5 min.: Doubts clarification and Review of the class.

Assignment / Questions: DC motor drives (Obj;- 1,2,3,4Out;-1,2,4)

Signature of faculty

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ASSIGNMENT SHEET – 1

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Assignment corresponds to Unit No. / Lesson ………………**1**………………………….

Q1. What is sampling process? State and Explain Shannon's sampling theorem

Q2. Obtain the Z transform of following functions

(a) $x(k)=(1/2)^k$, for k=0,1,2…
(b) x(t)=t sint

Q3. Determine the transfer function of a Zero Order Hold device. Also draw Input and output waveforms in the time domain.

Objective Nos.: …………………… 1,2……………………………………………………….

Outcome Nos.: ……………………1,3………………………………………………………….

Signature of HOD　　　　　　　　　　Signature of faculty

Date:　　　　　　　　　　Date:

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ASSIGNMENT SHEET – 2

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Assignment corresponds to Unit No. / Lesson ………………**2**………………………….

Q1. Draw the star/star circuit and delta/star circuit for three-phase half-wave diode rectifier. Also, find average value of output voltage, form factor and ripple factor.

Q2. Determine the transfer function of AC/DC rectifiers in S-domain and in Z-domain

Q3. Draw the circuit diagram and output wave forms of a three-phase full bridge VSI. Also obtain the transfer function in S-domain as well as in Z-domain.

Objective Nos.: …………………………1,2,3,4……………………………………………………….

Outcome Nos.: ……………………1,3,5,6…………………………………………………………

Signature of HOD

Date:

Signature of faculty

Date:

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ASSIGNMENT SHEET – 3

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR
This Assignment corresponds to Unit No. / Lesson ………………**3**………………………….

Q1. With the help of traditional modelling, determine the transfer function of Three-phase AC/AC voltage controllers.

Q2. Explain DC/DC converter family tree.

Objective Nos.: 1,2,3,4……………………………………………………….

Outcome Nos.: ……………………1,3,5,6………………………………………………………….

Signature of HOD Signature of faculty

Date: Date:

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ASSIGNMENT SHEET – 4

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Assignment corresponds to Unit No. / Lesson ………………**4**………………………….

Q1. Draw the block diagram of open loop analysis for AC/DC rectifiers with a first order load. Determine the transfer function in S-domain and Z-domain.

Q2. Draw the block diagram of closed loop control system with a PI controller for rectifier. Also, analyse the stability of the system.

Objective Nos.: ……………………1,2,3,4……………………………………………………….

Outcome Nos.: ………………………1,2,…………………………………………………………

Signature of HOD Signature of faculty

Date: Date:

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ASSIGNMENT SHEET – 5

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Assignment corresponds to Unit No. / Lesson ………………**5**………………………….

Q1. Explain the energy storage in DC motor.

Q2. Derive the expression for settling time of a single phase AC motor drive supplied by a chopper.

Objective Nos.: ……………………………………1,2,3,4………………………………………….

Outcome Nos.: ………………………………………1,3……………………………………….

Signature of HOD Signature of faculty

Date: Date:

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TUTOTIAL SHEET - 1

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Tutorial corresponds to Unit No. / Lesson ………1…………………………….

Q1. Determine the transfer function of a Zero Order Hold device. Also draw Input and output waveforms in the time domain.

Q2. Draw the impulse response of first order hold (FOH).

Q3. Define Shannon's sampling theorem.

Please write the Questions / Problems / Exercises which you would like to give to the students and also mention the Objectives/Outcomes to which these Questions / Problems / Exercises are related.

Objective Nos.: …………………………1,2……………………………………………………………….

Outcome Nos.: …………………….………1,3……………………………………………………………….

Signature of HOD

Date:

Signature of faculty

Date:

Gokaraju Rangaraju Institute of Engineering and Technology
(Autonomous)
Bachupally, Kukatpally, Hyderabad – 500 090, Telangana, India. (040) 6686 4440

TUTOTIAL SHEET - 2

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Tutorial corresponds to Unit No. / Lesson ………2…………………………….

Q1. Draw the circuit diagram and output wave forms a single-phase full bridge VSI. Also obtain the transfer function in S-domain as well as in Z-domain.

Q2. Draw the Y/Y circuit configuration Three-phase half-wave diode rectifier.

Q3. What is the difference between multistage and multi-level inverter?

Please write the Questions / Problems / Exercises which you would like to give to the students and also mention the Objectives/Outcomes to which these Questions / Problems / Exercises are related.

Objective Nos.: ………………………1,2,3,4……………………………………………………………….

Outcome Nos.: ……………………..……1,3,5,6……………………………………………………………….

Signature of HOD Signature of faculty

Date: Date:

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TUTOTIAL SHEET - 3

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Tutorial corresponds to Unit No. / Lesson ………3…………………………….

Q1. With the help of traditional modelling, determine the transfer function of Three-phase AC/AC voltage controllers.

Q2. Draw the topology of fundamental DC/DC converter.

Q3. What is the classification of developed converters?

Please write the Questions / Problems / Exercises which you would like to give to the students and also mention the Objectives/Outcomes to which these Questions / Problems / Exercises are related.

Objective Nos.: ……………………………1,2,3,4……………………………………………………….

Outcome Nos.: ……………………..………1,3,5.6……………………………………………………….

Signature of HOD Signature of faculty

Date: Date:

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TUTOTIAL SHEET - 4

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

This Tutorial corresponds to Unit No. / Lesson ………4…………………………….

Q1. Analyse the converters with a First order with Load plus an integral element.

Q2. Draw the block diagram of open loop control scheme for converters.

Q3. What is the transfer function of AC/DC rectifier in S-domain and in Z-domain.

Please write the Questions / Problems / Exercises which you would like to give to the students and also mention the Objectives/Outcomes to which these Questions / Problems / Exercises are related.

Objective Nos.: ……………1,2,3,4……………………………………………………………………….

Outcome Nos.: ……………1,2,7……..……………………………………………………………………….

Signature of HOD Signature of faculty

Date: Date:

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TUTOTIAL SHEET - 5

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**..........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR
This Tutorial corresponds to Unit No. / Lesson ………5…………………………….

Q1. Explain the energy storage in AC motor.

Q2. Explain an DC/AC voltage source and an AC/DC current source

Q3. What are the various parts of energy storage in DC motor?

Please write the Questions / Problems / Exercises which you would like to give to the students and also mention the Objectives/Outcomes to which these Questions / Problems / Exercises are related.

Objective Nos.: …………………1,2,3,4…………………………………………………………………….

Outcome Nos.: ……………….………1,7……………………………………………………………….

Signature of HOD Signature of faculty

Date: Date:

Gokaraju Rangaraju Institute of Engineering and Technology
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EVALUATION STRATEGY

Academic **Y**ear : 2021-22

Semester : II

Name of the Program: M.Tech Power Electronics Year: ……**I**………

Course/Subject: … Digital Control Of Power Electronics and Drive systems, Course Code..GR20D5036..

Name of the Faculty: ……**Dr D G Padhan**...........…………………………..Dept.: …**EEE**………

Designation: PROFESSOR

1. TARGET:

A) Percentage for pass: 40%

b) Percentage of class: 85%

2. COURSE PLAN & CONTENT DELIVERY:

- OHP presentation of the Lectures
- Solving exercise problems
- Model questions

3. METHOD OF EVALUATION

3.1 Continuous Assessment Examinations (CAE-I, CAE-II)

3.2 Assignments

3.3 Seminars

3.4 Quiz

3.5 Semester/End Examination

Signature of HOD

Date:

Signature of faculty

Date:

RESULT ANALYSIS

Gokaraju Rangaraju Institute of Engineering & Technology

M.Tech (PE) II Sem (EEE) Result Analysis

Academic Year: 2021-22

Total No. of Students Registered: 04

Course	Total No. of Students appeared	Total No. of Students Passed	No. of Students Failed	Count of Students with Grade Point					
				GP (10)	GP (9)	GP (8)	GP (7)	GP (6)	GP (5)
EDS	04	04	00	00	00	00	01	03	00
DCPED	04	04	00	00	00	02	01	01	00
APEC	04	04	00	00	00	02	01	01	00
AIMLT	04	04	00	00	01	00	02	01	00
ED Lab	04	04	00	04	00	00	00	00	00
DSP&MC Lab	04	04	00	03	01	00	00	00	00
MINI Proj.	04	04	00	01	01	02	00	00	00
PS	04	04	00	03	01	00	00	00	00

Arrears Position – M.Tech (PE) I year / II Semester

No.of students	All Pass	One Arrear	Two Arrears	Three Arrears	More than three arrears	Overall % of pass
04	04	00	00	00	00	100%

Performance overall Class Three Toppers

ROLL NO.	NAME	SGPA
21241D4303	Moshina Begum	8.22
21241D4302 21241D4304	Kothapalli Malini Surya Prakash Yadav	8.00
21241D4301	Dupati pujitha	7.11

Class coordinator

Dr Phaneendra Babu B

HOD, EEE

M.Tech (PE) - II Sem (EEE)

SECTION	Courses	EDS	DCPED	APEC	AIMLT	ED Lab	DSP&MC Lab	MINI Proj.	PS
	Course codes	GR20D5035	GR20D5036	GR20D5037	GR20D5040	GR20D5043	GR20D5044	GR20D50143	GR20D5157
A	TOTAL	04	04	04	04	04	04	04	04
	PASS	04	04	04	04	04	04	04	04
	PASS(%)	100	100	100	100	100	100	100	100
	FACULTY NAME	Dr D Raveendhra	Dr D G Padhan	Dr T Suresh Kumar	D Karuna K	Dr D Raveendhra	A Vinay Kumar	Dr B Phaneendra Babu	Dr J Sridevi
	FACULTY ID	1604	1283	1494	760	1604	881	1563	516

Class coordinator

Dr Phaneendra Babu B

HOD, EEE

HOD,EEE

1. **Program Educational Objectives (PEOs) – Vision/Mission Matrix** (Indicate the relationships by mark "X")

PEO's	Mission of the department			
	Higher Learning	Contemporary Education	Technical Knowledge	Research
Graduates will have a successful technical or professional careers, including supportive and leadership roles on multidisciplinary teams	X	X	X	X
Graduates will be able to acquire, use and develop skills as required for effective professional practices		X	X	
Graduates will be able to attain holistic education that is an essential prerequisite for being a responsible member of	X		X	
Graduates will be engaged in life-long learning, to remain abreast in their profession and be leaders in our technologically vibrant	X		X	X

2. **Program Educational Objectives (PEOs)-Program Outcomes (POs) Relationship Matrix** (Indicate the relationships by mark "X")

P-Outcomes / PEOs	a	b	c	d	e	f	g	h	i	j	k	l
1	X	X			X			X		X		X
2	X	X			X			X			X	
3			X	X	X	X	X					X
4					X	X	X	X	X	X	X	X

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

Course-Outcomes / Course-Objectives	1	2	3	4	5
1	X				
2	X	X	X	X	
3					
4	X				X
5	X				X

4. Course Objectives-Program Outcomes (POs) Relationship Matrix (Indicate the relationships by mark "X")

P-Outcomes / C-Objectives	a	b	c	d	e	f	g	H	i	j	k	l
1	X				X		X	X	X	X	X	
2	X	X	X	X	X	X	X	X			X	
3												
4	X	X	X	X	X	X	X	X	X		X	X
5	X	X	X	X	X	X	X	X		X	X	

5. Course Outcomes-Program Outcomes (POs) Relationship Matrix (Indicate the relationships by mark "X")

P-Outcomes / C-Outcomes	a	b	c	d	E	f	g	h	i	j	k	l
1	x		x					x	x			x
2	x	x			x		x			x		x
3	x		x	x				x				
4		x	x							x		x
5			x			x						x

6. Program Educational Objectives (PEOs)-Course Outcomes Relationship Matrix (Indicate the relationships by mark "X")

P-Objectives (PEOs) / Course-Outcomes	1	2	3	4
1	X		X	
2	X		X	
3	X	X		
4	X		X	
5	X	X		X

7. **Assignments and Assessments - Program Outcomes (POs) Relationship Matrix** (Indicate the relationships by mark “X”)

P-Outcomes / Assessments	a	b	c	d	e	f	g	h	i	j	k	l
Mid Exam	X		X		X			X			X	
Assignments	X	X		X	X	X		X			X	
Seminars/ Conferences	X	X	X	X			X		X	X	X	
Project Work	X	X		X	X	X		X			X	
Main Exam	X		X		X			X			X	
Behavioral Observation	X	X	X	X	X	X	X				X	X

8. **Assignments and Assessments – Program Educational Objectives (PEOs) Relationship Matrix** (Indicate the relationships by mark “X”)

P-Outcomes / Assessments	1	2	3	4
Mid Exam	X	X		X
Assignments	X	X	X	
Seminars/ Conferences	X	X		X
Project Work	X	X	X	
Main Exam	X		X	X
Behavioral Observation	X		X	X

CO Attainment for all Mid Exams

Digital Control of Power Electronics and Drive Systems Date of Exam:07/06/2022
M Tech (PE)- CO Attainment-Sem-II Mid-I 2021-22

ROLL NO	ObjQ1:CO1	Q1:CO1	Q2:CO1	Q3:CO1	Q4:CO2	Q5:CO2	Q6:CO2
21241D4301	2	2.5		4		3	
21241D4302	3	3.5		5			4
21241D4303	4.5		5		4		3
21241D4304	3.5		0		5		4
Grand Total	**13**	**6**	**5**	**9**	**9**	**3**	**11**
NSA	**4.0**	**2.0**	**2.0**	**2.0**	**2.0**	**1.0**	**3.0**
Attempt %=(NSA/Total no of students)*100	21.1	10.5	10.5	10.5	10.5	5.3	15.8
Average (attainment)= Total/NSA	3.3	3.0	2.5	4.5	4.5	3.0	3.7
Attainment%= (Avg/max. Marks for question)*100	65.00	60.00	50.00	90.00	90.00	60.00	73.33

	%
CO1	92.16
CO2	83.62

Digital Control of Power Electronics and Drive Systems Date of Exam:09/08/2022 M Tech (PE)- CO Attainment-Sem-II Mid-II 2021-22

ROLL NO	)jQ1:CO3, CO4, C	Q1:CO3	Q2:CO3	Q3:CO4	Q4:CO4	Q5:CO5	Q6:CO5
21241D4301	4	4		5		4	
21241D4302	4	4		5			5
21241D4303	5		5		4		4
21241D4304	5		5		4		5
Grand Total	**18**	**8**	**10**	**10**	**8**	**4**	**14**
NSA	**4.0**	**2.0**	**2.0**	**2.0**	**2.0**	**1.0**	**3.0**
SA/Total no of	**21.1**	**10.5**	**10.5**	**10.5**	**10.5**	**5.3**	**15.8**
(attainment)= T	**4.5**	**4.0**	**5.0**	**5.0**	**4.0**	**4.0**	**4.7**
Attainment%= (Avg/max. Marks for question)*100	**90.00**	**80.00**	**100.00**	**100.00**	**80.00**	**80.00**	**93.33**

	%
CO3	**90**
CO4	**90**
CO5	**86.67**

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY

(Autonomous)

Department of EEE

I M. Tech II-Sem (Power Electronics) **I-Mid** **Marks: 5M**

Time: 15 Minutes **Date of Exam: 07-06-2022**

Subject: **Digital Control of Power Electronics Drive Systems (GR20D5036)**

Name: **Roll Number:**

(Answer All Questions) **(10 X 0.5 = 5 Marks)**

1.	A signal with a maximum frequency of ω Hz must be sampled at least _________ times per second to reconstruct the original signal from the samples..				L1	CO1	[ ]
	a. 2ω	b. $2/\omega$	c. $\omega/2$	d. None of these			
2.	ZOH is called zero-order extrapolator as its polynomial used is of the ______________.				L1	CO1	[ ]
	a. zeroth order	b. first-order	c. second order	d. None of these			
3.	The output of the FOH between two consecutive sampling instants is a _________ function.				L2	CO1	[ ]
	a. step	b. ramp	c. parabolic	d. None of these			
4.	Traditional modeling for AC/DC controlled rectifiers is a _________ element in the *s*-domain.				L1	CO1	[ ]
	a. zero order	b. first order	c. second order	d. time-delay			
5.	Traditional modeling for AC/AC converters is a ____________ element in the *s*-domain.				L1	CO1	[ ]
	a. zero order	b. first order	c. second order	d. time-delay			
6.	A rectifier is a _________________ element.				L1	CO2	[ ]
	a. stable	b. unstable	c. critically stable	d. cannot say			
7.	Ripple factor is equal to _________________.				L2	CO2	[ ]
	a. (Form Factor-1)	b. (Power Factor - 1)	c. Power Factor – Form Factor	d. None of these			
8.	All DC/AC PWM inverters are treated as _______________.				L2	CO2	[ ]
	a. ZOH	b. FOH	c. SOH	d. None			
9.	In case of the single-phase full-wave diode rectifier, power factor of the bridge circuit is				L2	CO2	[ ]
	a. 0.707	b. 1	c. 0	d. 1.2			
10.	While mapping between S-plane and Z-plane, right hand plane of S-plane maps to _________ of the Z-plane.				L1	CO1	[ ]
	a. Inside unit circle	b. Unit circle	c. Outside unit circle	d. None			

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(An Autonomous Institute under JNTUH)

Department of EEE

I M. Tech II-Sem (Power Electronics) **I-Mid** **Marks: 15M**

Time: 75 Minutes **Date of Exam: 07/06/2022**

Subject: **Digital Control of Power Electronics Drive Systems (GR20D5036)**

(Answer All Questions) **(3 X 5 = 15 Marks)**

1	Obtain the Z transform of following functions (a) $x(k)=(1/2)^k$, for k=0,1,2… (b) x(t)=t sint	L3	CO1
OR			
2	Determine the initial value and final value of the sequence f(k) to which the Z transform is $$F(z)=\frac{4z^3-5z^2+8z}{(z-1)(z-0.5)^2}$$	L3	CO1
3	Determine the transfer function of a Zero Order Hold device. Also draw Input and output waveforms in the time domain.	L2	CO1
OR			
4	Draw the star/star circuit and delta/star circuit for three-phase half-wave diode rectifier. Also, find average value of output voltage, form factor and ripple factor.	L2	CO2
5	Determine the transfer function of AC/DC rectifiers in S-domain and in Z-domain.	L3	CO2
OR			
6	Draw the circuit diagram and output wave forms a three-phase full bridge VSI. Also obtain the transfer function in S-domain as well as in Z-domain.	L2	CO2

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY

(Autonomous)

Department of EEE

I M. Tech II-Sem (Power Electronics) **II-Mid** **Marks: 5M**

Time: 15 Minutes **Date of Exam: 16-08-2022**

Subject: Digital Control of Power Electronics Drive Systems (GR20D5036)

Name: **Roll Number:**

(Answer All Questions) **(10 X 0.5 = 5 Marks)**

1.	A signal with a maximum frequency of ω Hz must be sampled at least _________ times per second to reconstruct the original signal from the samples..				L1	CO1	[ ]
	a. 2ω	b. $2/\omega$	c. $\omega/2$	d. None of these			
2.	ZOH is called zero-order extrapolator as its polynomial used is of the _______________.				L1	CO1	[ ]
	a. zeroth order	b. first-order	c. second order	d. None of these			
3.	The output of the FOH between two consecutive sampling instants is a _________ function.				L2	CO1	[ ]
	a. step	b. ramp	c. parabolic	d. None of these			
4.	Traditional modeling for AC/DC controlled rectifiers is a _________ element in the *s*-domain.				L1	CO1	[ ]
	a. zero order	b. first order	c. second order	d. time-delay			
5.	Traditional modeling for AC/AC converters is a ____________ element in the *s*-domain.				L1	CO1	[ ]
	a. zero order	b. first order	c. second order	d. time-delay			
6.	A rectifier is a __________________ element.				L1	CO2	[ ]
	a. stable	b. unstable	c. critically stable	d. cannot say			
7.	Ripple factor is equal to __________________.				L2	CO2	[ ]
	a. (Form Factor-1)	b. (Power Factor - 1)	c. Power Factor – Form Factor	d. None of these			
8.	All DC/AC PWM inverters are treated as ________________.				L2	CO2	[ ]
	a. ZOH	b. FOH	c. SOH	d. None			
9.	In case of the single-phase full-wave diode rectifier, power factor of the bridge circuit is				L2	CO2	[ ]
	a. 0.707	b. 1	c. 0	d. 1.2			
10.	While mapping between S-plane and Z-plane, right hand plane of S-plane maps to _________ of the Z-plane.				L1	CO1	[ ]
	a. Inside unit circle	b. Unit circle	c. Outside unit circle	d. None			

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(An Autonomous Institute under JNTUH)

Department of EEE

I M. Tech II-Sem (Power Electronics) **II-Mid** **Marks: 15M**

Time: 75 Minutes **Date of Exam: 16/08/2022**

Subject: **Digital Control of Power Electronics Drive Systems (GR20D5036)**

(Answer All Questions) **(3 X 5 = 15 Marks)**

1	Explain DC/DC converter family tree.	L3	CO3
	OR		
2	With the help of traditional modelling, determine the transfer function of Three-phase AC/AC voltage controllers	L3	CO3
3	Draw the block diagram of open loop analysis for AC/DC rectifiers with a first order load. Determine the transfer function in S-domain and Z-domain.	L2	CO4
	OR		
4	Draw the block diagram of closed loop control system with a PI controller for rectifier. Also, analyse the stability of the system.	L2	CO4
5	Explain the energy storage in DC motor.	L3	CO5
	OR		
6	Derive the expression for settling time of a single-phase AC motor drive supplied by a chopper.	L2	CO5

CODE: GR20D5036	GR 20	SET - 4

M.Tech I Year II Semester Regular Examinations, September 2022

DIGITAL CONTROL OF POWER ELECTRONIC AND DRIVE SYSTEMS

(Power Electronics)

Time: 3 hours | Max Marks: 70

Instructions:

1. Question paper comprises of Part-A and Part-B
2. Part-A (for 20 marks) must be answered at one place in the answer book.
3. Part-B (for 50 marks) consists of five questions with internal choice, answer all questions.

PART – A

(Answer ALL questions. All questions carry equal marks)

10 * 2 = 20 Marks

1. a. Discuss the comparison of digital control and analog control. [2] CO1, BL2
   b. Give the significance of zero-order hold in the control of rectifiers. [2] CO1, BL2
   c. Write the mathematical equations of average value of output voltage describing three-phase half wave rectifier. [2] CO2, BL1
   d. Draw the PWM signals used to operate three-phase current source inverter. [2] CO2, BL2
   e. Draw the block diagram of dc-dc boost converter using mathematical equations of the converter. [2] CO3, BL2
   f. Develop the circuit diagram and transfer function of three phase AC/AC voltage converter. [2] CO3, BL3
   g. Produce the transfer function and the block diagram representation of PI controller. [2] CO4, BL3
   h. What is the effective way of controlling a power electronic controller and why? (Open loop or closed loop) [2] CO4, BL2
   i. Draw the block diagram of a dc motor drive. [2] CO5, BL2
   j. How energy can be retrieved from an ac motor drive? [2] CO5, BL1

PART – B

(Answer ALL questions. All questions carry equal marks)

5 * 10 = 50 Marks

2. (a) Differentiate between pulse width modulation and pulse amplitude modulation with an example. [10] CO1, BL4
   (b) Derive the first order transfer function of ac-ac converter. CO1, BL3

OR

3. (a) Discuss in detail concept of the laplace-transform in digital control of power electronics. [6] CO1, BL2
   (b) What is the use of digital-to-analog conversion in the control of power electronic devices? [4] CO1, BL1

4. (a) Develop the mathematical model of three-phase full-wave-controlled AC/DC rectifier. CO2, BL3 [10]

(b) Provide the list of formula and parameters to describe the characteristics of a controlled rectifier. CO2, BL2

OR

5. (a) Derive the mathematical model for three-phase full bridge voltage source inverter. CO2, BL5 [10]

(b) Explain in detail about the multilevel PWM inverter. CO2, BL2

6. Develop the mathematical model of [10]
(a) Multi-element resonant power converter. CO3, BL3
(b) AC/DC/AC PWM converter. CO3, BL3

OR

7. Illustrate the mathematical modelling of single-phase AC/AC voltage controller with [10]
(a) on-off control method CO3, BL2
(b) phase angle control method

8. (a) Explain stability analysis of PI control for ac/dc rectifiers. CO4, BL2 [10]

(b) Analyse the open loop control of inverter with a first-order load. CO4, BL3

OR

9. Design a PI controller to control the output voltage of inverter connected to the battery source. Draw and derive all the relevant figures and formulae. CO4, BL5 [10]

10. Explain in detail about the energy storage in case of an AC motor drive to retain the energy. CO5, BL2 [10]

OR

11. (a) Estimate the energy storage in DC Motors. CO5, BL2 [10]

(b) Explain the concept of DC motor drive with an example. CO5, BL2

*****

Mathematical Modeling of Digital Power Electronics

Z and Laplace Transforms

- **Transform difference/differential equations into algebraic equations that are easier to solve**
- **Are complex-valued functions of a complex frequency variable**

Laplace: $s = \sigma + j\, 2\, \pi\, f$

Z: $z = r\, e^{\,j\, \omega}$

- **Transform kernels are complex exponentials**

Laplace: $e^{s\,t} = e^{\sigma\, t\ +\ j\, 2\, \pi\, f\, t} = e^{\sigma\, t}\ \ e^{\,j\, 2\, \pi\, f\, t}$

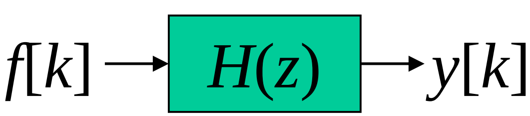
Z: $z^k = (r\, e^{\,j\, \omega})^k = r^k\ \ e^{\,j\, \omega\, k}$

dampening factor **oscillation term**

Z and Laplace Transforms

- **No unique mapping from *Z* to Laplace domain or from Laplace to *Z* domain**
  - Mapping one complex domain to another is not unique
- **One possible mapping is impulse invariance**
  - Make impulse response of a discrete-time linear time-invariant (LTI) system be a sampled version of the continuous-time LTI system.

Z



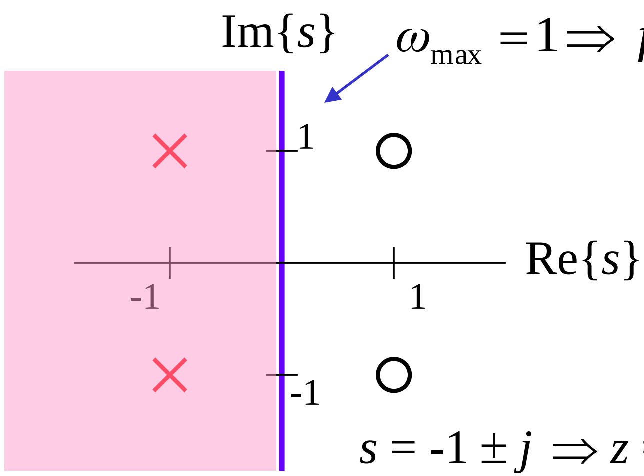
Laplace

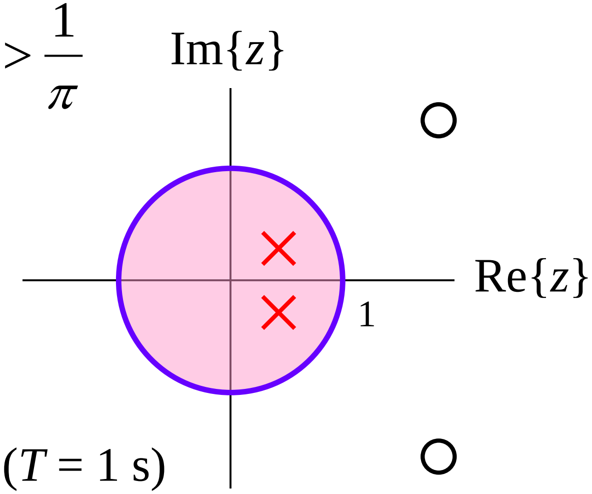
$$H(s) = H(z)\,|_{z=e^{sT}}$$

Impulse Invariance Mapping

- **Impulse invariance mapping is** $z = e^{s\,T}$

$$\omega_{\max} = 1 \Rightarrow f_{\max} = \frac{1}{2\pi} \Rightarrow f_s > \frac{1}{\pi}$$





$s = j\,2\,\pi\,f$

$$s = \text{-}1 \pm j \Rightarrow z = 0.198 \pm j\,0.31 \;(T = 1 \text{ s})$$

$$s = 1 \pm j \Rightarrow z = 1.469 \pm j\,2.287 \;(T = 1 \text{ s})$$

Laplace Domain	***Z Domain***
Left-hand plane	**Inside unit circle**
Imaginary axis	**Unit circle**
Right-hand plane	**Outside unit circle**

lowpass, highpass bandpass, bandstop allpass, or notch filter?

Laplace Transforms and z-Transforms

S/N	Laplace transform $F(s)$	z-transform $F(z)$
1	1	1
2	e^{-kTs}	z^{-k}
3	$\frac{1}{s}$	$\frac{z}{z-1}$
4	$\frac{1}{s^2}$	$\frac{Tz}{(z-1)^2}$
5	$\frac{2}{s^3}$	$\frac{T^2 z(z+1)}{(z-1)^3}$
6	$\frac{(k-1)!}{s^k}$	$\lim_{a\to 0} (-1)^{k-1} \frac{\partial^{k-1}}{\partial a^{k-1}} \left[\frac{z}{z\, e^{-aT}}\right]$

7	$\dfrac{1}{s+a}$	$\dfrac{z}{z-\mathrm{e}^{-aT}}$
8	$\dfrac{1}{(s+a)^2}$	$\dfrac{Tz\,\mathrm{e}^{-aT}}{(z-\mathrm{e}^{-aT})^2}$
9	$\dfrac{(k-1)!}{(s+a)^k}$	$(-1)^k \dfrac{\partial^k}{\partial_a^k} \dfrac{z}{z-\mathrm{e}^{-aT}}$
10	$\dfrac{a}{s(s+a)}$	$\dfrac{z(1-\mathrm{e}^{-aT})}{(z-1)(z-\mathrm{e}^{-aT})}$
11	$\dfrac{1}{(s+a)(s+b)}$	$\dfrac{1}{(b-a)}\left[\dfrac{z}{z-\mathrm{e}^{-aT}}-\dfrac{z}{z-\mathrm{e}^{-bT}}\right]$
12	$\dfrac{a}{s^2(s+a)}$	$\dfrac{Tz}{(z-1)^2}-\dfrac{(1-\mathrm{e}^{-aT})z}{a(z-1)(z-\mathrm{e}^{-aT})}$

13	$\dfrac{a}{s^3(s+a)}$	$\dfrac{T^2z}{(z-1)^3}+\dfrac{(aT-2)Tz}{2a(z-1)^2}+\dfrac{z}{a^2(z-1)}-\dfrac{z}{a^2(z-e^{-aT})}$
14	$\dfrac{a^2}{s(s+a)^2}$	$\dfrac{z}{z-1}-\dfrac{z}{z-e^{-aT}}-\dfrac{aT\,e^{-aT}z}{(z-e^{-aT})^2}$
15	$\dfrac{a^2}{s^2(s+a)^2}$	$\dfrac{1}{a}\left[\dfrac{(aT+2)z2z^2}{(z-1)^2}+\dfrac{2z}{z-e^{-aT}}+\dfrac{aT\,e^{-aT_z}}{(z-e^{-aT})^2}\right]$
16	$\dfrac{\omega}{s^2+\omega^2}$	$z\sin\omega T$
17	$\dfrac{s}{s^2+\omega^2}$	$\dfrac{z(z-\cos\omega T)}{z^2-2z\cos\omega T+1}$

18	$\dfrac{\omega}{s^2 - \omega^2}$	$\dfrac{z \sinh \omega T}{z^2 - 2z \cosh \omega T + 1}$
19	$\dfrac{s}{s^2 - \omega^2}$	$\dfrac{z(z - \cosh \omega T)}{z^2 - 2z \cosh \omega T + 1}$

S/N	Laplace transform $F(s)$	z-transform $F(z)$
20	$\dfrac{\omega}{(s+a)^2+\omega^2}$	$\dfrac{z\,\mathrm{e}^{-aT}\sin\omega T}{z^2-2z\,\mathrm{e}^{-aT}\cos\omega T+\mathrm{e}^{-2aT}}$
21	$\dfrac{a^2+\omega^2}{s[(s+a)^2+\omega^2]}$	$\dfrac{z}{z-1}-\dfrac{z^2-z\,\mathrm{e}^{-aT}\sec\phi\;\cos(\omega T-\phi)}{z^2-2z\,\mathrm{e}^{-aT}\cos\omega T+\mathrm{e}^{-2aT}}$
22	$\dfrac{s+a}{(s+a)^2+\omega^2}$	$\dfrac{z^2-z\,\mathrm{e}^{-aT}\cos\omega T}{z^2-2z\,\mathrm{e}^{-aT}\cos\omega T+\mathrm{e}^{-2aT}}$

SHANNON'S SAMPLING THEOREM

- The requirement that the sampling frequency ω_C be at least twice as large as the highest frequency (Nyquist frequency) contained in the signal $f(t)$ is formally known as the Shannon's sampling theorem.
- Nyquist sampling theorem states that an analog signal can be perfectly re-created from its sample values if the sampling interval is chosen correctly. For example, a signal with a maximum frequency of ω Hz must be sampled at least 2ω times per second to reconstruct the original signal from the samples.

- The sampling frequency ω_C must be greater than twice of the input signal frequency, the output signal can be successfully sampled. The sampling frequency condition is $\omega_C > 2\omega_S$, where $\omega_C = \omega_S/2$ is called the Nyquist frequency.
- Below the Nyquist sampling frequency, signal frequency information is lost. At Nyquist sampling frequency, amplitude data are lost.

SAMPLE-AND-HOLD DEVICES

- The important equipment (device) for the sampling and holding process of the digitized operation.

- **All switching circuits including all AC/DC rectifiers, DC/AC inverters, DC/DC converters and AC/AC (AC/DC/AC) converters are working in the discrete-time state.**

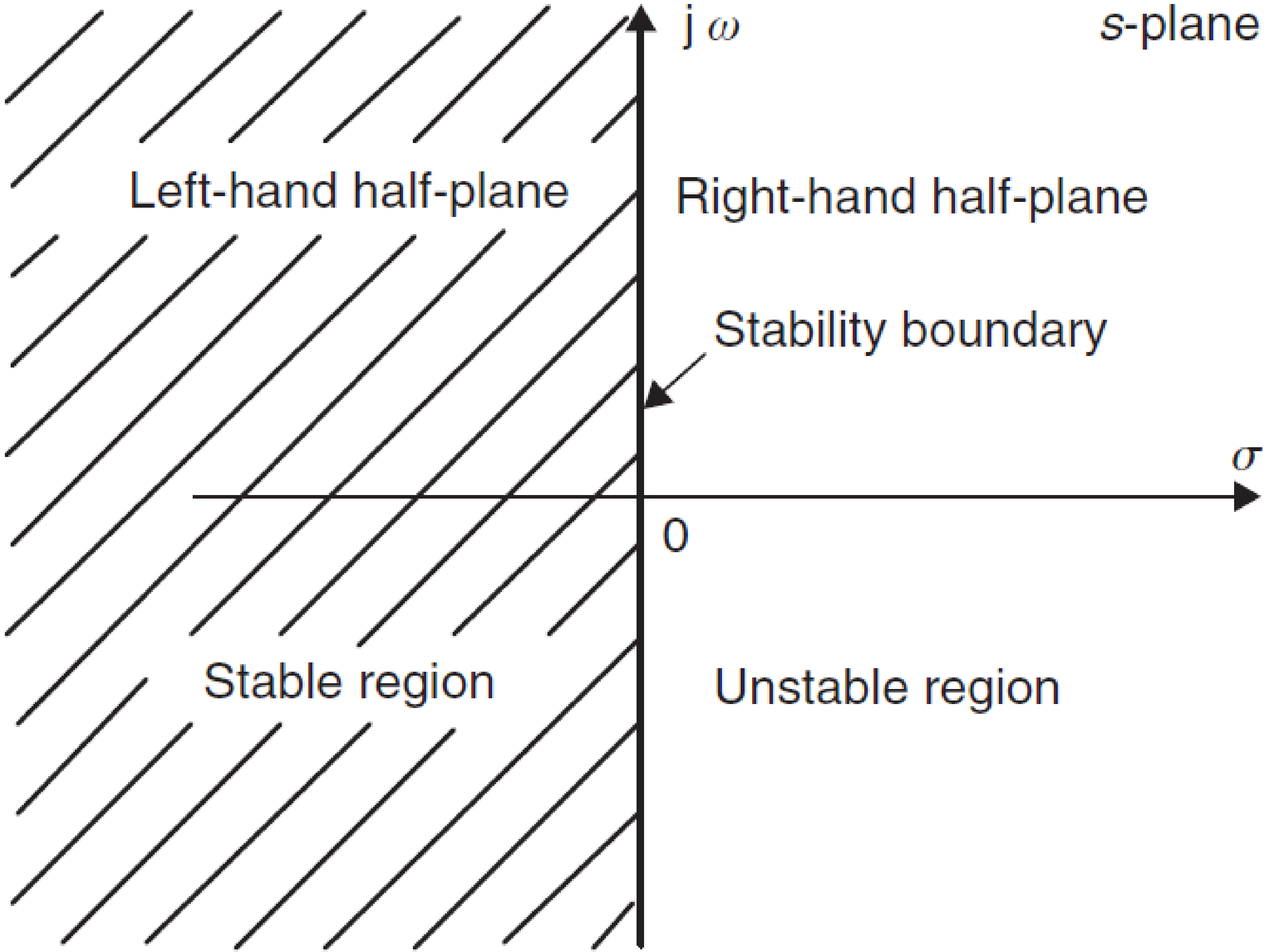
- **Therefore, they have to be described by digital control theory rather than analog control.**

- **The differences between analog and digital control systems are in the following aspects:**

➢ **transfer function's form,**

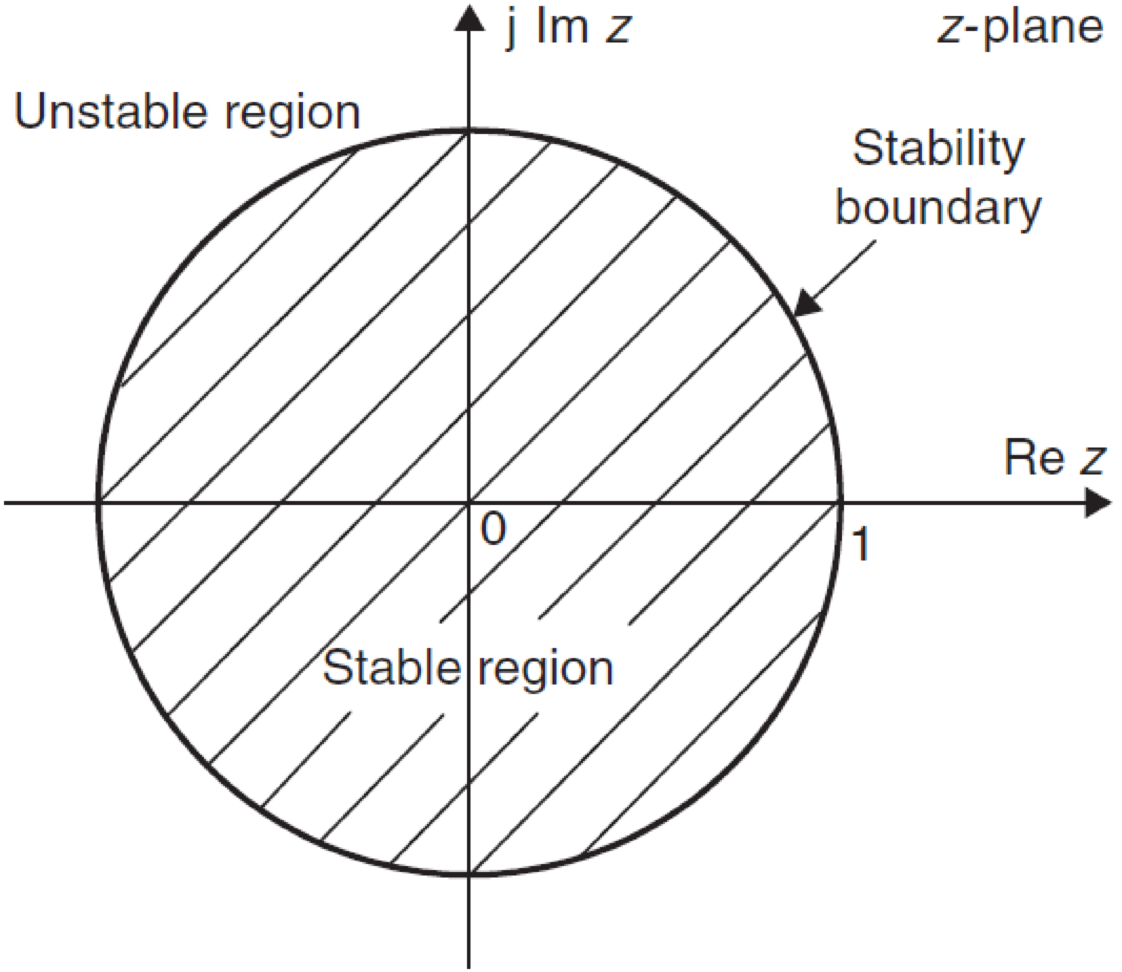
➢ **stability characteristics,**

➢ **unit-step responses and impulse responses.**


j ω
s-plane
Left-hand half-plane
Right-hand half-plane
Stability boundary
σ
0
Stable region
Unstable region

- **A good analog control system has the following step response with the typical characteristics:**
  - **fast response, i.e. the settling time is less than 4.7 times of the time constants;**
  - **oscillation cycle number is not more than 2;**
  - **the overshoot is not more than 5%.**

Stability boundary in the *z*-plane.



A ZERO-ORDER HOLD (ZOH) FOR AC/DC CONTROLLED RECTIFIERS

- **AC/DC rectifiers have many forms**
- single-phase half-wave controlled rectifier;
- single-phase full-wave controlled rectifier;
- three-phase half-wave controlled rectifier;
- three-phase full-wave controlled rectifier;
- double anti-star half-wave controlled rectifier with balanced inductor;
- delta-star three-phase full-wave controlled rectifier;
- four-quadrant operation controlled rectifiers:

(a) four-quadrant operation controlled rectifiers with cycling current,

(b) four-quadrant operation controlled rectifiers without cycling current.

RECONSTRUCTION OF SAMPLED SIGNALS

- A data-reconstruction device also known as a *filter* is often used to interface between digital and analog components.
- The hold circuit in the S/H device is the most common filtering device in the discrete-data systems.
- Although the S/H device comes in a single unit, for mathematical simplification, only the hold device is modeled.

- The hold device is the simplest form of a general data-reconstruction problem.
- The problem of data reconstruction can be regarded as a given sequence of numbers $f(0)$, $f(T), f(2T), \ldots, f(kT), \ldots$.
- An analog signal $f(t)$, where $t > 0$ is to be reconstructed from the information contained in the sequence.
- This data-reconstruction process may be regarded as an extrapolation process, since the analog signal is to be constructed based on information available only at past sampling instants.

- Power series expansion of $f(t)$ in the interval between the sampling instants kT and $(k+1)T$ is used to generate a desired approximation.
- The approximation is:

$$f_k(t) = f(kT) + f^{(1)}(kT)(t-kT) + \frac{f^{(2)}(kT)}{2!}(t-kT)^2 + \cdots$$

or

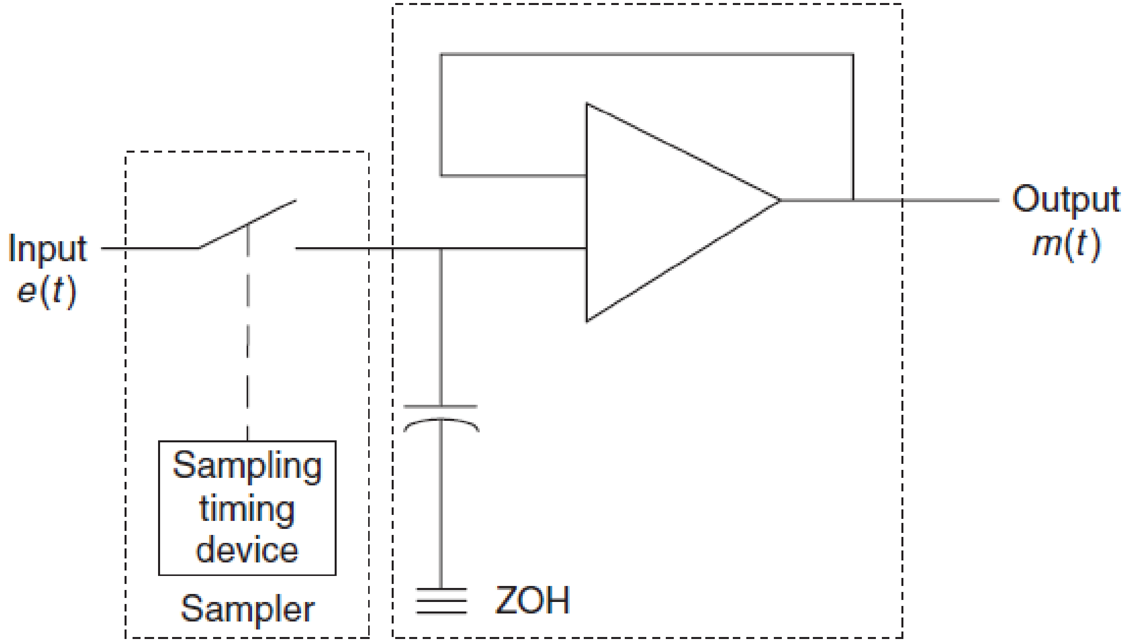
$$f_k(t) = \sum_{n=0}^{\infty} \frac{f^{(n)}(kT)}{n!}(t-kT)^n$$

- The higher the order of the derivation, the larger will be the number of delayed pulses required. In general, the number of delayed pulse data required to approximate the value of $f(n)(kT)$ is $n+1$.

- The extrapolating device consists of a series of time delays, and the number of delays depends on the accuracy of the estimate of the time function $f(t)$ during the time interval from kT to $(k+1)T$.
- Although utilizing a higher-order derivative produces a more accurate extrapolation, it causes a reduction on the stability of the closed-loop control systems and it also makes the circuitry more complicated and expensive.

DATA CONVERSION:THE ZERO-ORDER HOLD

- The most widely used holding device is the zero-order hold (ZOH) as it is less complicated and less expensive.

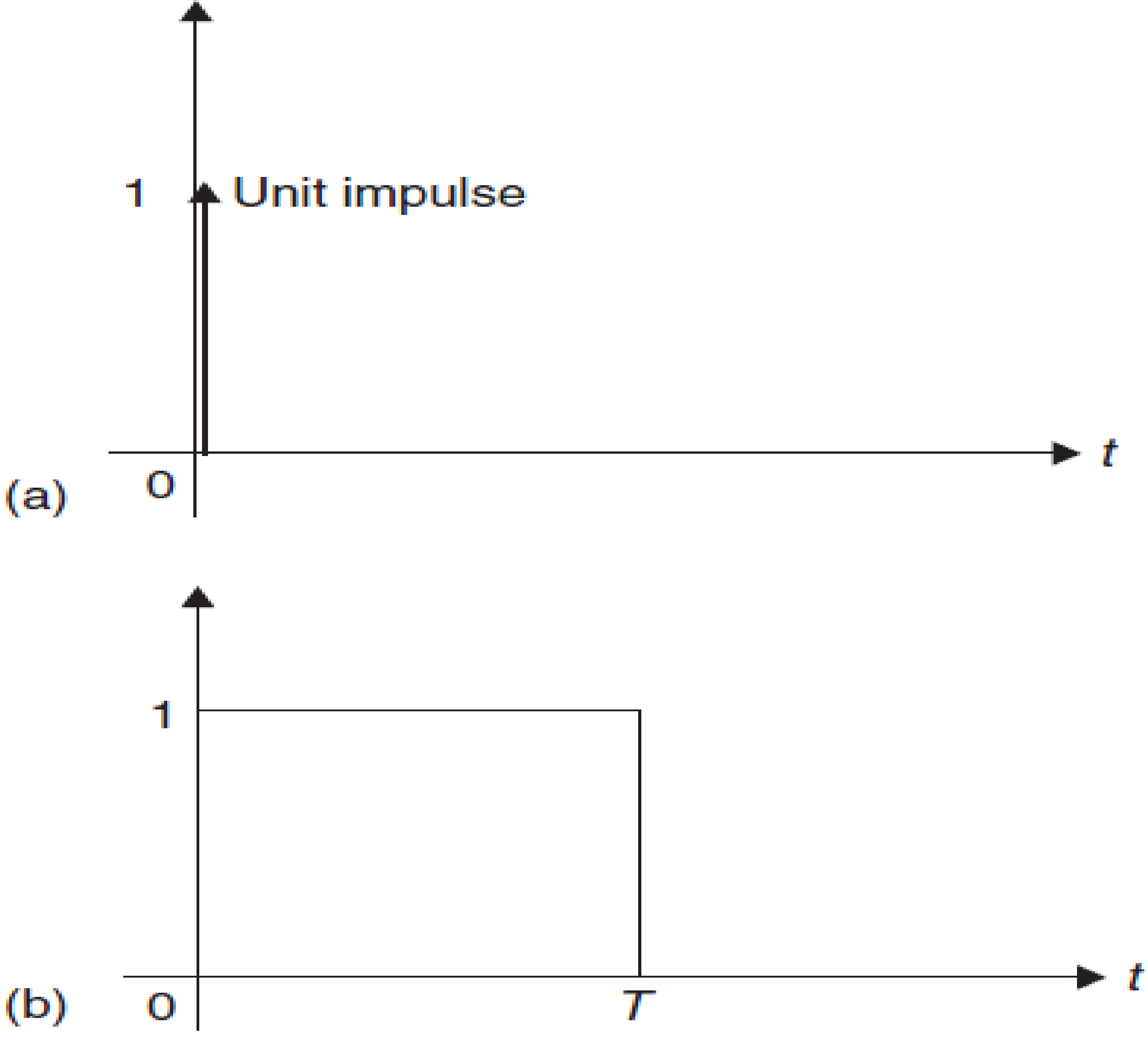


A simple ZOH device.

- It is called zero-order extrapolator as its polynomial used is of the zeroth order.
- It holds the value of the sampled value $f(kT)$ for $kT \le t < (k+1)T$ until the next sample $f[(k+1)T]$ arrives:

$$f_k(t) = f(kT)$$

- This equation is used for approximation of $f(t)$ during the time interval $kT \le t < (k+1)T$.
- If a unit impulse input signal is applied to a ZOH, the impulse response is shown in following figure



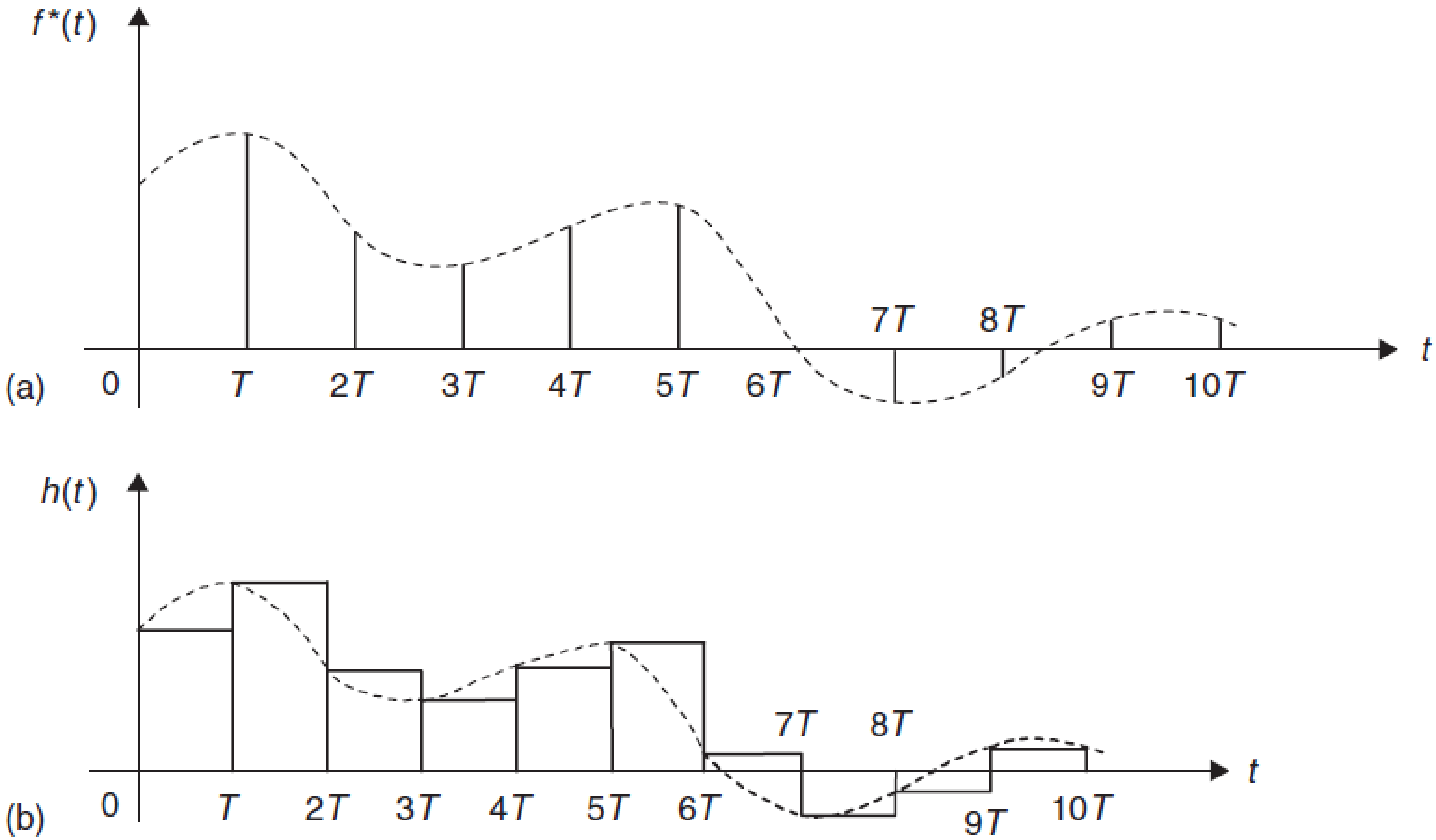
Responses of a ZOH: (a) unit-impulse input to and (b) impulse response of ZOH.

- The ZOH is a linear device as it satisfies the principle of superposition. The impulse response of a ZOH is expressed as:

$$g_{h0}(t) = u_s(t) - u_s(t - T)$$

- The response of the ZOH to the unit-impulse input is equivalent to the difference between two unit-step function.
- By taking a Laplace transform, the transfer function is obtained as:

$$G_{h0}(s) = \frac{1 - e^{-Ts}}{s}$$



Input and output waveforms of a ZOH in the time domain: (a) input signal $f(t)$ and sampled signal $f*(t)$, and (b) output waveform of ZOH.

- The ZOH is a data-reconstruction or data-filtering device. Hence it is useful to examine its frequency domain characteristics.
- By replacing *s* by jω in the transfer function, we get,

$$G_{h0}(j\omega) = \frac{1 - e^{-Tj\omega}}{j\omega}$$

$$G_{h0}(j\omega) = \frac{2e^{-j\omega T/2}(e^{j\omega T/2} - e^{-j\omega T/2})}{j2\omega} = \frac{2\sin(\omega T/2)}{\omega}e^{-j\omega T/2}$$

$$G_{h0}(j\omega) = T\frac{\sin(\omega T/2)}{\omega T/2}e^{-j\omega T/2} = \frac{2\pi}{\omega_S}\frac{\sin(\pi\omega/\omega_S)}{\pi\omega/\omega_S}e^{-j(\pi\omega/\omega_S)}$$

- Since T is the sampling period in seconds, and $T = 2\pi/\omega_S$ where ω_S is the sampling frequency in rad/s.

- The magnitude of $G_{h0}(j\omega)$ is:

$$|G_{h0}(j\omega)| = \frac{2\pi}{\omega_S}\left|\frac{\sin(\pi\omega/\omega_S)}{\pi\omega/\omega_S}\right|$$

- The phase of $G_{h0}(j\omega)$ is:

$$\angle G(j\omega_S) = \angle\sin(\pi\omega/\omega_S) - \pi\omega/\omega_S$$

- The change of sign from + to − can be regarded as a phase change of -180°.

THE FIRST-ORDER HOLD

- The first-order hold (FOH) uses the first two terms of the power series to extrapolate the time function $f(t)$ over the time interval $kT \leq t < (k+1)T$.
- The equation for the FOH is:

$$f_k(t) = f(kT) + f^{(1)}(kT)(t - kT)$$

- where the first-order derivative of $f(t)$ at $t = kT$ is approximated as

$$f^{(1)}(kT) = \frac{f(kT) - f[(k-1)T]}{T}$$

- **Thus**

$$f_k(t) = f(kT) + \frac{f(kT) - f[(k-1)T]}{T}(t - kT)$$

- The output of the FOH between two consecutive sampling instants is a ramp function.
- The slope of the ramp is equal to the difference of $f(kT)$ and $f[(k+1)T]$.
- By applying a unit impulse at $t = 0$ as input, an impulse response of the FOH is obtained. The corresponding output is obtained by setting $k = 0$, 1, 2, . . . for the various time intervals. For $k = 0$,

$$f_0(t) = f(0) + \frac{f(0) - f(-T)}{T} t \quad 0 \le t \le T$$

- For a unit-impulse input, $f(0)=1$ and $f(-T)=0$, the impulse response of the FOH for $0 \le t \le T$ is:

$$g_{h1}(t) = 1 + \frac{t}{T}$$

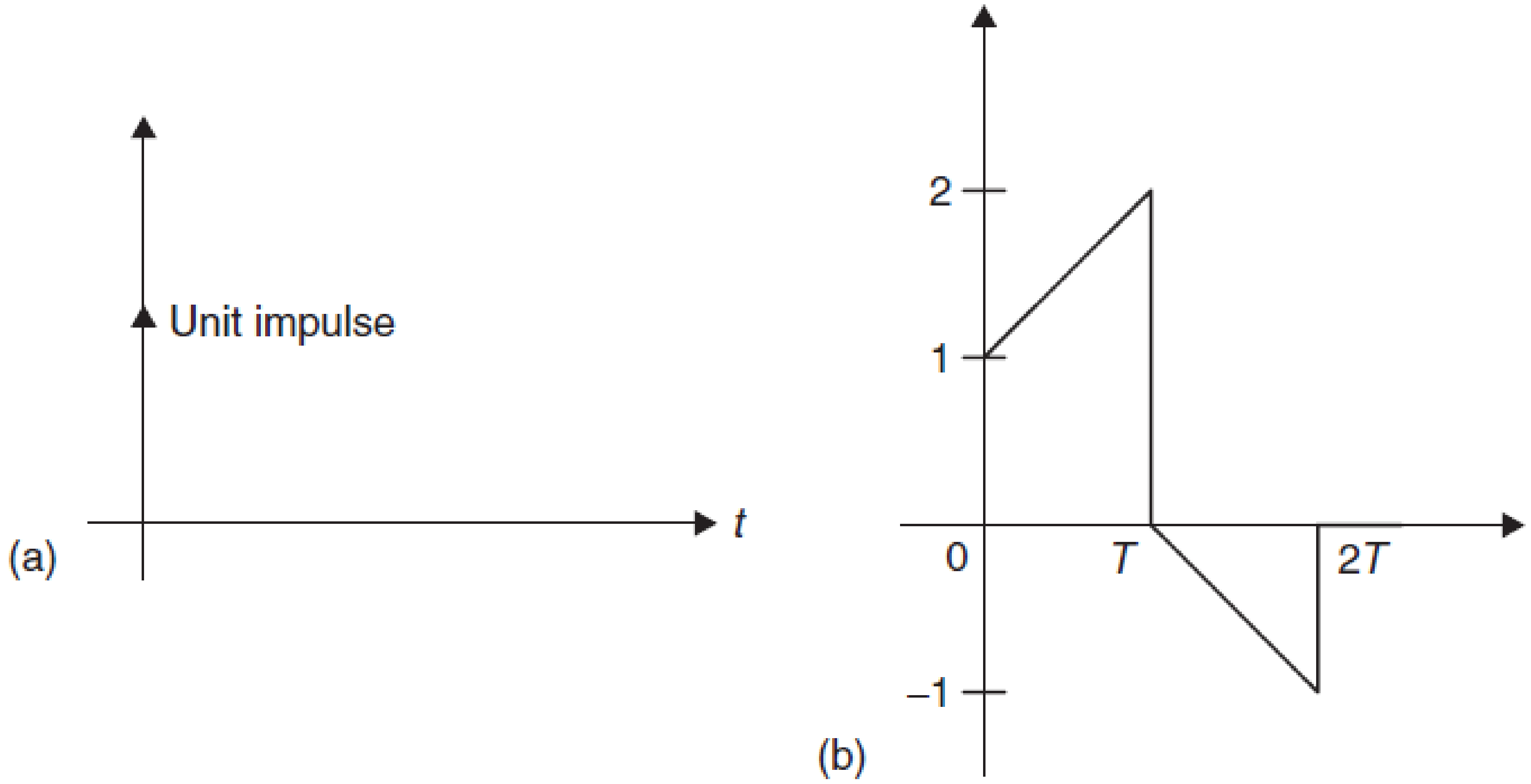
- For $k = 1$,

$$f_1(t) = f(T) + \frac{f(T) - f(0)}{T}(t - T)$$

- The impulse response of the FOH over time interval $T \leq t \leq 2T$ is:

$$g_{h1}(t) = -\frac{t-T}{T}$$

- If a unit-impulse input signal applied to a FOH, the impulse response is shown in following figure



Responses of an FOH: (a) unit-impulse input signal and (b) impulse response of the FOH.

- The impulse response of the FOH for $t > 2T$ is zero, since $f(t)=0$ for $t > 2T$.
- Functionally, the impulse response in Figure (b) can be written as:

$$g_{h1}(t) = u_S(t) + \frac{t}{T}u_S(t-T) - \frac{2(t-T)}{T}u_S(t-T) + \frac{(t-2T)}{T}u_S(t-2T)u_S(t-2T) + u_S(t-2T)$$

- The transfer function of the FOH is obtained by taking the Laplace transform of the last equation:

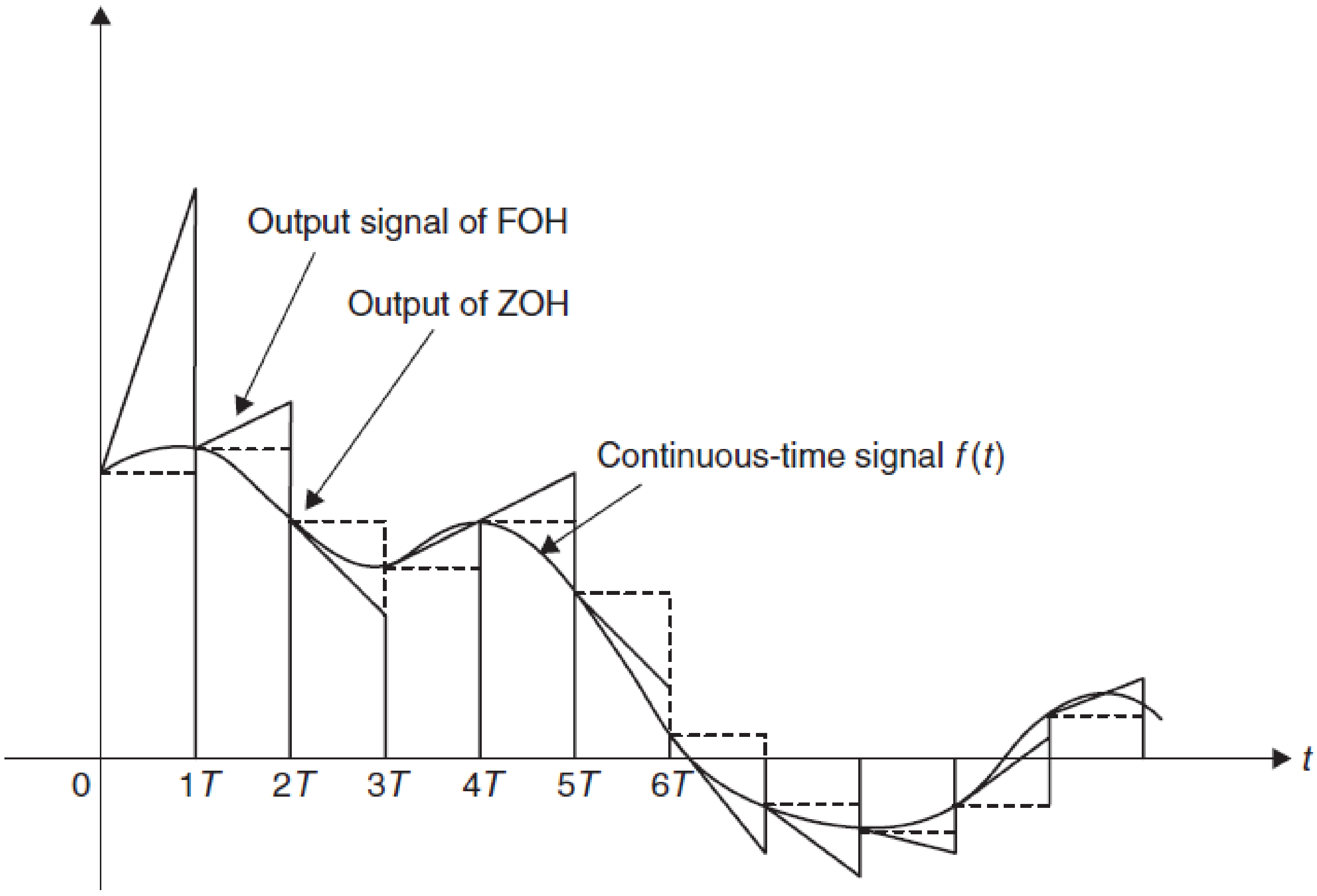
$$G_{h1}(s) = \frac{1+Ts}{T}\left[\frac{1-e^{-Ts}}{s}\right]^2$$

or simply,

$$G_{h1}(s) = \frac{1+Ts}{T}[G_{h0}(s)]^2$$

- The frequency response of the FOH:

$$G_{h1}(j\omega) = \frac{1 + Tj\omega}{T}\left[\frac{1 - e^{Tj\omega}}{j\omega}\right]^2$$



Reconstruction of a continuous-time signal by means of an FOH.

- The magnitude and phase response of $Gh1(j\omega)$ are obtained as:

$$|G_{h0}(j\omega)| = \frac{2\pi}{\omega_s}\sqrt{1 + \frac{4\pi^2\omega^2}{\omega_s^2}}\left[\frac{\sin \pi\omega/\omega_s}{\pi\omega/\omega_s}\right]^2$$

$$\angle G_{h1}(j\omega) = \tan^{-1}\left(\frac{2\pi\omega}{\omega_s}\right) - \frac{2\pi\omega}{\omega_s}$$

THE SECOND-ORDER HOLD

- The Second-order hold(SOH) uses the first three terms of the power series to extrapolate the time function $f(t)$ over the time interval $kT \leq t < (k+1)T$.
- The equation for the SOH is:

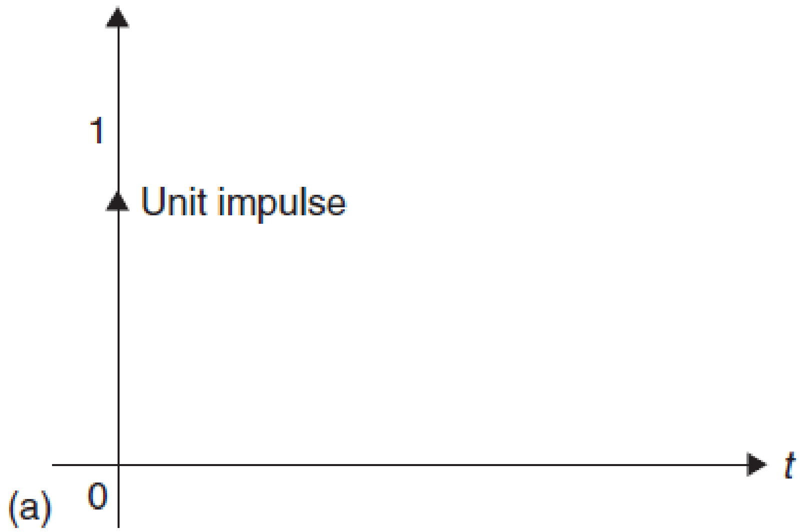
$$f_k(t) = f(kT) + f^{(1)}(kT)(t - kT) + \frac{f^{(2)}(kT)}{2!}(T - kT)^2$$

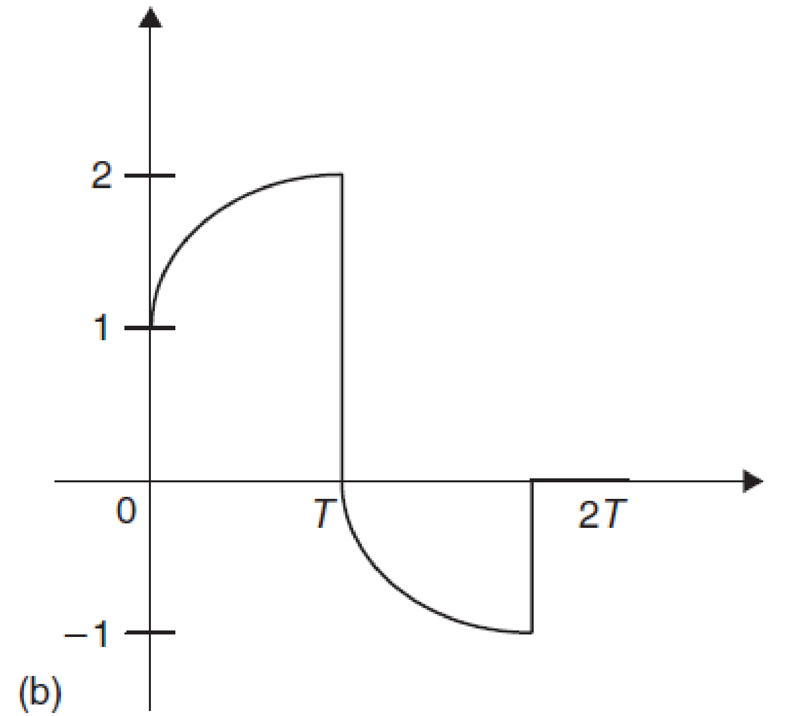
- The output of the second order hold between two consecutive sampling instants may be a parabola function. The simplest of the curve is a square-law to the difference of $f(kT)$ and $f[(k+1)T]$.

- By applying a unit impulse at $t = 0$ as input, an impulse response of the second-order hold is obtained. The corresponding output is obtained by setting $k = 0, 1, 2, \ldots$ for the various time intervals.
- For $k = 0$, a unit impulse input, $f(0) = 1$ and $f(-T) = 0$, the impulse response of the second order hold for $0 \le t \le T$ is

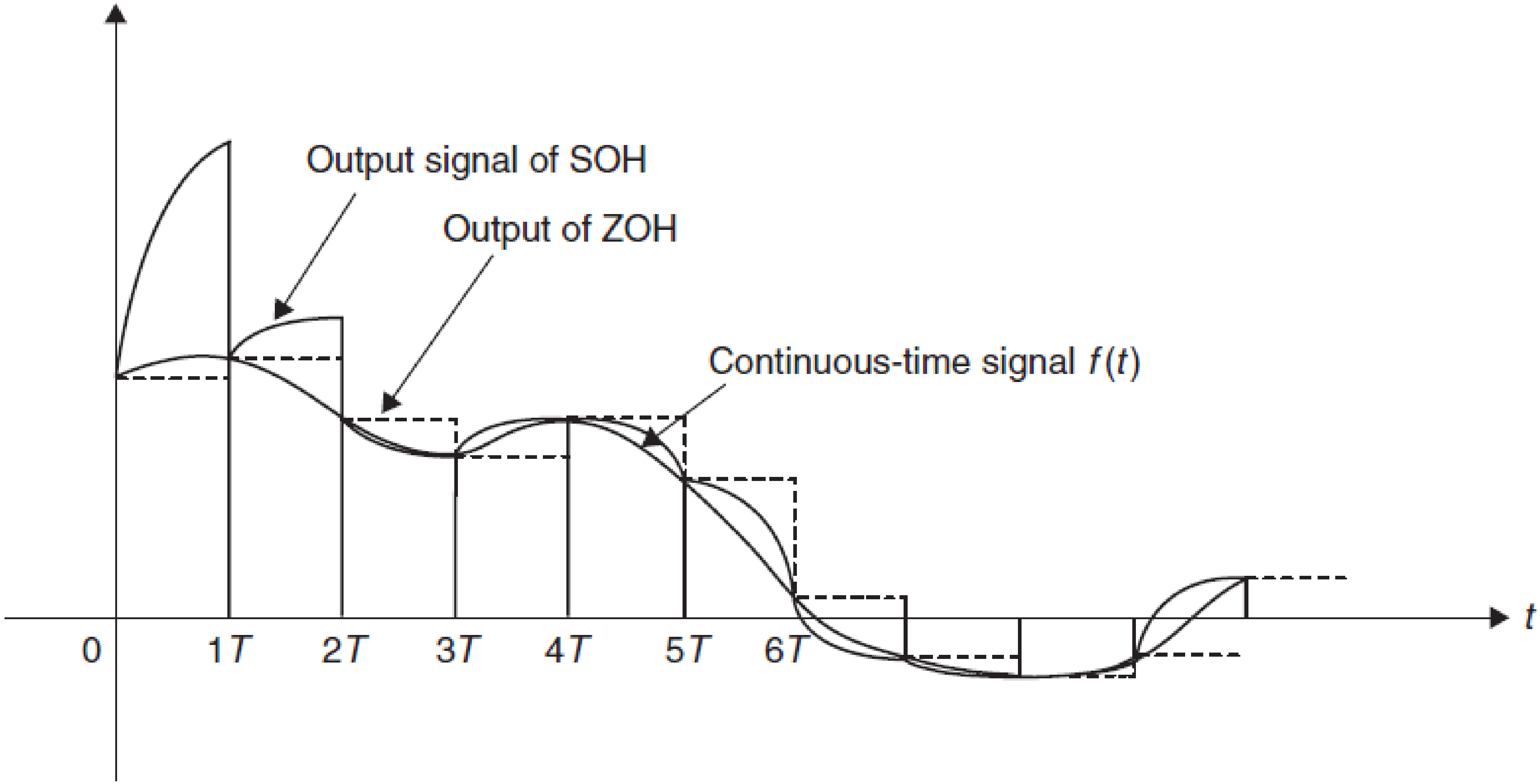
$$g_{h2}(t) = 2 - \left(1 + \frac{t}{T}\right)^2 .$$

- If a unit impulse input signal is applied to an SOH, the impulse response is shown in following figure





- Responses of an SOH: (a) unit-impulse input to and (b) impulse response of SOH.



- Reconstruction of a continuous-time signal by means of an SOH.

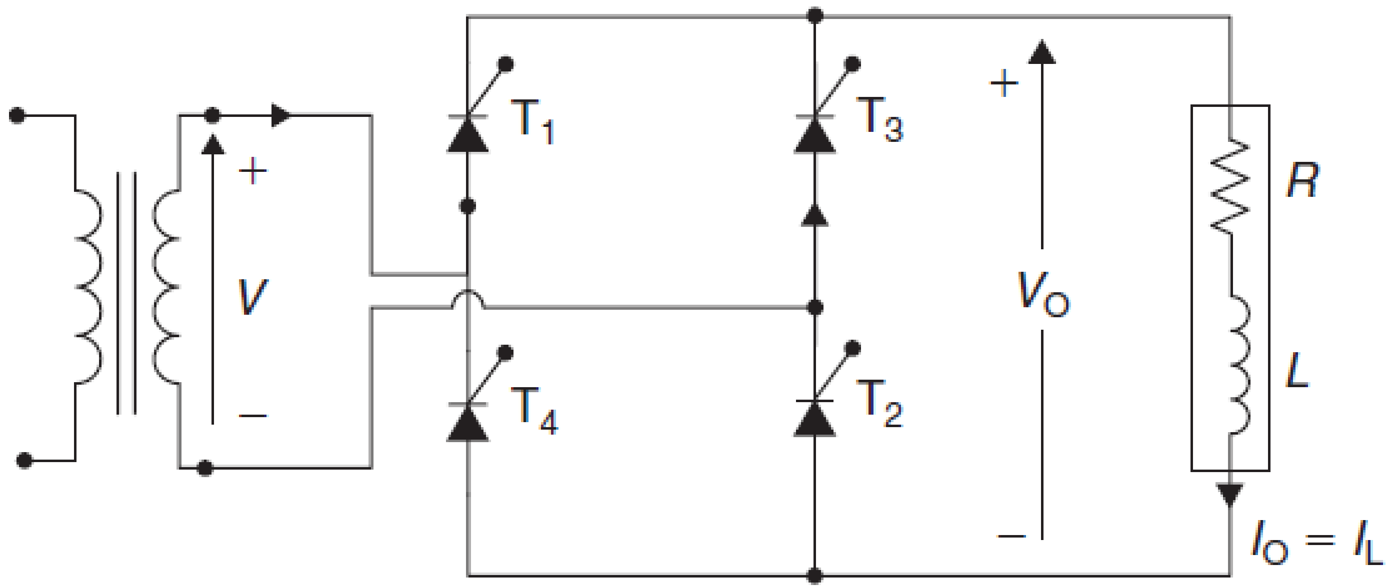
- The typical second-order transfer function in the *s*-domain is shown as follows:

$$G(s) = \frac{M}{1 + s\tau + s^2\tau\tau_d} = \frac{M}{1 + s\tau + \xi s^2\tau^2}$$

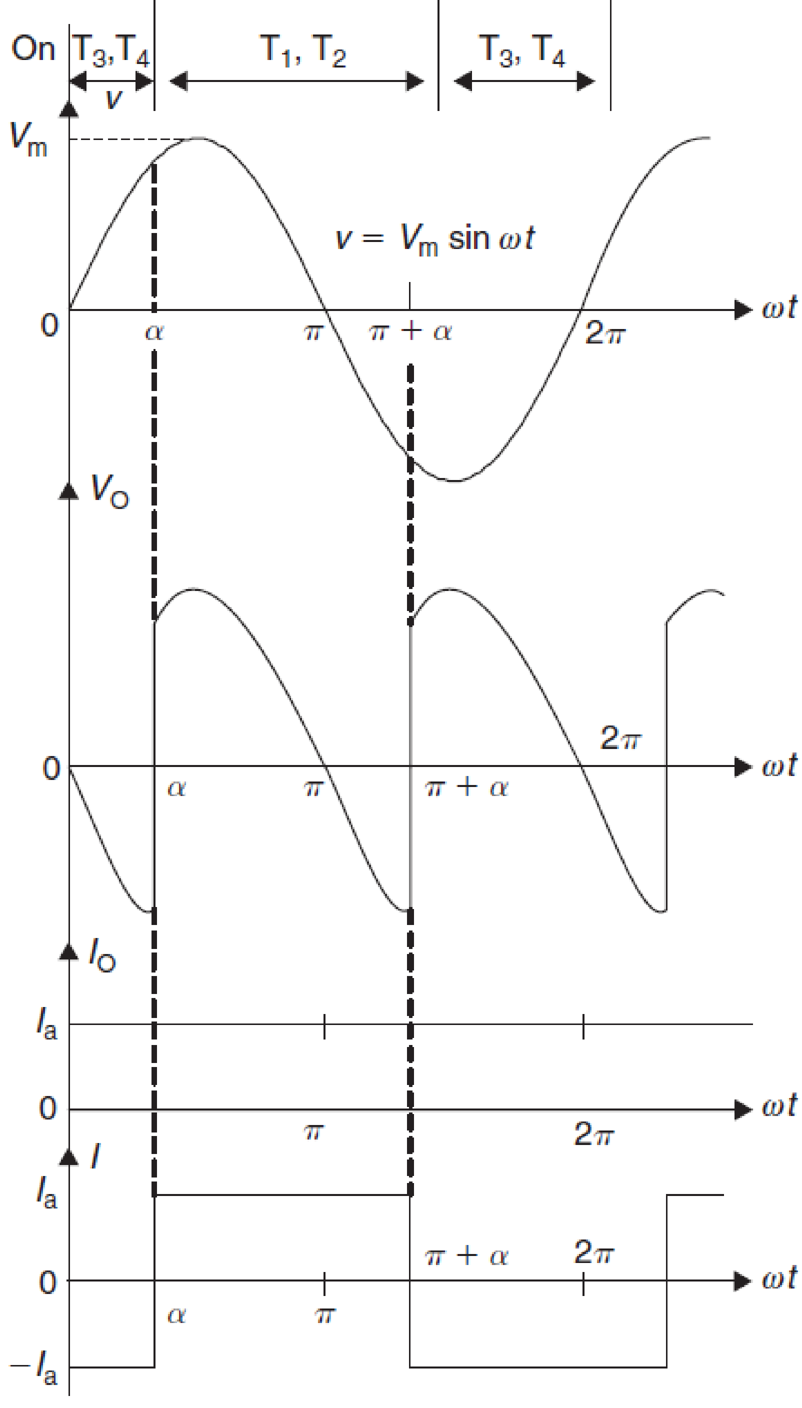
- where*M* is the voltage-transfer gain; τ, the time constant; τ_d, the damping time constant

(in which $\tau_d = \xi\tau$)

A ZERO-ORDER HOLD (ZOH) FORAC/DC CONTROLLED RECTIFIERS



A single-phase fully controlled AC/DC rectifier



The input and output voltage and current waveforms

- In general situation, the load of the rectifiers is an *L*–*R* circuit with the time constant $\tau = L/R$. If the output current is continuous, then the average value of the output DC voltage is:

$$V_{\mathrm{d}} = V_{\mathrm{d\text{-}max}} \cos\alpha$$

- where α is the firing angle of the applied firing pulse. *V*d is the output DC average voltage of the rectifier. *V*d-max is the maximum output DC average voltage of the rectifier corresponding to the firing angle $\alpha=0$.

- Refer to the single-phase fully controlled AC/DC rectifier with an *R–L* load shown in Figure . The corresponding input and output voltage and current waveforms are shown in Figure.

- If the AC input power supply with the frequency f =50 Hz (T =1/f =20 ms), then each device is conducted in half a cycle, i.e. the conduction

angle is 180◦ (or π rad) or in the interval of 10 ms. The current commutation happens twice a cycle.

- The output voltage is out of control in a half-cycle once the firing pulse is applied.
- Therefore, it is the element to keep the output voltage in a period of $T/2=1/2f$.
- By per unit system, the voltage transfer gain is unity (1) in a sampling interval $T/2=10$ ms.
- That is:

$$G(t) = \frac{V_{\text{O}}}{V_{\text{in}}}\Big|_{\text{per-unit}} = 1$$

- Analogously, a single-phase half-wave AC/DC rectifier has the sampling interval to be 20 ms.
- A three-phase half-waveAC/DC rectifier has the sampling interval to be 6.67 ms (i.e. *T/*3)
- A three-phase full-wave AC/DC rectifier has the sampling interval to be 3.33 ms (i.e. *T*/6).

Traditional Modeling for AC/DC Controlled Rectifiers

- Traditional modeling for AC/DC controlled rectifiers is a time-delay element in the *s*-domain. The delayed time is statistically as the sampling interval T or commutation period σ. For example, if the power supply frequency f =50 Hz, a single-phase halfwave controlled rectifier has the time delay $T = \sigma$ =20 ms. The corresponding transfer function of this rectifier in per-unit system is:

$$G(s) = \mathrm{e}^{-Ts} = \mathrm{e}^{-\sigma s}$$

- If the rectifier is used in a current control system or speed control system, and the current/speed responses are in the stage 0.1–1 s, we can consider the variable in a sampling interval of 20 ms is comparably small, i.e. $Ts=\sigma s \rightarrow 0$. Hence, above Equation can be rewritten as:

$$G(s) = e^{-\sigma s} = 1 - \sigma s = \frac{1}{1 + \sigma s}$$

- This mathematical modeling is widely used in industrial applications

A Zero-Order Hold for AC/DC Controlled Rectifiers in Digital Control

- The rectifiers cannot be considered only a time-delayed element. Since its output voltage is out of control once the firing pulse was applied, it should be looked as a sample-and-hold element.
- Therefore, its mathematical modeling in per-unit digital control system should be a zero-order hold (ZOH) in both the *s*- and *z*-domains:

$$G(s) = \frac{1 - e^{-Ts}}{s}$$

$$G(z) = \mathbb{Z}[G(s)] = \mathbb{Z}\left[\frac{1 - e^{-Ts}}{s}\right] = \frac{z}{z-1} - \frac{z}{(z-1)}\frac{1}{z} = 1$$

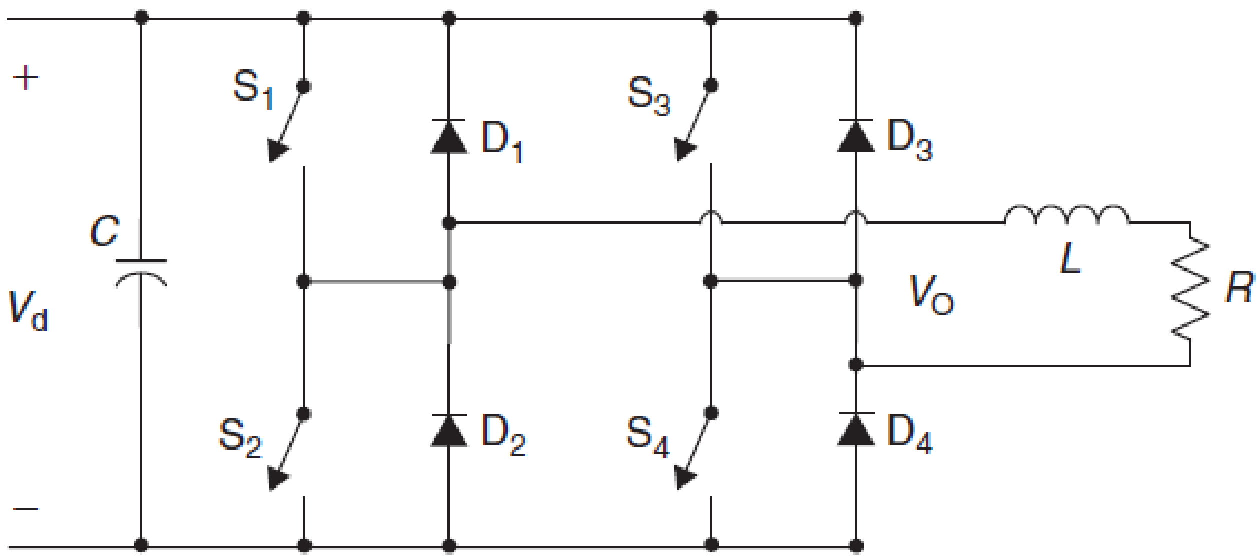
It means that the AC/DC controlled rectifier performs a sampling time delay in the *s*-domain and one-step delay (T) in a digital control system.

A FIRST-ORDER TRANSFER FUNCTION FOR DC/AC PULSE-WIDTH-MODULATION INVERTERS

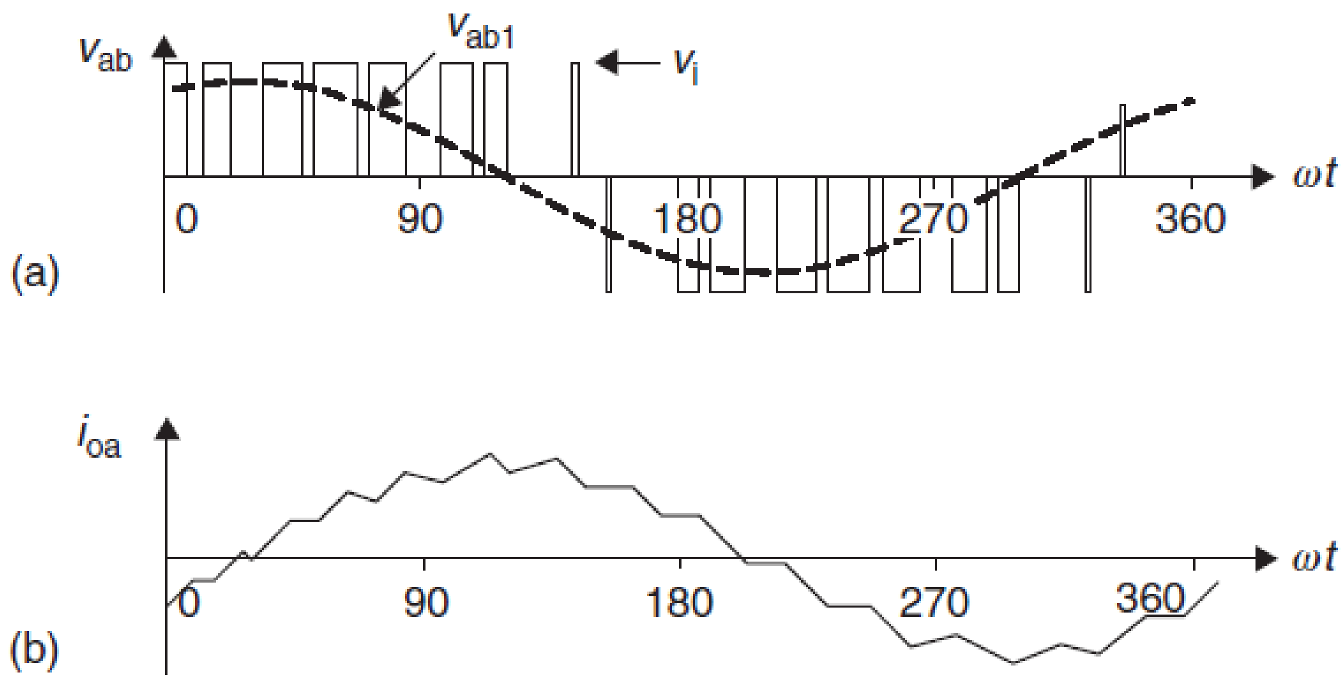
Pulse-width-modulation (PWM) DC/AC inverters have many forms which are listed below:

- DC/AC PWM inverter,
- DC/AC single-phase PWM inverter,
- multi-level PWM inverter,
- multi-level single-phase PWM inverter,
- vector multi-level PWM inverter,
- space vector modulation (SVM) multi-level SPWM inverter.

- The devices of all types of the DC/AC inverters can be a BJT, GTO and MOSFET.
- They are controlled by the PWM scheme with the certain carrier (chopping) frequency f_C.
- In a sampling interval $T = 1/f_C$, the pulse-width angle can be changed only once, i.e. the output voltage of an DC/AC PWM inverter is changed period by period.
- Therefore, all types of the DC/AC PWM inverters are working in discrete state.



The single-phase PWM DC/AC inverter with an *L*–*R* circuit.



The output (a) voltage and (b) current waveforms.

- Refer to the single-phase PWM DC/AC inverter with an *R*–*L* load shown in Figure. The corresponding output voltage and current waveforms are shown in Figure with the carrier frequency f_C =400 Hz for indication although particular f_C may be very higher.
- If the input reference AC voltage signal with the frequency f =50 Hz (T =1/f =20 ms) and the triangle waveform with carrier frequency f_C = 400 Hz (T_C =2.5 ms), each device is conducted in a conduction period=mT_C, where m is the modulation ratio.

- The conduction period is less than a cycle TC (sampling interval) since the modulation ratio m is usually smaller than unity (1) for linear modulation.

- The conduction angle is smaller than 360° (or 2π rad), or <2.5 ms. The current commutation happens once a chopping cycle.
- The output voltage is out of control in a half-chopping cycle once the PWM pulse is applied. Therefore, it is the element to keep the output voltage in a sampling period of $T_C = 1/f_C$.

- By per-unit system, the voltage transfer gain is a linear element in a sampling interval T_C =2.5 ms. That is,

$$G(t) = \frac{V_O}{V_{in}}\Big|_{\text{per-unit}} = 1 - e^{-t/T_C}$$

- Analogously, different chopping frequency only changes the sampling interval. The mathematical modeling is not changed.

Traditional Modeling for DC/AC PWM Inverters

- Traditional modeling for DC/AC PWM inverters is a first-order element in the *s*-domain.
- The output voltage of a DC/AC PWM inverter is a periodic pulse train with the repeating frequency f_O as requested.
- This output periodic pulse train has plenty of harmonics corresponding to both the requested frequency f_O and the carrier frequency f_C.
- Usually, the carrier frequency f_C must be much higher than the requested output frequency f_O to avoid yielding high total harmonic distortion (THD).

- No matter how higher the applied carrier frequency f_C is, THD cannot be zero.
- A low-pass filter must be set to filter the higher-order harmonics in order to obtain pure output sinusoidal waveform.
- The low-pass filter is usually an R–C circuit with the time constant $\tau = R$–C or an R–L circuit with the time constant $\tau = L/R$.
- the time constant τ is much larger than the pulse width ($\tau >> T = 1/f_C$) to avoid the parasitic power losses and additional distortion.

- The purpose to set the filter is to retain the fundamental harmonics in 50 Hz and filter the higher-order harmonics out, and then obtain very low THD.
- The transfer function of this rectifier in per-unit system is:

$$G(s) = \frac{1}{1 + \tau s}$$

- the first-order transfer function is the feature of the first-order filter, but the characteristics of the DC/AC PWM inverters.
- The transfer function of the DC/AC PWM inverters is ignored. It is treated as a proportional element.

A First-Order Hold for DC/AC PWM Inverters in Digital Control

- if the inverters used to drive an induction motor, the stator circuit is a natural first-order filter with time constant $\tau = L/R$, which is usually lower than the power supply cycle $T = 1/f_O$.
- The DC/AC PWM inverters cannot be considered as only a proportional element. Since its output voltage is out of control once the pulse width is applied, it should be looked as a sample and linear-varying element.

- mathematical modeling in per-unit digital control system should be a first-order hold (FOH) in both *s*- and *z*-domains:

$$G(s) = \frac{1}{1 + Ts}$$

$$G(z) = \mathbb{Z}[G(s)] = \mathbb{Z}\left[\frac{1}{1 + Ts}\right] = \frac{z}{z - 1/e}$$

- where T is the sampling interval $T = 1/f_C$
- DC/AC PWM inverter performs a first-order inertial element with time constant T in the *s*-domain and a linear element in one step (T) in a digital control system in the *z*-domain.

- The transfer function has one zero and one pole $z = 1/e$ inside the unit-cycle.
- Therefore, a DC/AC inverter is always a stable element.

A SECOND-ORDER TRANSFER FUNCTION FOR DC/DC CONVERTERS

DC/DC converters have many forms which are listed below:

- fundamental converters such as buck, boost and buck–boost converters;
- voltage-lift converters;
- super-lift converters;
- transformer-type converters;

- The devices of all types of the DC/DC converters can be transistor, BT, GTO and MOSFET.
- They are controlled by the PWM pulse with certain conduction duty cycle *k*.
- In a sampling interval/period *T*, the conduction duty cycle *k* can be changed only once,
- The output voltage of a DC/DC converter is changed period by period.
- Therefore, all types of the DC/DC converters are working in a discrete state.

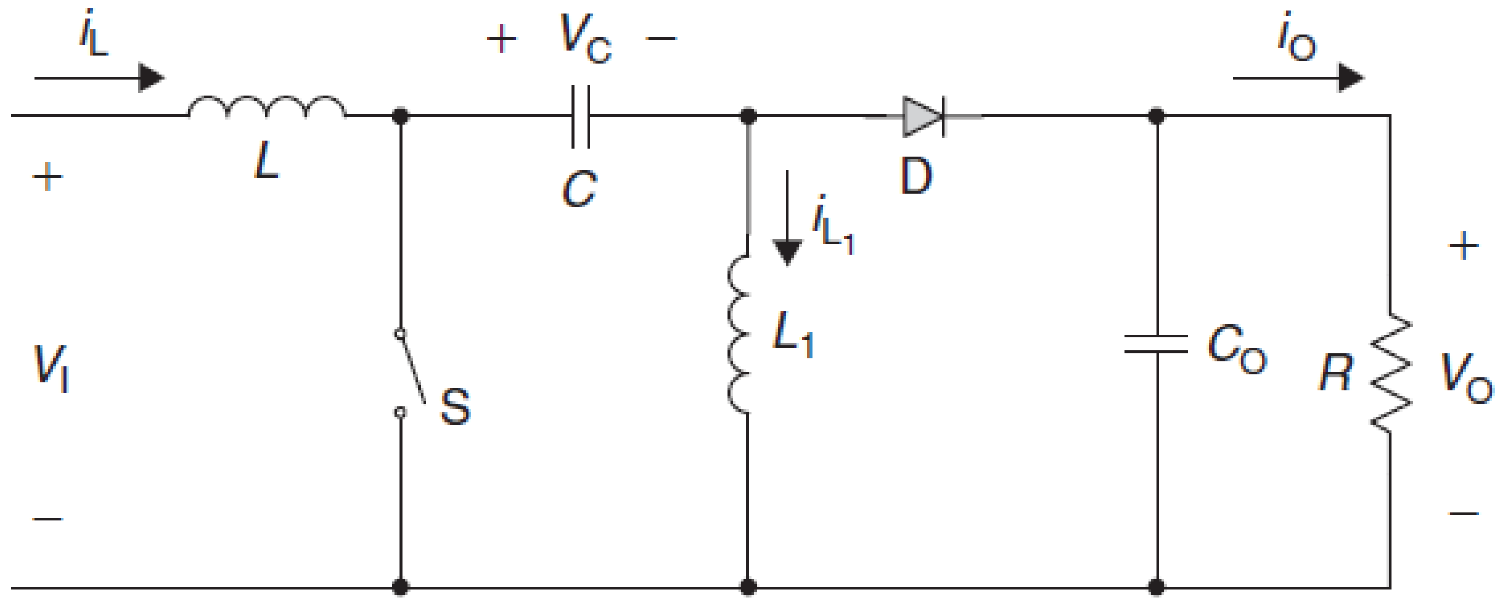
- the load of the power DC/DC converters is a resistive load *R*. If the output current is continuous, the output DC voltage average value in a steady state is:

$$V_O = MV_I$$

$$M = \frac{V_O}{V_I}$$

- where V_I and V_O are the input and output DC voltages, and *M* is the voltage transfer gain.
- If the switching frequency is *f* (the switching period $T = 1/f$) and the conduction duty cycle is *k*, the switching-on period is *kT* and switching-off period is $(1-k)T$.

- The voltage transfer gain M is usually dependent to the conduction duty cycle k, and independent from the switching frequency f .
- buck converter has the voltage transfer gain $M = k$,
- boost converter has the voltage transfer gain $M = 1/(1-k)$ and
- buck–boost converter has the voltage transfer gain $M = k/(1-k)$.



single-ended primary inductance converter (SEPIC)

- Refer to the single-ended primary inductance converter (SEPIC) shown, the inductor current i_{L1} increases with slope $+V_C/L_1$ on and decreases with slope $-V_O/L_1$ during switching off. Thus:

$$\frac{V_C}{L_1}kT = \frac{V_O}{L_1}(1-k)T$$

$$V_C = \frac{1-k}{k}V_O$$

- The inductor current iL increases with slope $+V_I/L$ during switching on and decreases with slope $-(V_C + V_O - V_I)/L$ during switching off. Thus:

$$\frac{V_I}{L}kT = \frac{V_C + V_O - V_I}{L}(1-k)T$$

$$V_O = \frac{k}{1-k} V_I$$

$$M = \frac{V_O}{V_I} = \frac{k}{1-k}$$

- Since the inductor L is in series connected to the source voltage, the inductor average current I_L is:

$$I_L = I_I$$

- Since the inductor L_1 is in parallel connected to the capacitor C during switching off, the inductor average current I_{L1} is ($I_{CO\text{-}on} = I_O$ and $I_{CO\text{-}off} = I_I$):

$$I_{L_1} = I_O$$

- The variation of the current i_L is:

$$\Delta i_{\mathrm{L}} = \frac{V_{\mathrm{I}}}{L} kT$$

- Therefore, the variation ratio of the current i_L is:

$$\xi = \frac{\Delta i_{\mathrm{L}}/2}{I_{\mathrm{L}}} = \frac{V_{\mathrm{I}}}{2I_{\mathrm{I}}L} kT = \frac{k}{2M^2}\frac{R}{fL}$$

- The variation of the current i_{L1} is:

$$\Delta i_{\mathrm{L}_1} = \frac{V_{\mathrm{C}}}{L_1} kT$$

- Therefore, the variation ratio of the current i_{L1} is:

$$\xi_1 = \frac{\Delta i_{\mathrm{L}_1}/2}{I_{\mathrm{L}_1}} = \frac{V_{\mathrm{C}}}{2I_{\mathrm{O}}L_1} kT = \frac{1-k}{2}\frac{R}{fL_1}$$

- The output voltage is out of control in a period *T* once the duty cycle *k* is applied. Therefore, it is the element to keep the output voltage in a period $T = 1/f$.
- By per-unit system, the voltage transfer gain is unity (1) in a sampling interval.
- a power DC/DC converter is a second-order element, and its transfer function is:

$$G(s) = \frac{V_O}{V_I}\Big|_{\text{per-unit}} = \frac{1}{1 + s\tau + s^2\tau\tau_d}$$

- where τ is the time constant and τd is the damping time constant.

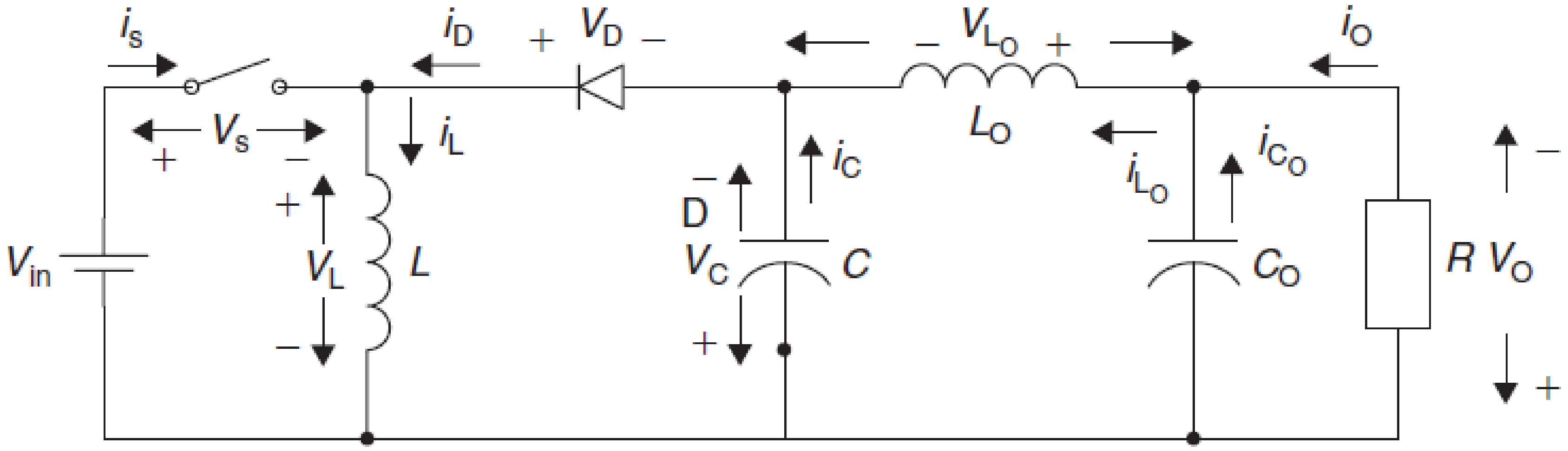
Traditional Modeling for DC/DC Converters

- Traditional modeling for DC/DC converters is a complex element in the *s*-domain.
- the transfer function with the orders is equal to the number of the passive energy-storage parts: inductors and capacitors.
- The simplest fundamental converters, such as buck, boost and buck–boost converters which have one inductor and one capacitor, possess a second-order transfer function.
- Other converters with multiple inductors and capacitors must have high-order transfer function.

- a buck converter has the transfer function as:

$$G(s) = \frac{M}{1 + s\frac{L}{R} + s^2 LC} = \frac{M}{1 + s\tau + s^2 \tau\tau_d}$$

- where *M* is the voltage transfer gain, *τ* is the time constant *L*/*R* and *τ*d is the damping time constant *RC*.
- For the DC/DC converters with two inductors plus two capacitors, their transfer function is in the fourth order.
- For example, the negative output Luo-converter elementary circuit shown in Figure has the transfer function:



Elementary circuit of N/O Luo-converter

$$G(s) = \frac{M}{1 + s\frac{L_1+L_2}{R} + s^2(L_1C_1 + L_1C_2 + L_2C_2) + s^3\frac{L_1L_2C_1}{R} + s^4L_1L_2C_1C_2}$$

A Second-Order Hold for DC/DC Converters in Digital Control

- the mathematical modeling in per-unit digital control system should be a second-order transfer function in the *s*-domain:

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d}$$

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d} = \frac{1}{(s + s_1)(s + s_2)}$$

$$s_1 = \sigma + j\omega \quad \text{and} \quad s_2 = \sigma - j\omega$$

- Correspondingly, a power DC/DC converter is a second-order hold (SOH) in the *z*-domain:

$$G(z) = \mathbb{Z}[G(s)] = \mathbb{Z}\left[\frac{1}{(s+s_1)(s+s_2)}\right] = \frac{1}{s_1 - s_2}\left(\frac{z}{z - e^{-Ts_2}} - \frac{z}{z - e^{-Ts_1}}\right)$$

- It means that the DC/DC converter performs a second-order response with oscillation in the *s*-domain and one-step delay (*T*) in a digital control system.

A FIRST-ORDER TRANSFER FUNCTION FORAC/AC (AC/DC/AC) CONVERTERS

AC/AC (AC/DC/AC) converters have many forms which are listed below:

- single phase-input single phase-output (SISO) amplitude modulated AC/AC converter,
- multiphase-input multiphase-output (MIMO) amplitude modulated AC/AC converter,
- SISO cycloconverter,
- MIMO cycloconverter,
- matrix AC/AC converter,
- AC/DC/AC converters,
- PWM converters.

- The devices of all types of the AC/DC converters can be thyristor (SRC), transistor, GTO and Triac.
- They are controlled by the corresponding firing pulse with certain firing angle α or the PWM scheme with the certain carrier (chopping) frequency fc.
- In a sampling interval T =1/fc, the pulse-width angle can be changed only once, i.e. the output voltage of a DC/AC PWM inverter is changed period by period.
- Therefore, all types of the AC/AC PWM inverters are working in discrete state.

- The input reference signal *v*in(*t*) is a sinusoidal waveform:

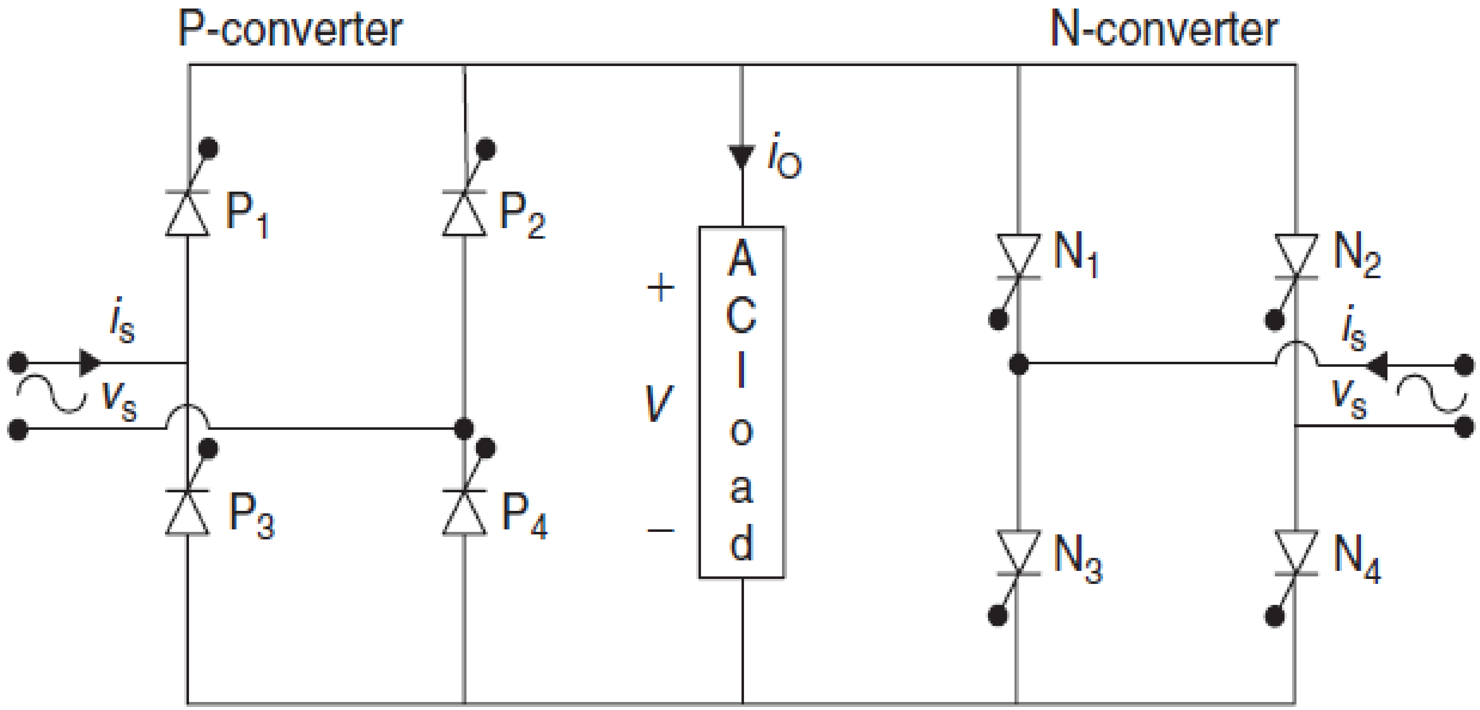
$$v_{\text{in}}(t) = V_{\text{m}} \sin \omega t$$

- The load of the inverters is an *L–R* circuit with time constant *τ* =*L/R*, or the delayed angle is:

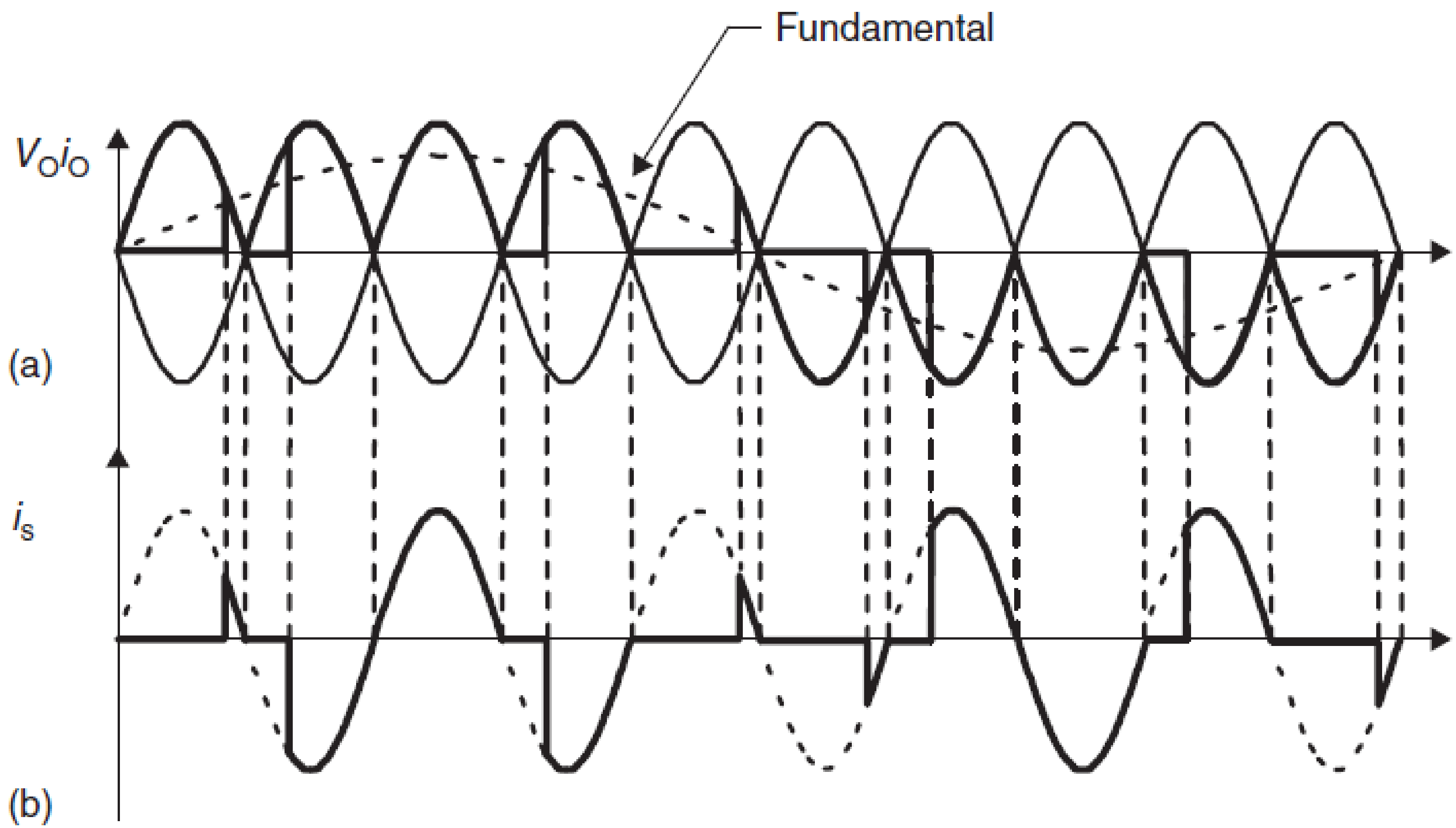
$$\phi = \tan^{-1} \frac{\omega L}{R}$$

- If the output current is continuous, the outputAC voltage instantaneous value after the filter should be:

$$v_{\text{O}}(t) = V_{\text{m}} \sin(\omega t - \phi)$$



An SISO AC/AC cycloconverter.



Waveforms of an SISO AC/AC cycloconverter (50–10 Hz) with *R* load. (a) Load voltage and load current; and (b) input supply current

- Refer to the SISOAC/ACcycloconverter shown in Figure .
- The source AC voltage with frequency f_S is a sinusoidal waveform, and the output voltage should follow the input reference voltage with frequency f .
- The corresponding input and output voltage and current waveforms are shown in Figure.
- If the input reference AC voltage signal with the frequency f =10 Hz (T =1/f =100 ms), each bridge is conducted in a conduction period=T/2=50 ms.

- The output voltage is out of control in a half-chopping cycle once the PWM pulse is applied.
- Therefore, it is the element to keep the output voltage in a period of $T_S/2=1/2f_S$.
- By per-unit system, the voltage transfer gain is a linear element in a sampling interval $T_S/2=10$ ms. That is,

$$G(t) = \frac{V_O}{V_{in}}|_{\text{per-unit}} = 1 - e^{-t/\tau}$$

- Analogously, different chopping frequency only changes the sampling interval. The mathematical modeling is not changed.

Traditional Modeling for AC/DC Controlled Rectifiers

- Traditional modeling for AC/AC converters is a first-order element in the *s*-domain.
- A low-pass filter must be set to filter the higher-order harmonics in order to obtain pure output sinusoidal waveform.
- The low-pass filter is usually an *R*–*C* circuit with the time constant $\tau = RC$ or an *R*–*L* circuit with the time constant $\tau = L/R$.
- The time constant τ is much larger than the pulse width ($\tau >> T = 1/f_C$) to avoid the parasitic power losses and additional distortion.

- Transfer function of rectifier in per-unit system is:

$$G(s) = \frac{1}{1 + \tau s}$$

- The first-order transfer function is the feature of the first-order filter, but the characteristics of the AC/AC PWM inverters.
- The transfer function of the AC/AC PWM inverters is ignored. It is treated as a proportional element.
- The traditional mathematical modeling is not really used to describe the AC/AC PWM inverters

A FOH for AC/AC Converters in Digital Control

- The AC/AC converters cannot be considered only as a proportional element. Since its output voltage is out of control once the pulse width is applied,
- It should be looked as a sample and linear-varying element.
- Its mathematical modeling in per-unit digital control system should be a FOH in both the *s*- and *z*-domains:

$$G(s) = \frac{1}{1 + Ts}$$

$$G(z) = \mathbb{Z}[G(s)] = \mathbb{Z}\left[\frac{1}{1 + Ts}\right] = \frac{z/T}{z - 1/e}$$

where *T* is the sampling interval $T = 1/f_C$.

- It means that the DC/AC PWM inverter performs a first-order inertial element with time constant *T* in the *s*-domain
- and a linear rising/falling element in one step (*T*) in a digital control system.

Unit-II

Digitally Controlled AC/DC Rectifiers

- In this Chapter we assume that the input voltage is a sinusoidal wave with the frequency f =50 Hz. The transformer is used in the rectifiers with the following turn's ratio: 1:1 for Y/Y connection,
- √3 : 1 for Delta/Star connection,
- 1 : √3 for Star/Delta connection
- and 1:1 (or using √3 :√3) for Delta/Delta connection in convenient analysis.
- The parameters used to describe the characteristics are listed below:

- **v(t): instantaneous phase voltage:**

$$\mathbf{v(t) = \sqrt{2} V_{rms} \sin(\omega t)}$$

- V_{rms}: root-mean-square (rms) voltage
- Vm: maximum (amplitude) voltage:

$$V_m = \sqrt{2} V_{rms}$$

- V_O: average output voltage
- *FF*: form factor (*FF*):

$$FF = \frac{V_{rms}}{V_d}$$

- **RF: ripple factor (RF):**

$$RF = \frac{\sqrt{\sum_{n=1}^{\infty} V_n}}{V_\mathrm{d}} \approx FF - 1$$

- V_d: zeroth-order (DC) voltage component
- V_1: first-order (fundamental) harmonic voltage
- *Vn*: *n*th-order harmonic voltage
- *PF*: power factor (*PF*):

$$PF = \cos\phi = \frac{P}{S}$$

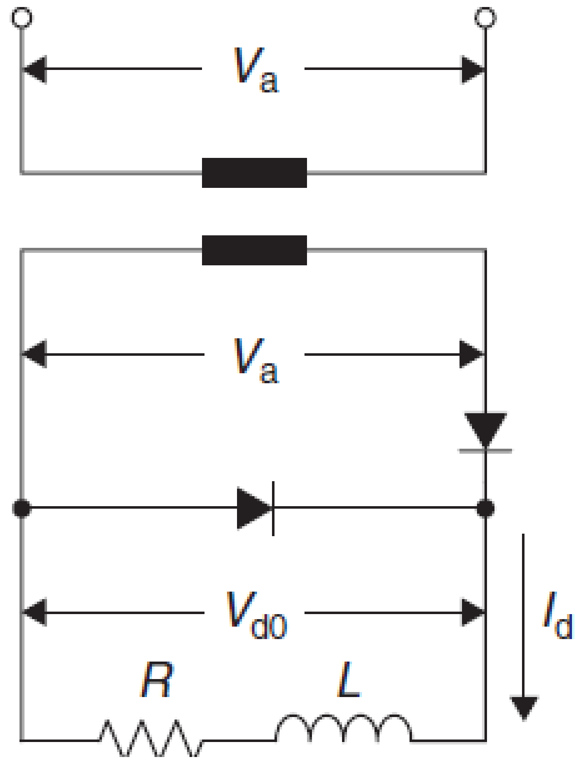
- *P*: real power
- *Q*: reactive power
- *S*: apparent power:
- **THD: total harmonic distortion (THD):**

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n}}{V_1}$$

- **The generally used AC/DC diode rectifiers are introduced below:**
- **1. Single-phase half-wave rectifiers**
- **2. Single-phase full-wave rectifiers**
- **3. Three-phase half-wave rectifiers**
- **4. Three-phase full-wave rectifiers**

Single-Phase Half-Wave Diode Rectifier

- **The simplestAC/DC diode rectifier is the single-phase half-wave diode rectifier shown in Figure**
- **The only diode is conducted in the duration of 180◦ (or π rad) a cycle.**
- **Since the load is an R–L circuit with freewheel diode, the output voltage average value is:**



Single-phase half-wave diode rectifier with *L*–*R* load.

$$V_O = \frac{1}{2\pi}\int_0^{2\pi} V_m \sin(\omega t)\, d(\omega t) = \frac{\sqrt{2}V_{rms}}{2\pi}\int_0^{\pi} \sin(\omega t)\, d(\omega t) = \frac{\sqrt{2}}{\pi}V_{rms} = 0.45V_{rms}$$

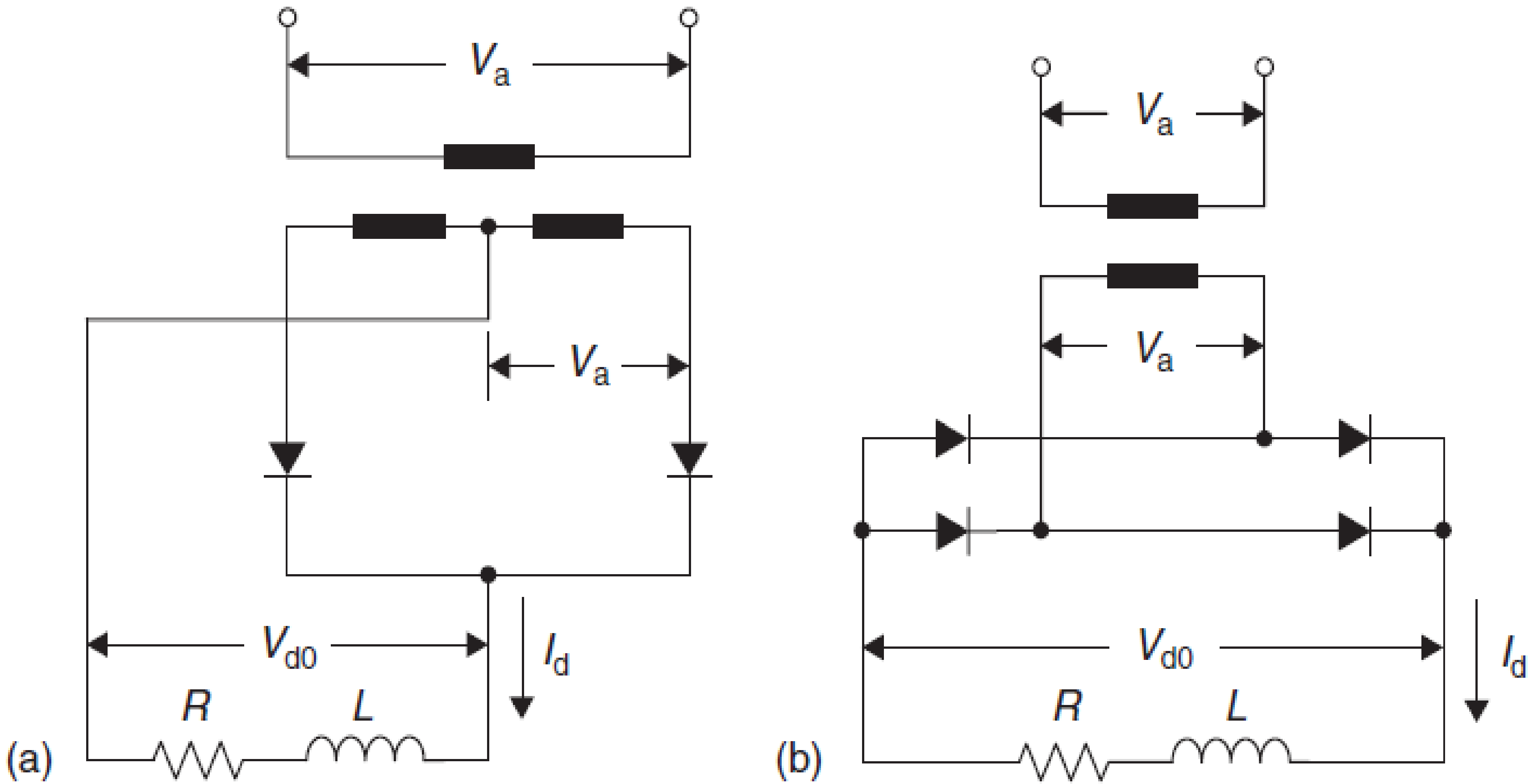
$$FF = \frac{\pi}{2} = 1.57$$

$$RF = 0.57$$

$$PF = \frac{1}{\sqrt{2}} = 0.707$$

Single-Phase Full-Wave Diode Rectifier

- The single-phase full-wave diode rectifier has two configurations.
- The first circuit is called *center-tap* (*midpoint*) *circuit* shown in Figure (a) consisting of two diodes,
- and the second circuit is called *bridge* (*Graetz*) *circuit* shown in Figure (b) consisting of four diodes. Each diode is conducted in a cycle in 180◦.



Single-phase full-wave diode rectifier with *L–R* load. (a) Center-tap (midpoint) circuit and (b) bridge (Graetz) circuit.

- Since the load is an *R–L* circuit, the output voltage average value is:

$$V_O = \frac{1}{2\pi}\int_0^{2\pi} V_m \sin(\omega t)\,d(\omega t) = \frac{2\sqrt{2}}{\pi}V_{rms} = 0.9V_{rms}$$

$$FF = \frac{\pi}{2\sqrt{2}} = 1.11$$

$$RF = 0.11$$

- **The power factor (PF) of the center-tap (midpoint) circuit shown in Figure (a) is:**

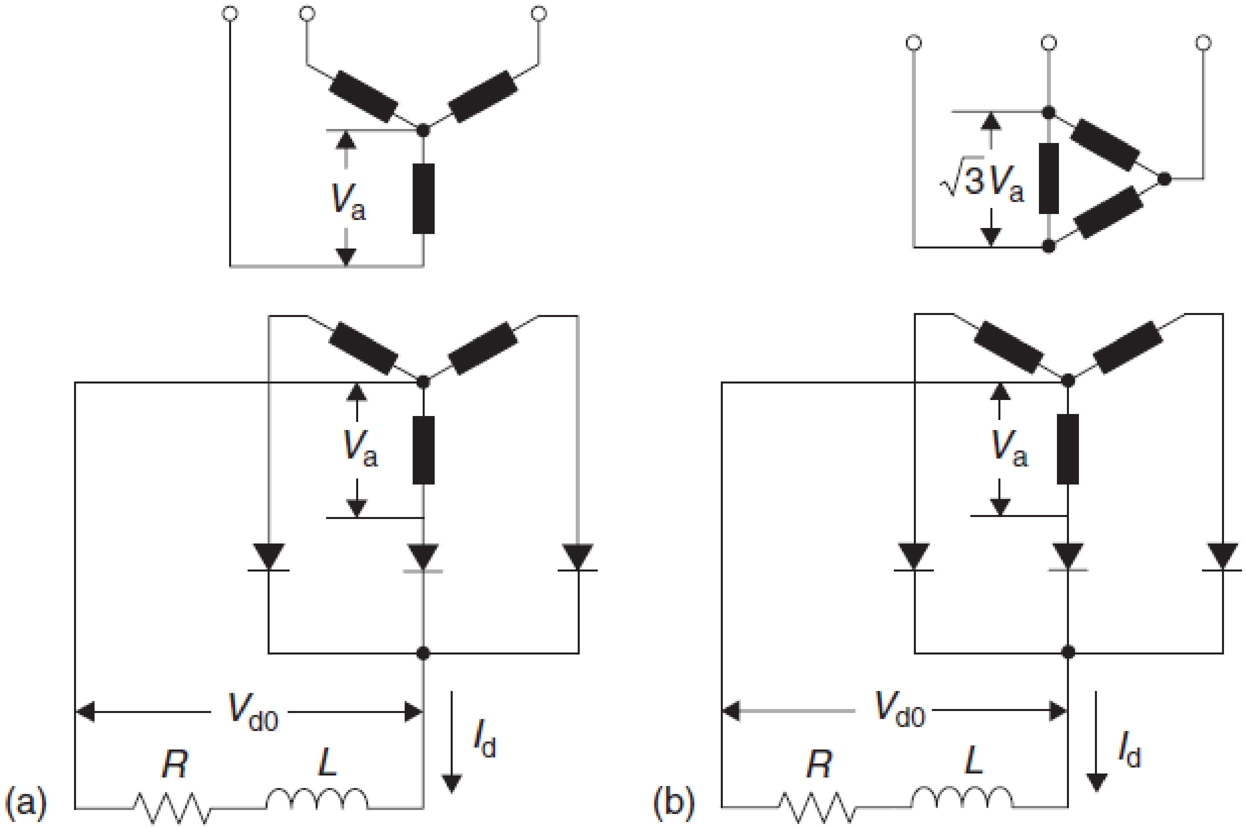
$$PF = \frac{1}{\sqrt{2}} = 0.707$$

- The power factor of the bridge (Graetz) circuit shown in Figure (b) is:

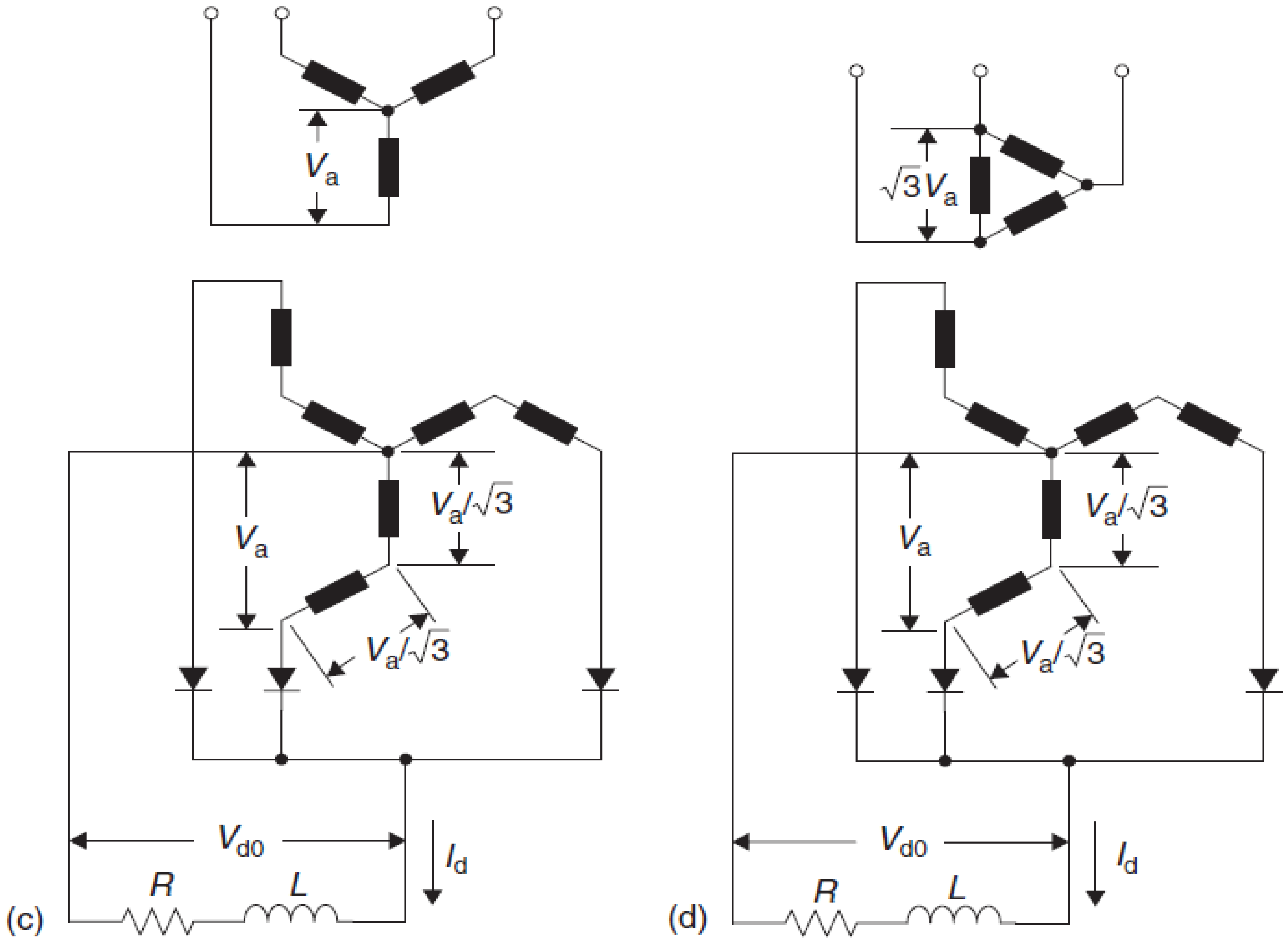
$$PF = 1$$

Three-Phase Half-Wave Diode Rectifier

- The three-phase half-wave diode rectifier shown in Figure has four configurations, all consisting of three diodes.



Three-phase half-wave diode rectifier. (a) Y/Y circuit, (b) Delta/Star circuit



(c) Y/Y bending circuit and (d) Delta/Star bending circuit.

- **Each diode is conducted in 120◦-cycle. Since the load is an R–L circuit, the output voltage average value is:**

$$V_O = \frac{1}{2\pi/3} \int_{\pi/6}^{5\pi/6} V_m \sin(\omega t)\, d(\omega t) = \frac{3\sqrt{6}}{2\pi} V_{rms} = 1.17 V_{rms}$$

$$FF = 1.01615$$

$$RF = 0.01615$$

$$PF = 0.686$$

Three-Phase Full-Wave Diode Rectifier

- Each diode is conducted in a cycle in 120◦. Since the load is an *R–L* circuit, the output voltage average value is:

$$V_O = \frac{2}{2\pi/3} \int_{\pi/6}^{5\pi/6} V_m \sin(\omega t)\, d(\omega t) = \frac{3\sqrt{6}}{\pi} V_{rms} = 2.34 V_{rms}$$

$$FF = 1.00088$$

$$RF = 0.00088$$

$$PF = 0.956$$

MATHEMATICAL MODELING FORAC/DC RECTIFIERS

- The output voltage of the controlled AC/DC rectifiers relies on the firing angle α of the firing pulse.
- When the firing angle $\alpha=0$, we obtain the maximum output voltage of all controlled AC/DC rectifiers, which are equal to those of the diode AC/DC rectifiers.
- In general condition the load is an R–L circuit with the time constant $\tau = L/R$, which is usually larger than the sampling interval T.

- The output current is continuous and the output average voltage is generally equal to:

$$V_{\mathrm{d}} = V_{\mathrm{d\text{-}max}} \cos \alpha$$

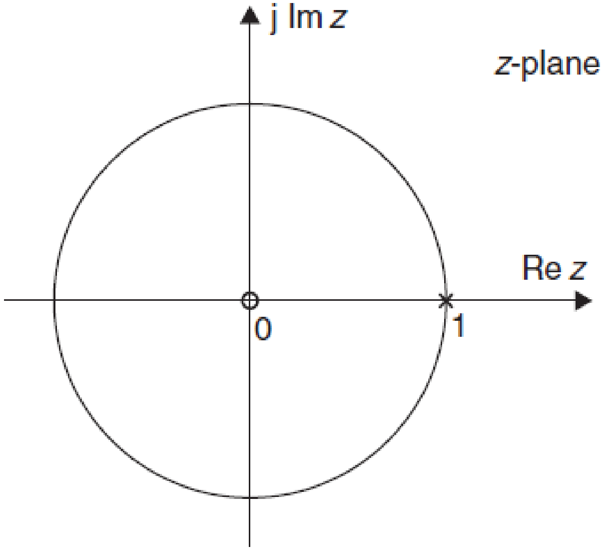
- where V_d is the output average voltage and $V_{d\text{-}max}$ is the maximum output DC voltage corresponding to the firing angle $\alpha=0$.
- By per-unit system the voltage transfer gain is unity. The transfer function in the time domain is a constant value (unit-step function) $u(t)$, and it has the following form in the s-domain:

$$G(s) = \frac{1}{s}$$

- In digital control system, all AC/DC rectifiers are treated as a ZOH, which has the transfer function:

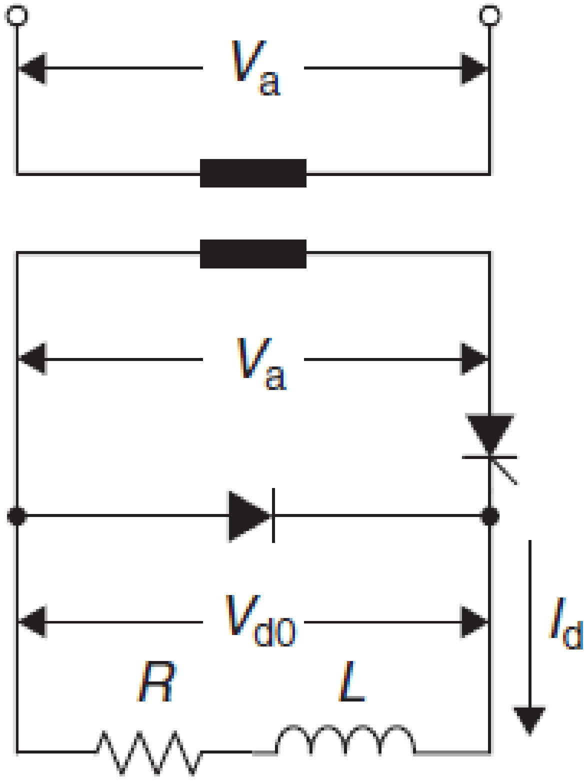
$$G(z) = \frac{z}{z-1}$$

- The rectifier is the element that possesses one zero at $z = 0$ and one pole at $z = 1$, which is located on the unit-cycle. The zero and pole in the z-plane are shown in Figure. Therefore, a rectifier is a critical stable element.

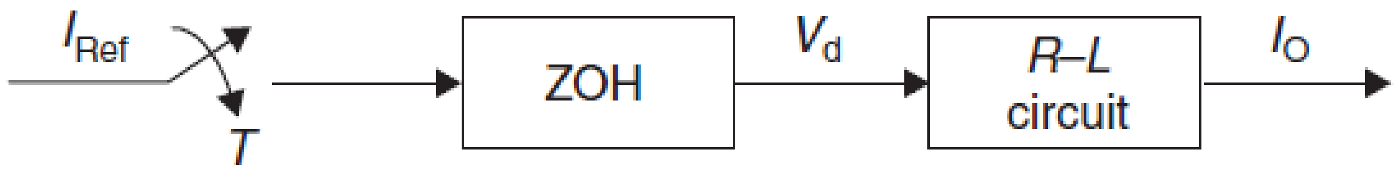


The zero and pole in the z-plane.

SINGLE-PHASE HALF-WAVE CONTROLLED AC/DC RECTIFIER

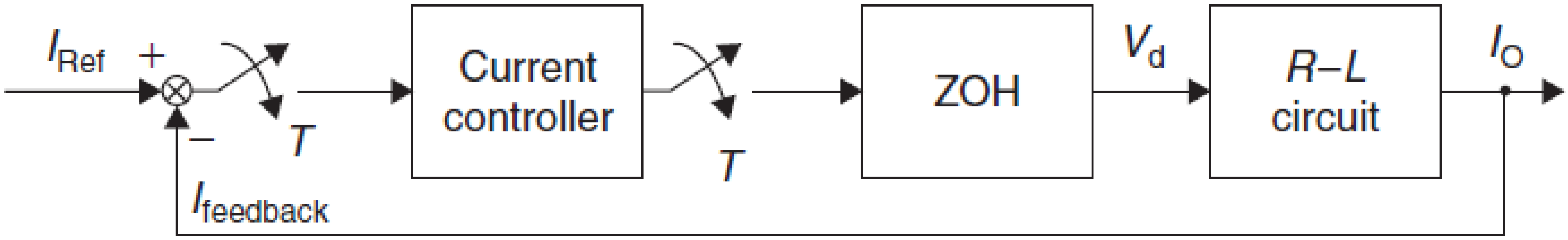


- The load is an *R–L* circuit with a freewheeling diode. The SCR is conducted in the period from α to π, i.e. the conduction angle is $\pi - \alpha$.



Open-loop control block diagram.

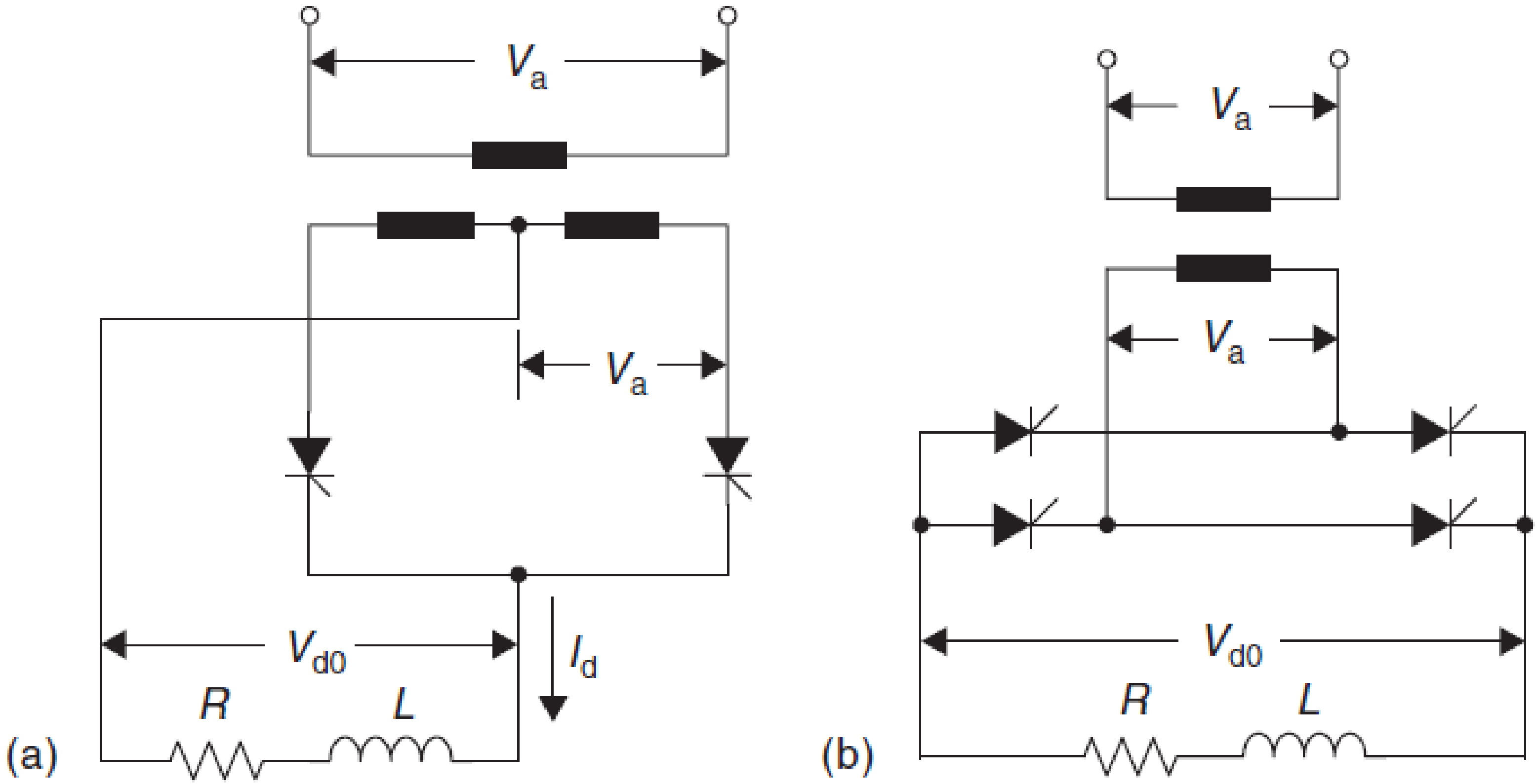
- The sampling interval is $T = 1/f$,
- If f =50 Hz, then T =20 ms.
- This control can be implemented by a digital computer, which offers a firing pulse a cycle in 20 ms.
- The actuator is usually an *R–L* load. The final output parameter is the current I_O shown in Figure



Closed-loop control block diagram

- The closed-loop control block diagram is shown in Figure
- The sampling interval is $T = 1/f$.
- A current controller is always requested in a closed-loop control system. It can be a PI controller in digital form.
- This control can be implemented by a digital computer, which offers a firing pulse a cycle in 20 ms.

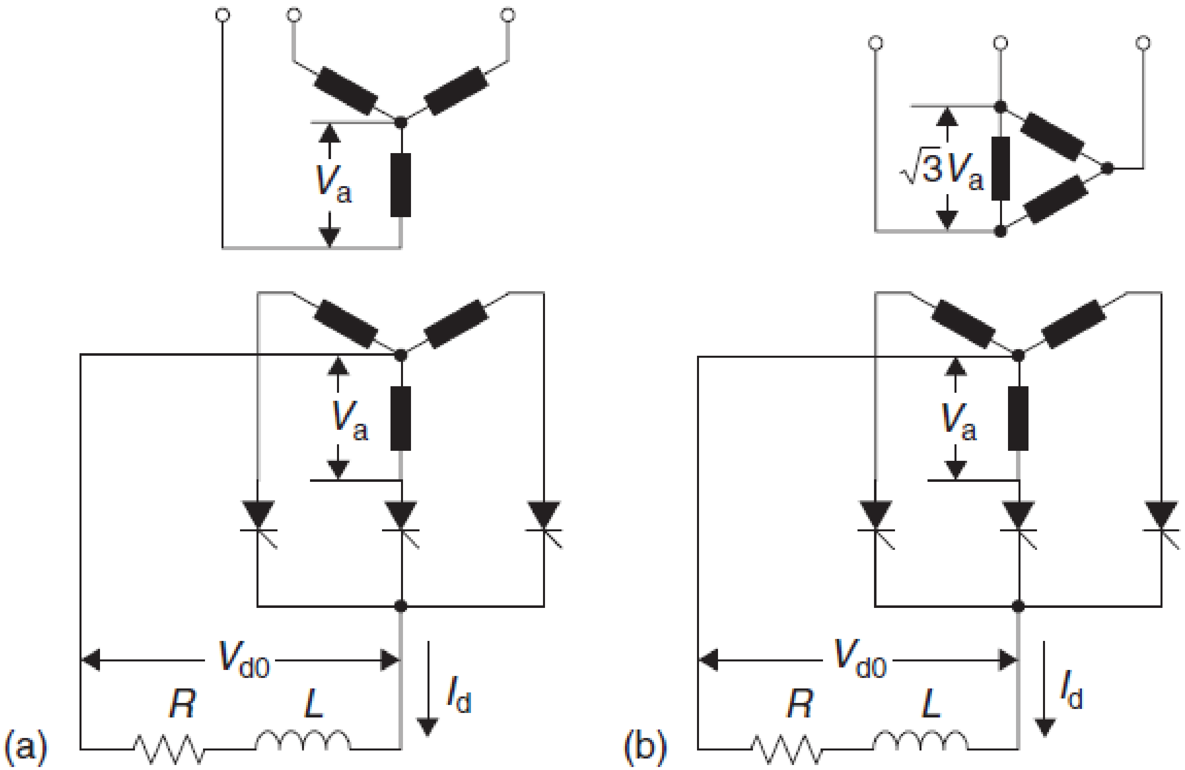
SINGLE-PHASE FULL-WAVEAC/DC RECTIFIER



Single-phase full-wave controlled AC/DC rectifier with *L*–*R* load. (a) Center-tap circuit and (b) bridge circuit.

- Each SCR is conducted from α to $(\pi+\alpha)$.
- The sampling interval is $T = 1/2f$, where f is the AC power supply source frequency.
- If $f = 50$ Hz, then $T = 10$ ms
- The open-loop and closed loop control block diagrams are shown in the previous slides

THREE-PHASE HALF-WAVE CONTROLLED AC/DC RECTIFIER

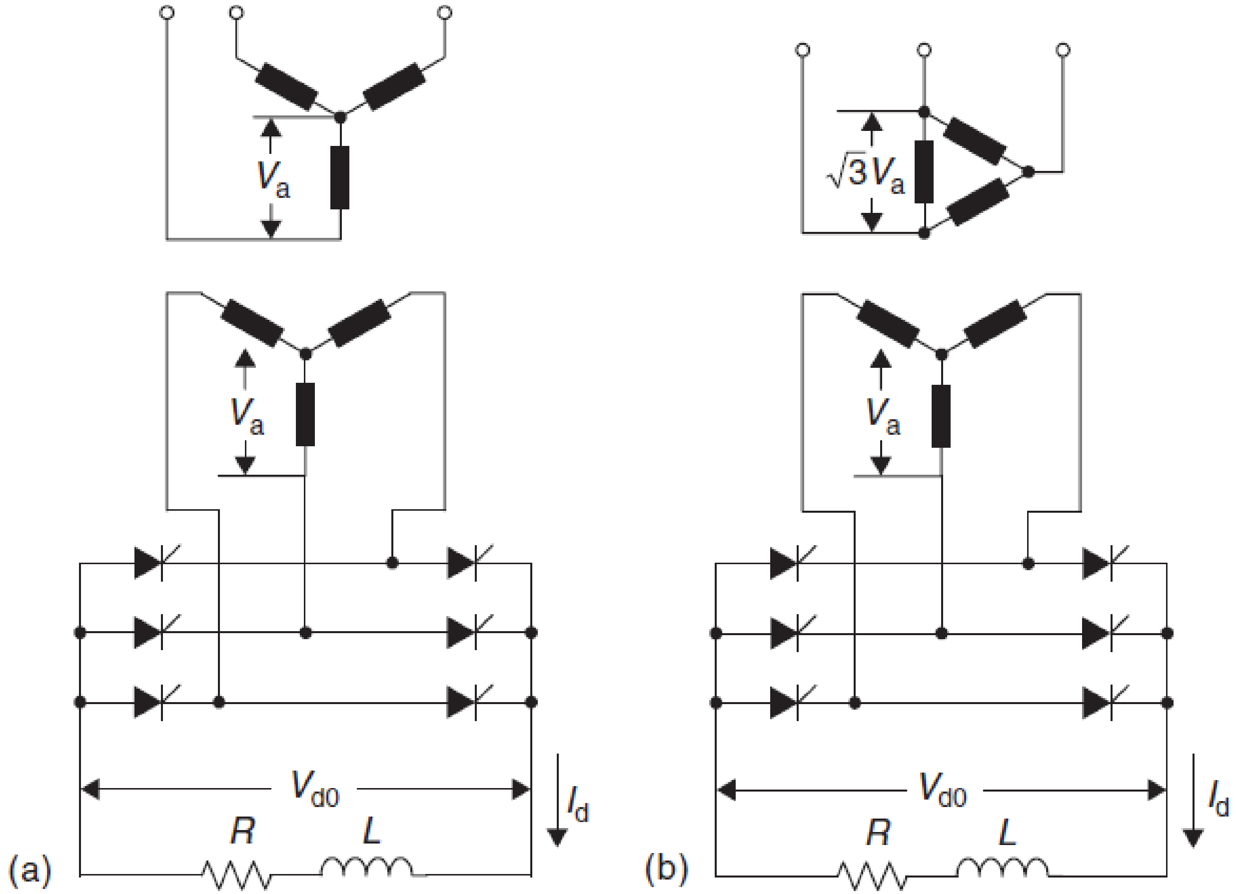


Thee-phase half-wave controlledAC/DC rectifier. (a)Y/Y circuit, (b) Delta/Y circuit

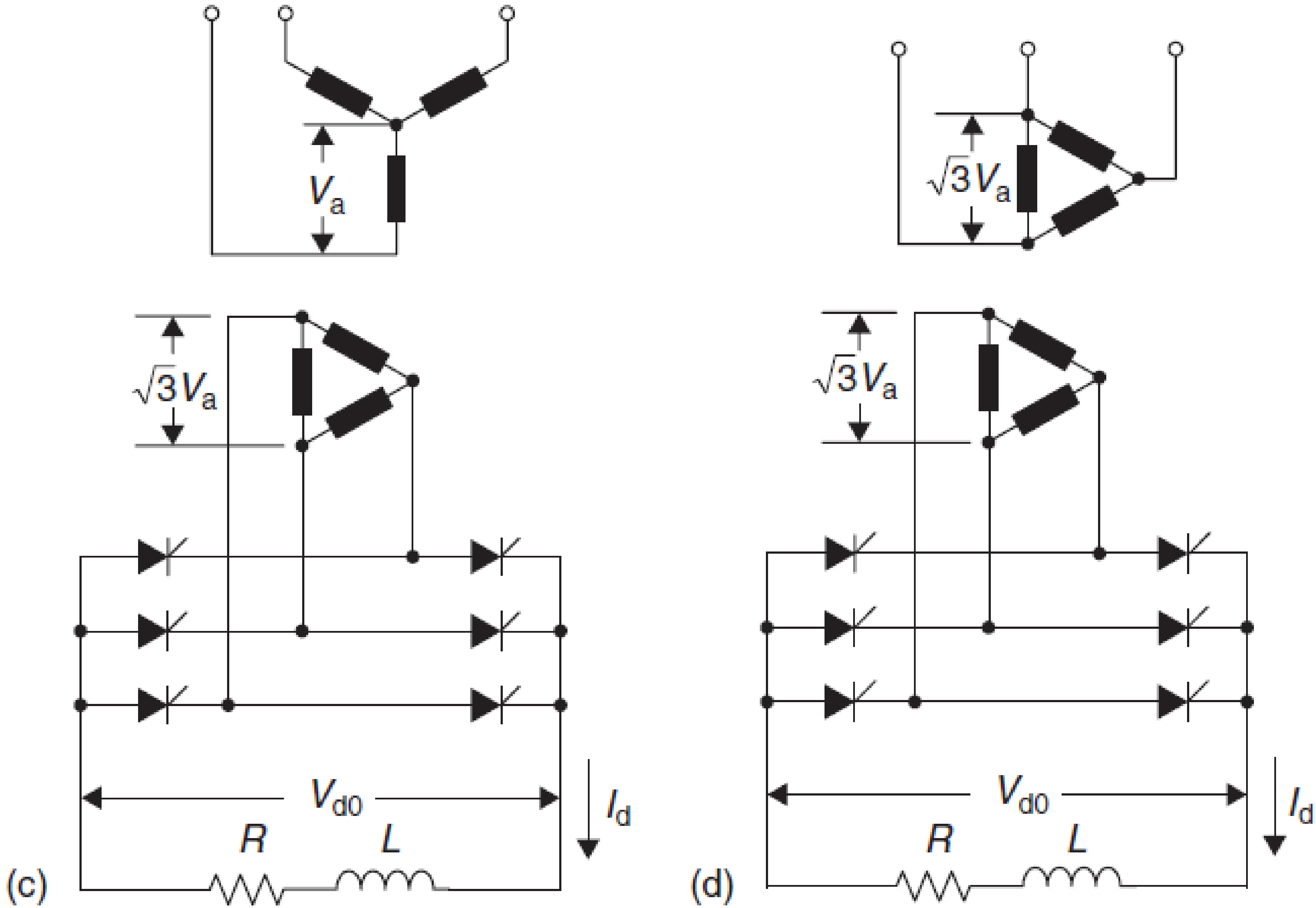
- The load is an *R*–*L* circuit with continuous load current.
- Each SCR is conducted from α to $(2\pi/3+\alpha)$.
- The open-loop control block diagram is still shown in previous slide
- The sampling interval is $T = 1/3f$,
- If $f = 50$ Hz, then $T = 6.67$ ms.
- This control can be implemented by a digital computer, which offers a firing pulse to each SCR a cycle in 20 ms.
- The actuator is usually an *R*–*L* load.
- The final output parameter is the current I_O shown in Figure

- The closed-loop control block diagram is shown in earlier slides.
- The sampling interval is $T = 1/3f$
- If $f = 50$ Hz, then $T = 6.67$ ms.
- This control can be implemented by a digital computer, which offers a firing pulse to each SCR a cycle in 20 ms.
- The actuator is usually an R–L load.
- The final output parameter is the current I_O shown in Figure

THREE-PHASE FULL-WAVE CONTROLLED AC/DC RECTIFIER



Three-phase full-wave controlledAC/DC rectifier. (a)Y/Y circuit. (b)Delta/Y circuit



Three-phase full-wave controlledAC/DC rectifier(c) Y/Delta circuit and (d) Delta/Delta circuit

- The load is an *R–L* circuit with continuous load current.
- Each SCR is conducted from α to $(2\pi/3+\alpha)$
- The open-loop control block diagram is shown in Previous slides
- The sampling interval is $T=1/3f$
- If $f=50$ Hz, then $T=6.67$ ms
- This control can be implemented by a digital computer, which offers a firing pulse to each SCR a cycle in 20 ms.
- The actuator is usually an *R–L* load
- The final output parameter is the current I_O shown in Figure

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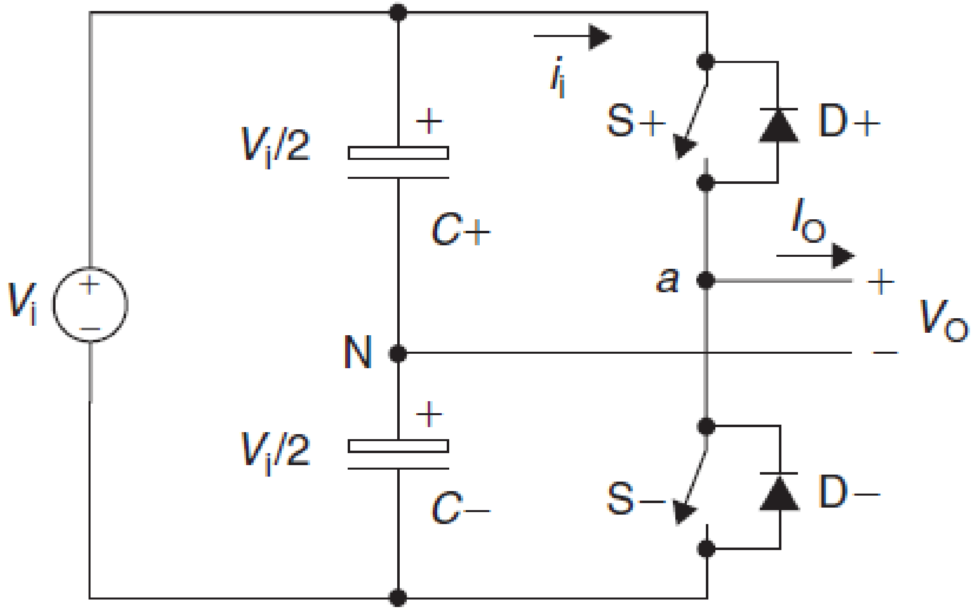
- The actuator is usually an R–L load.
- The final output parameter is the current I_O

Digitally Controlled DC/AC Inverters

The generally used DC/AC inverters are introduced below:

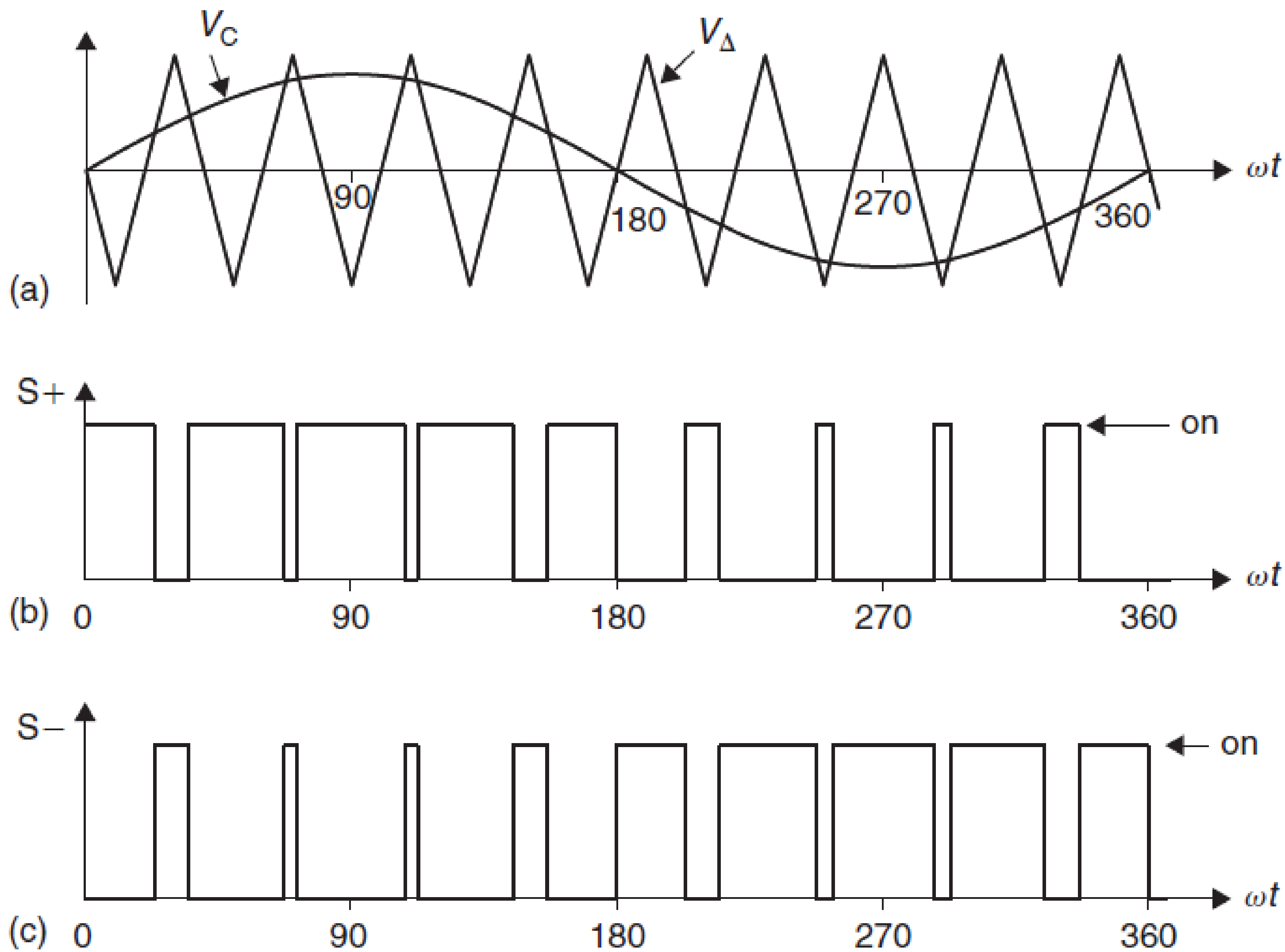
- Single-phase half-bridge voltage source inverter (VSI)
- Single-phase full-bridge VSI
- Three-phase full-bridge VSI
- Three-phase full-bridge current source inverter (CSI)
- Multistage PWM inverters
- Multilevel PWM inverters
- Soft-switching inverters

Single-Phase Half-Bridge VSI

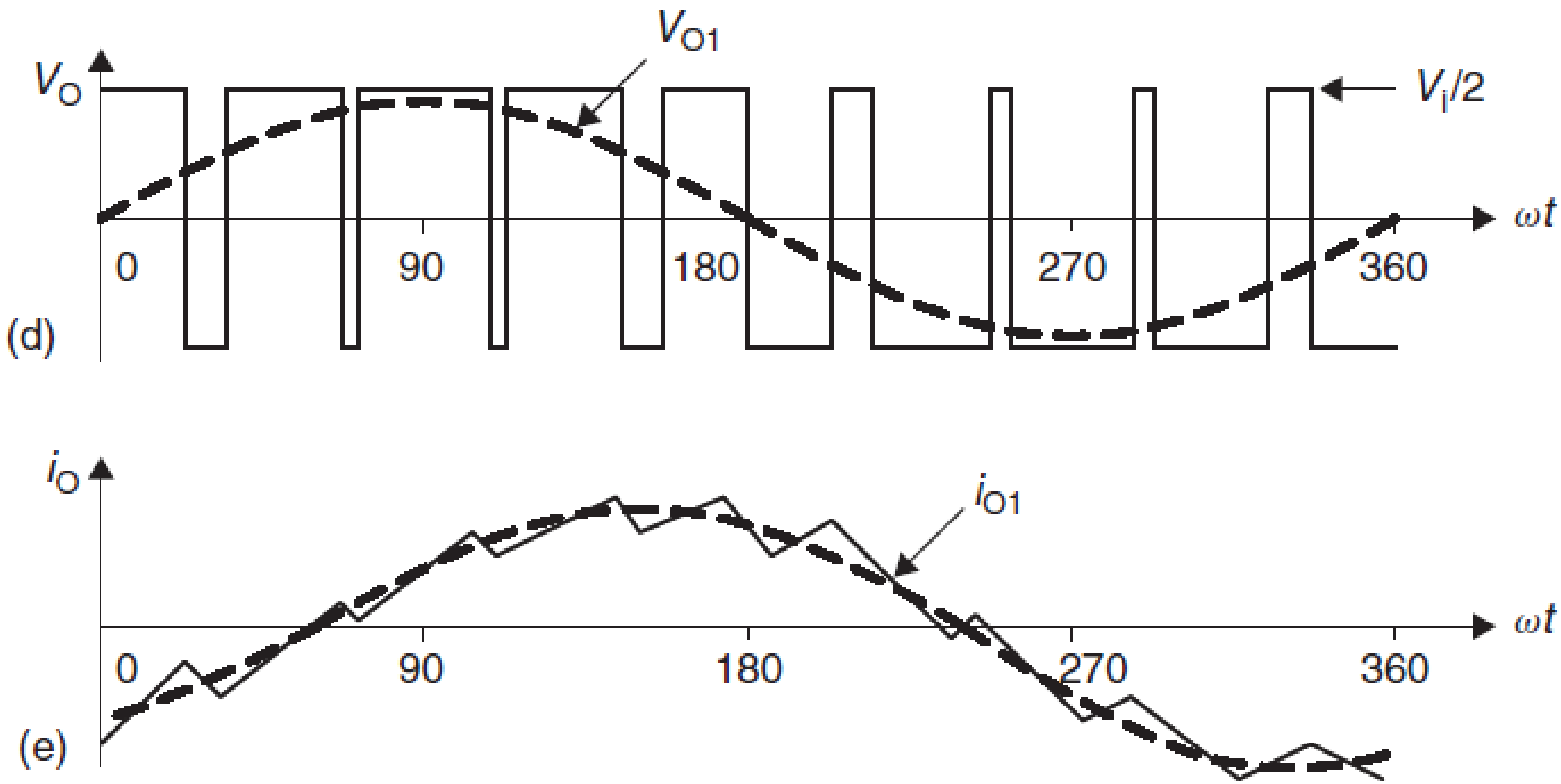


Single-phase half-bridge VSI

- The carrier-based PWM technique is applied in this single-phase half-bridge VSI.
- Two large capacitors are required to provide a neutral point N, therefore, each capacitor keep the half of the input DC voltage.
- Two switches S+ and S− are switched by the PWM signal.

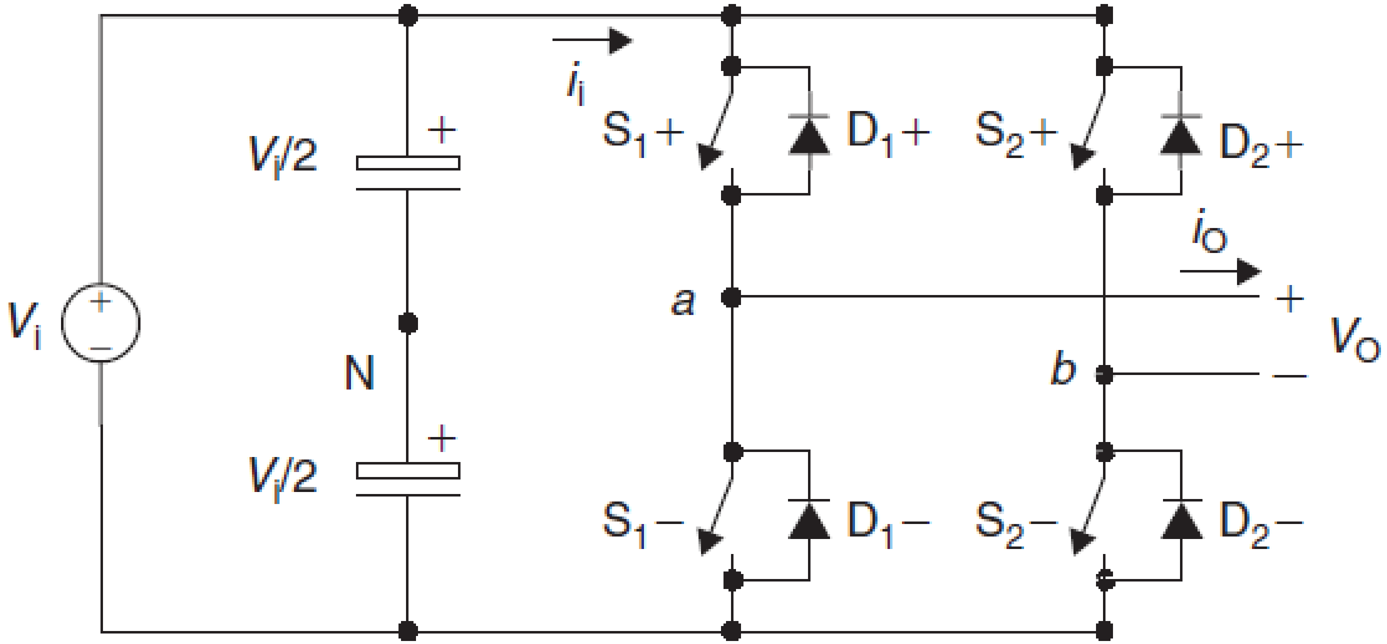


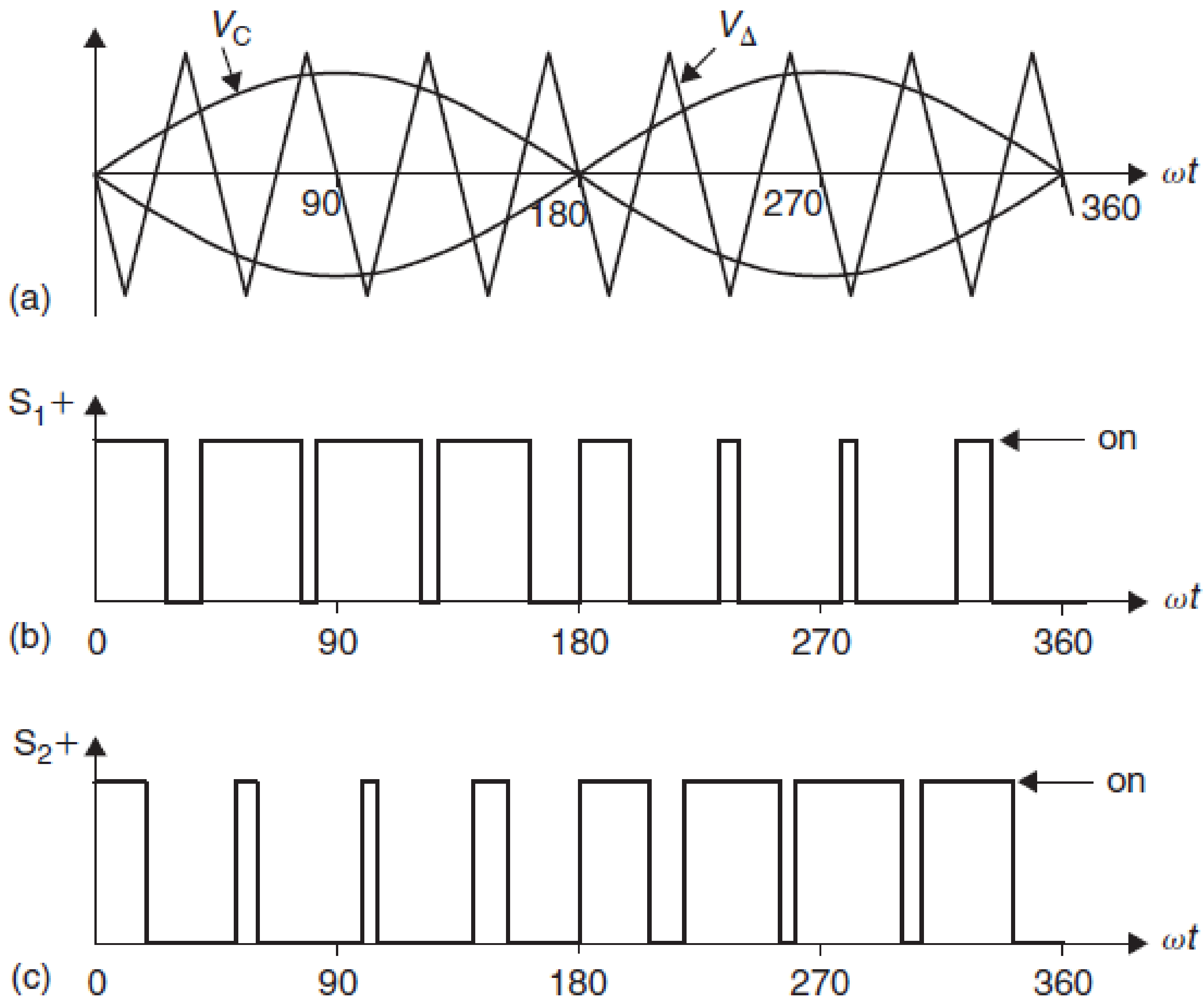
V_C
V_Δ
ωt
90
180
270
360
(a)
S+
on
ωt
(b)
0
90
180
270
360
S−
on
ωt
(c)
0
90
180
270
360



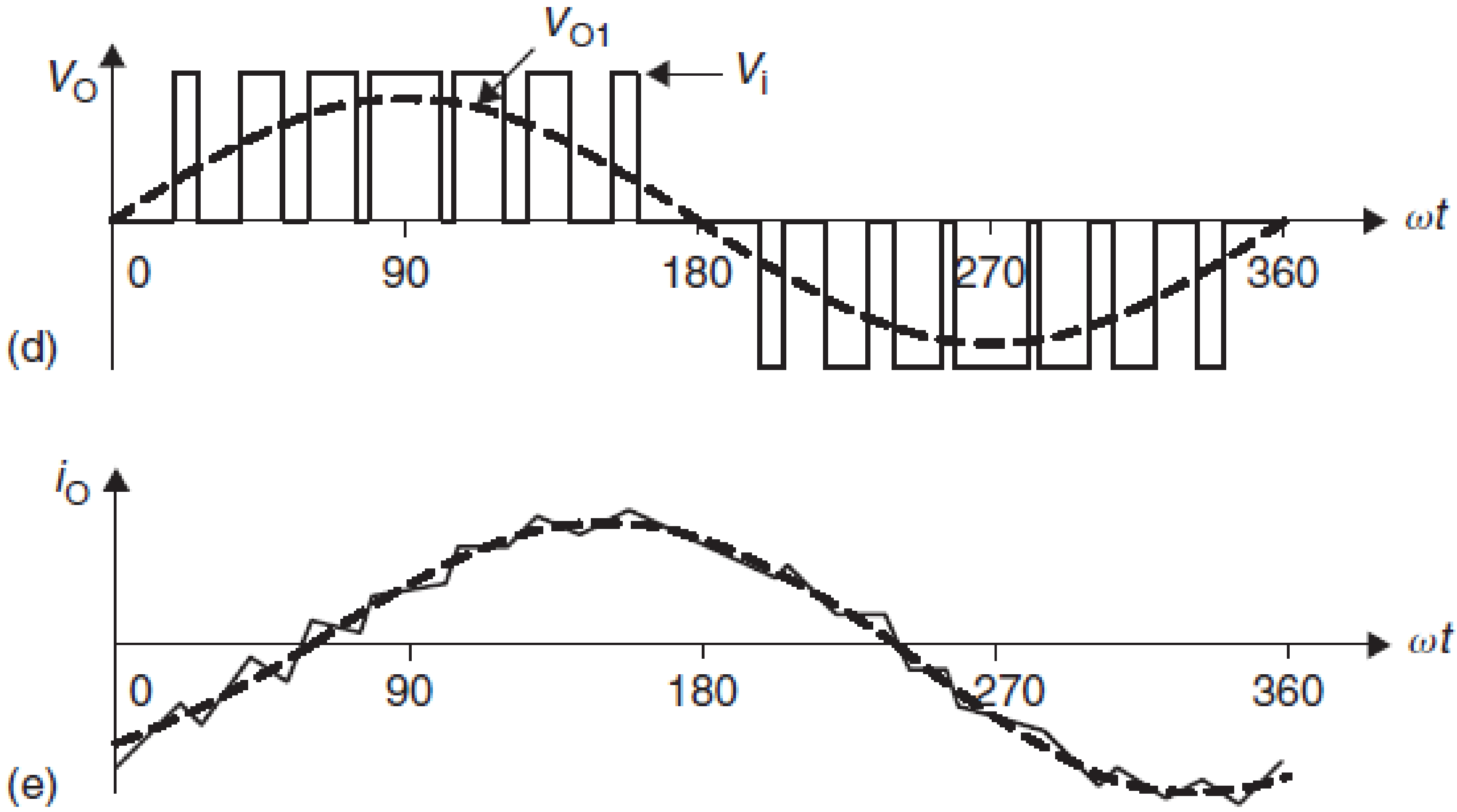
Ideal waveforms associated with the single-phase half-bridge VSI (m_a=0.8, m_f=9). (a) Carrier and modulating signals, (b) switch S+ state, (c) switch S− state, (d) AC output voltage and (e) AC output current

Single-Phase Full-Bridge VSI





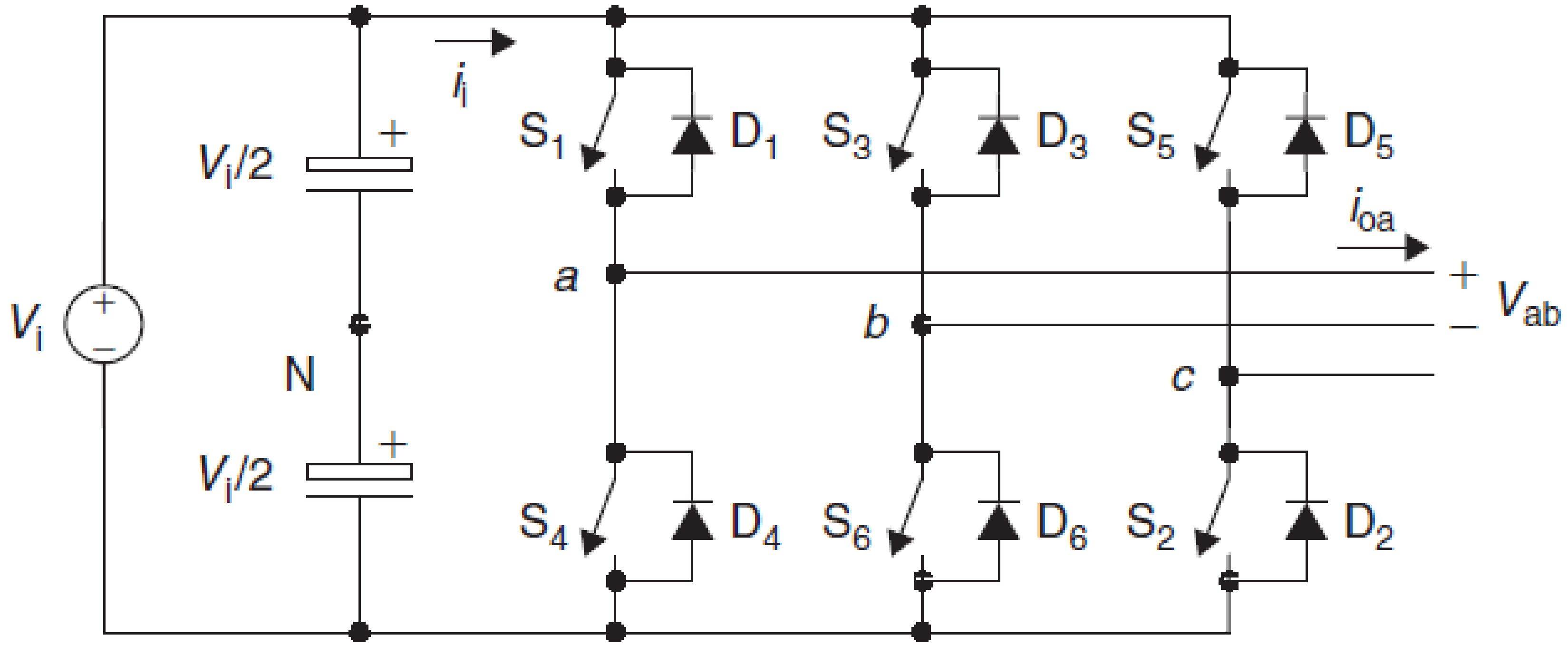
V_C
V_Δ
ωt
90
180
270
360
(a)
S_1+
on
ωt
(b)
0
90
180
270
360
S_2+
on
ωt
(c)
0
90
180
270
360



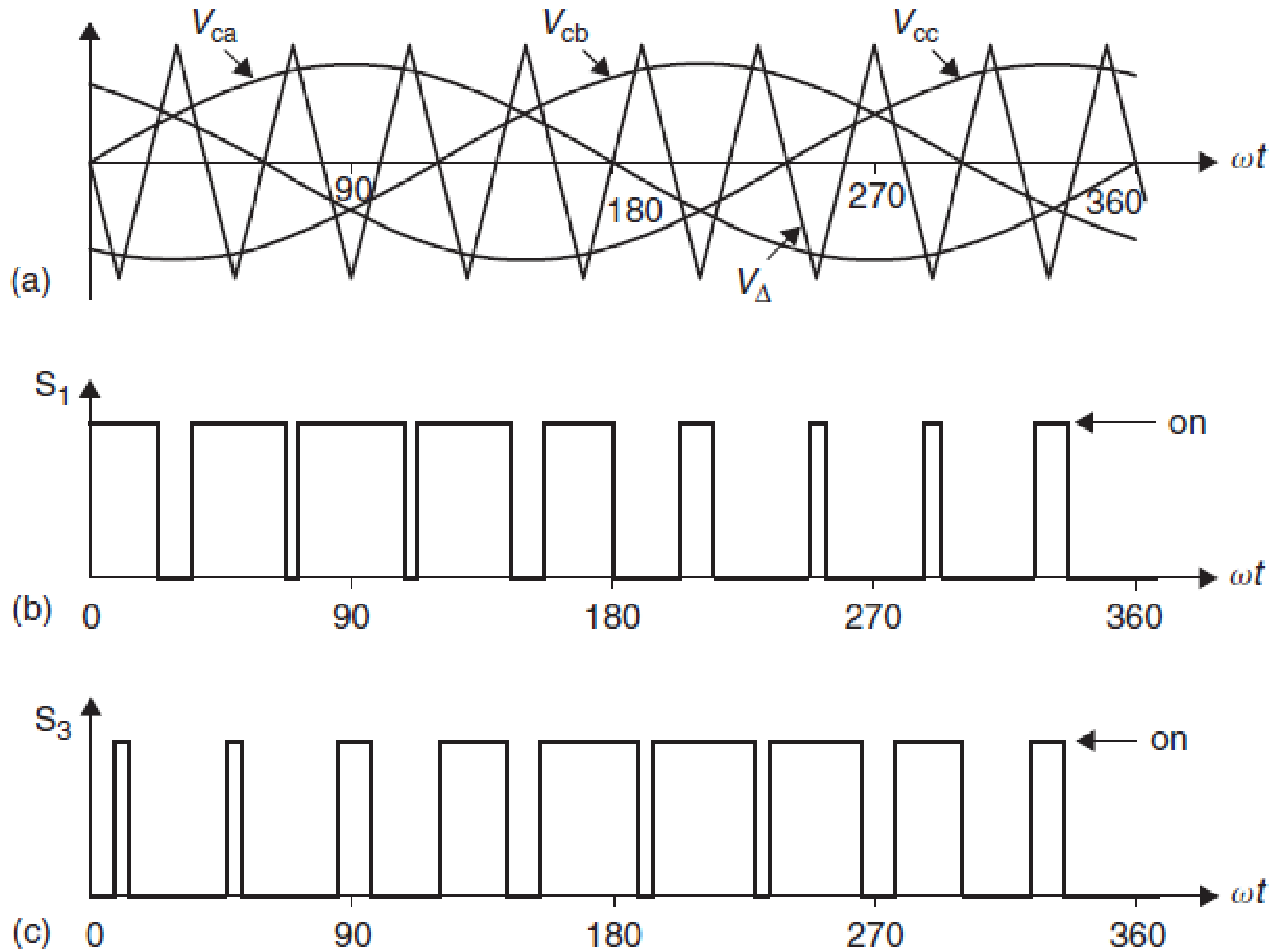
Ideal waveforms associated with the full-bridge VSI (m_a=0.8, m_f =8). (a) Carrier and modulating signals, (b) switch S_1+ and S_1− state, (c) switch S_2+ and S_2− state, (d) AC output voltage and (e) AC output current.

- The carrier-based PWM technique is applied in this single-phase full-bridge VSI.
- Two large capacitors may be used to provide a neutral point N, therefore, each capacitor keep the half of the input DC voltage.
- Four switches S1+ and S1– plus S2+ and S2– are applied and switched by the PWM signal.

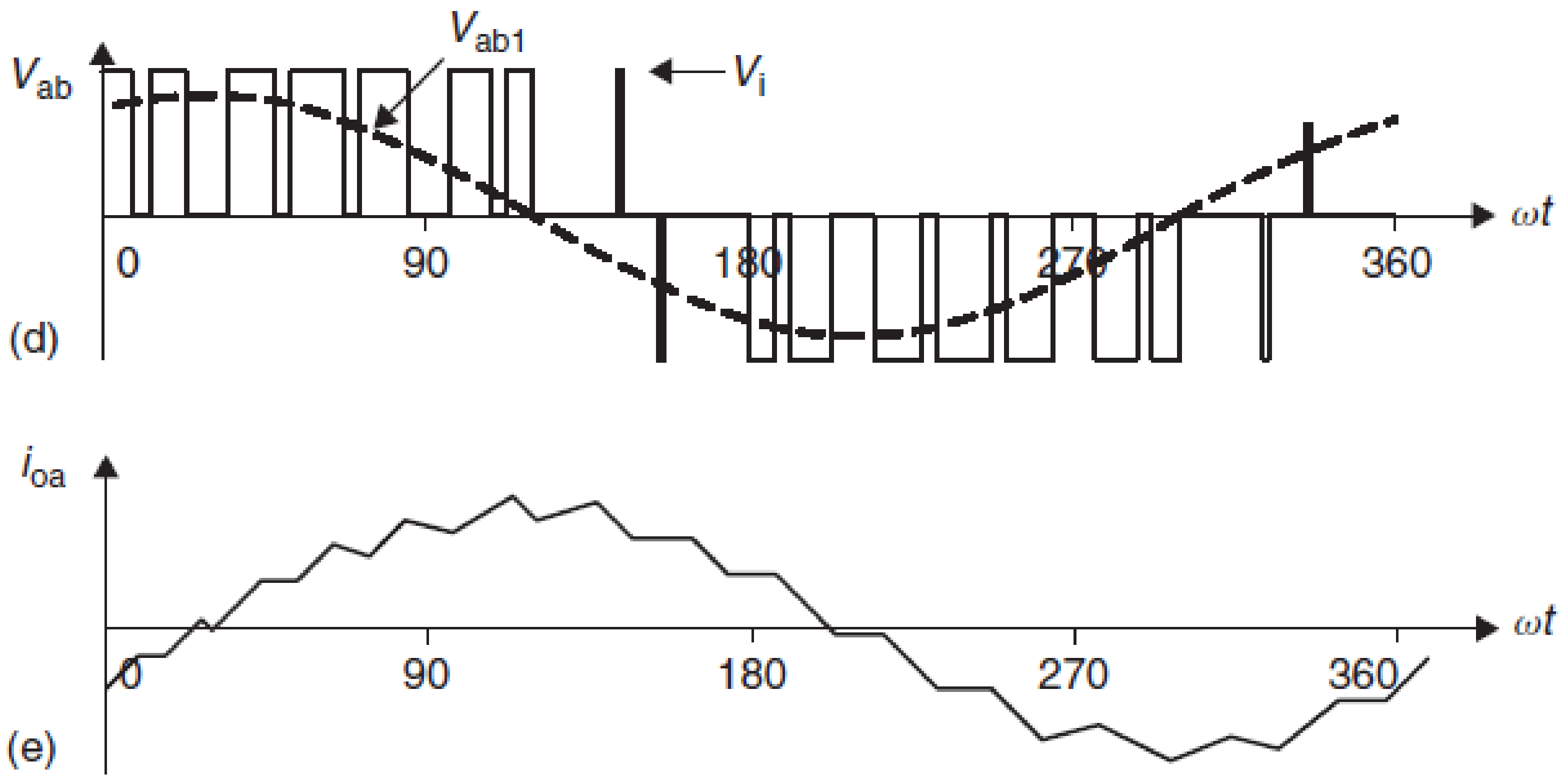
Three-Phase Full-Bridge VSI



- The carrier-based PWM technique is applied in this three-phase full-bridge VSI.
- Two large capacitors may be used to provide a neutral point N, therefore, each capacitor keep the half of the input DC voltage.
- Six switches S1–S6 are applied and switched by the PWM signal.

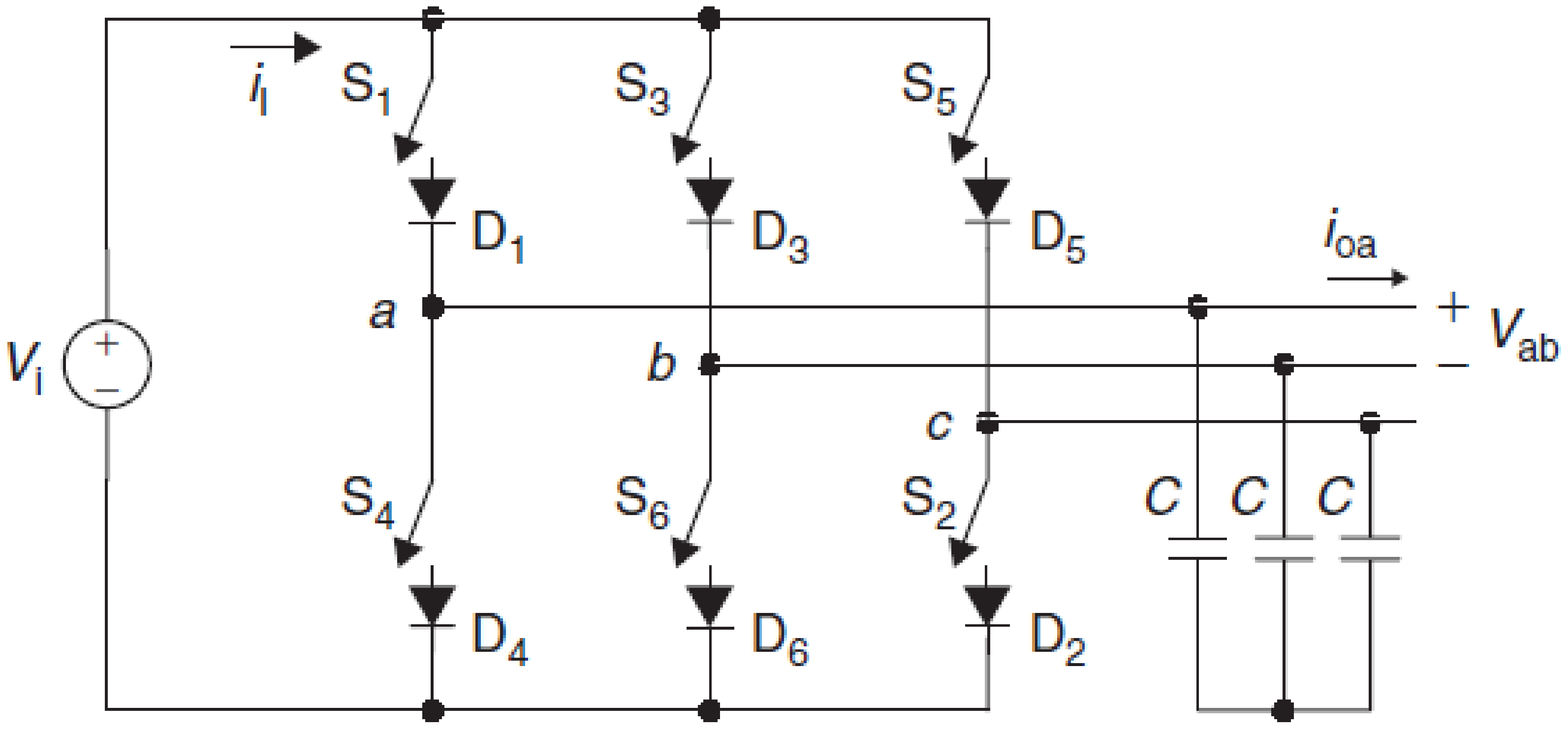


V_{ca}
V_{cb}
V_{cc}
ωt
90
180
270
360
V_Δ
(a)
S_1
on
ωt
(b)
0
90
180
270
360
S_3
on
ωt
(c)
0
90
180
270
360

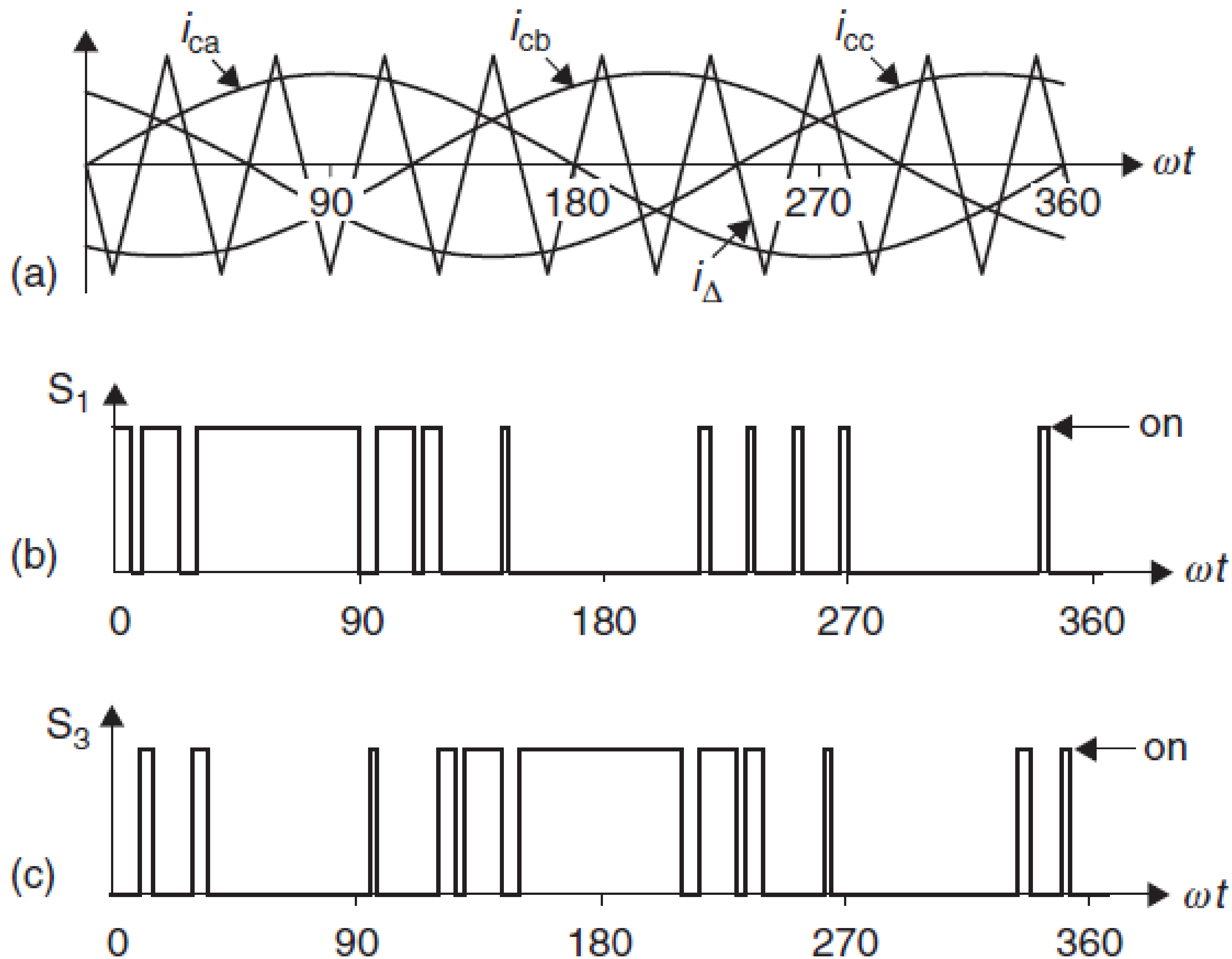


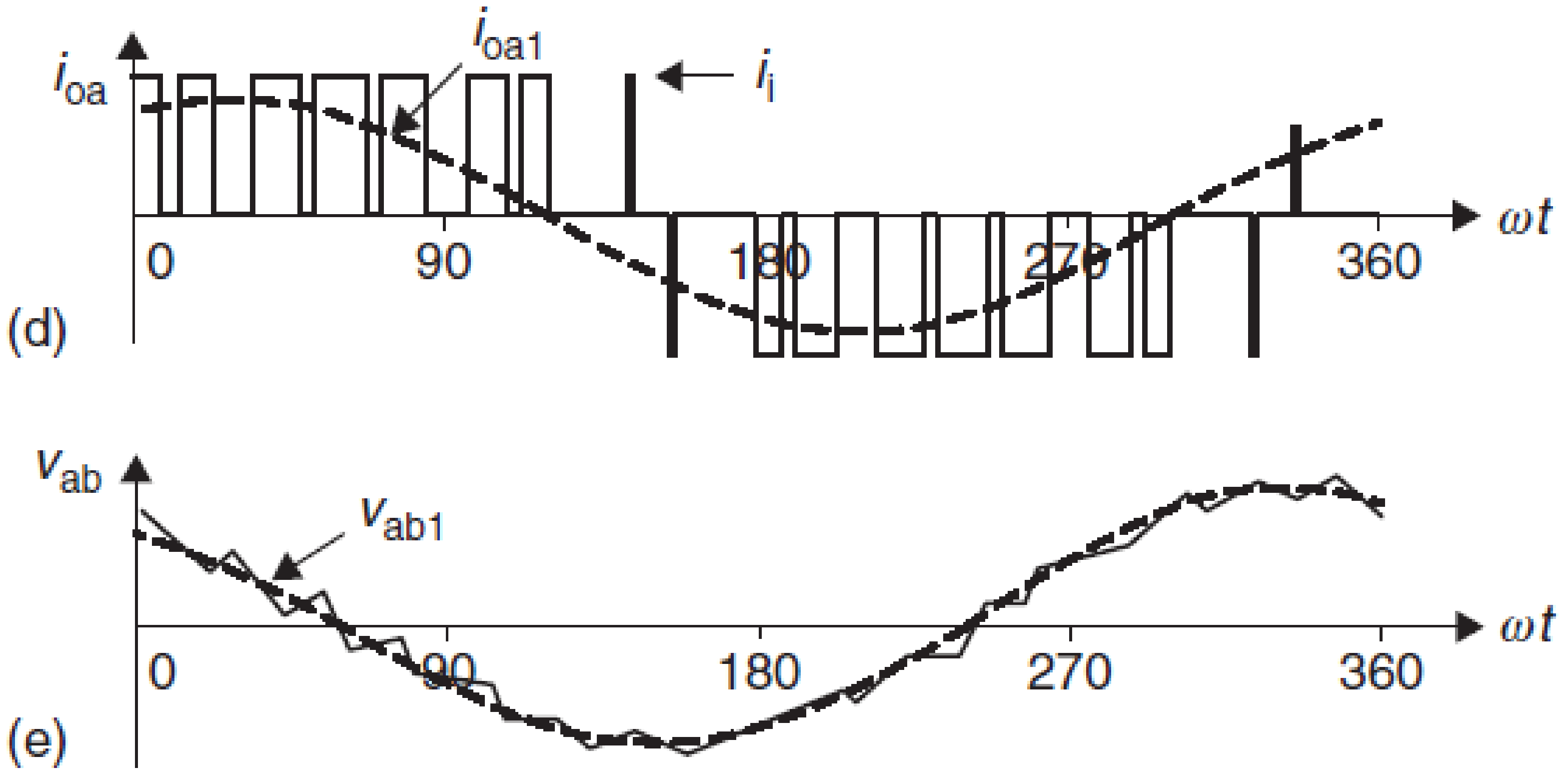
Idealwaveforms associated with the three-phase full-bridgeVSI (m_a =0.8, m_f=9). (a) Carrier and modulating signals, (b) switch S_1+state, (c) switch S_3 state, (d)ACoutput voltage and (e) AC output current

Three-Phase Full-Bridge CSI



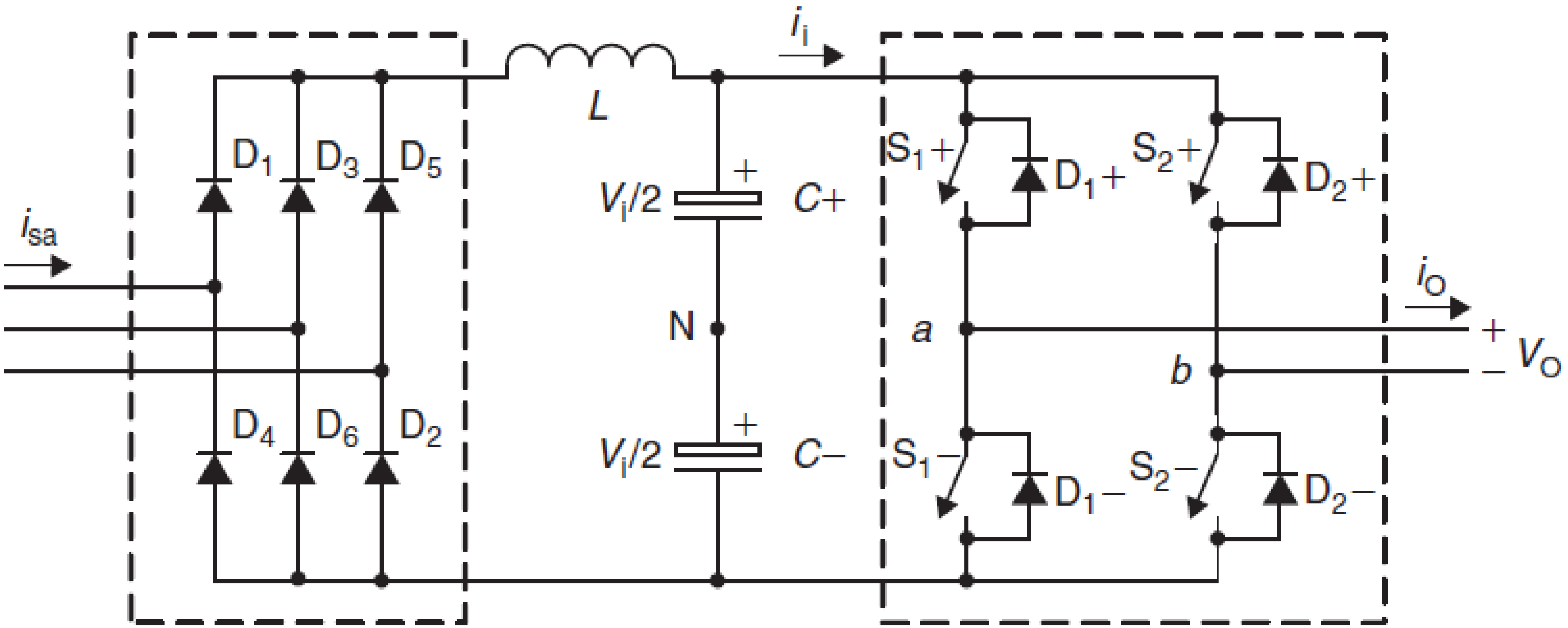
- The carrier-based PWM technique is applied in this three-phase full-bridge CSI.
- The main objective of these static power converters is to produce AC output current waveforms from a DC current power supply.
- Six switches S1–S6 are applied and switched by the PWM signal.


i_{ca}
i_{cb}
i_{cc}
ωt
90
180
270
360
(a)
i_Δ
S_1
on
(b)
ωt
0
90
180
270
360
S_3
on
(c)
ωt
0
90
180
270
360



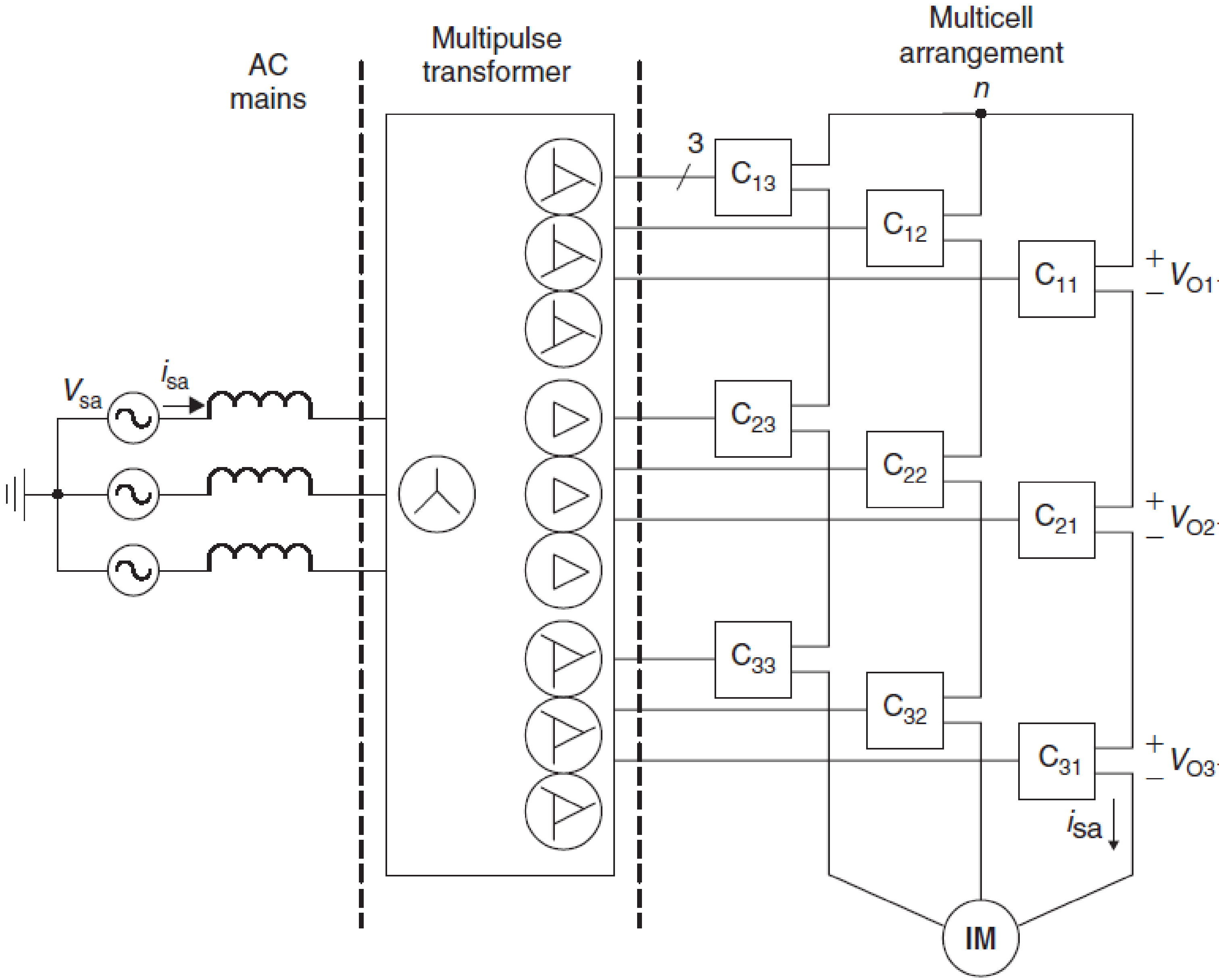
Idealwaveforms associated with the three-phase full-bridge CSI (m_a =0.8, m_f=9). (a) Carrier and modulating signals, (b) switch S_1+state, (c) switch S_3 state, (d)ACoutput current and (e) AC output voltage

Multistage PWM Inverter



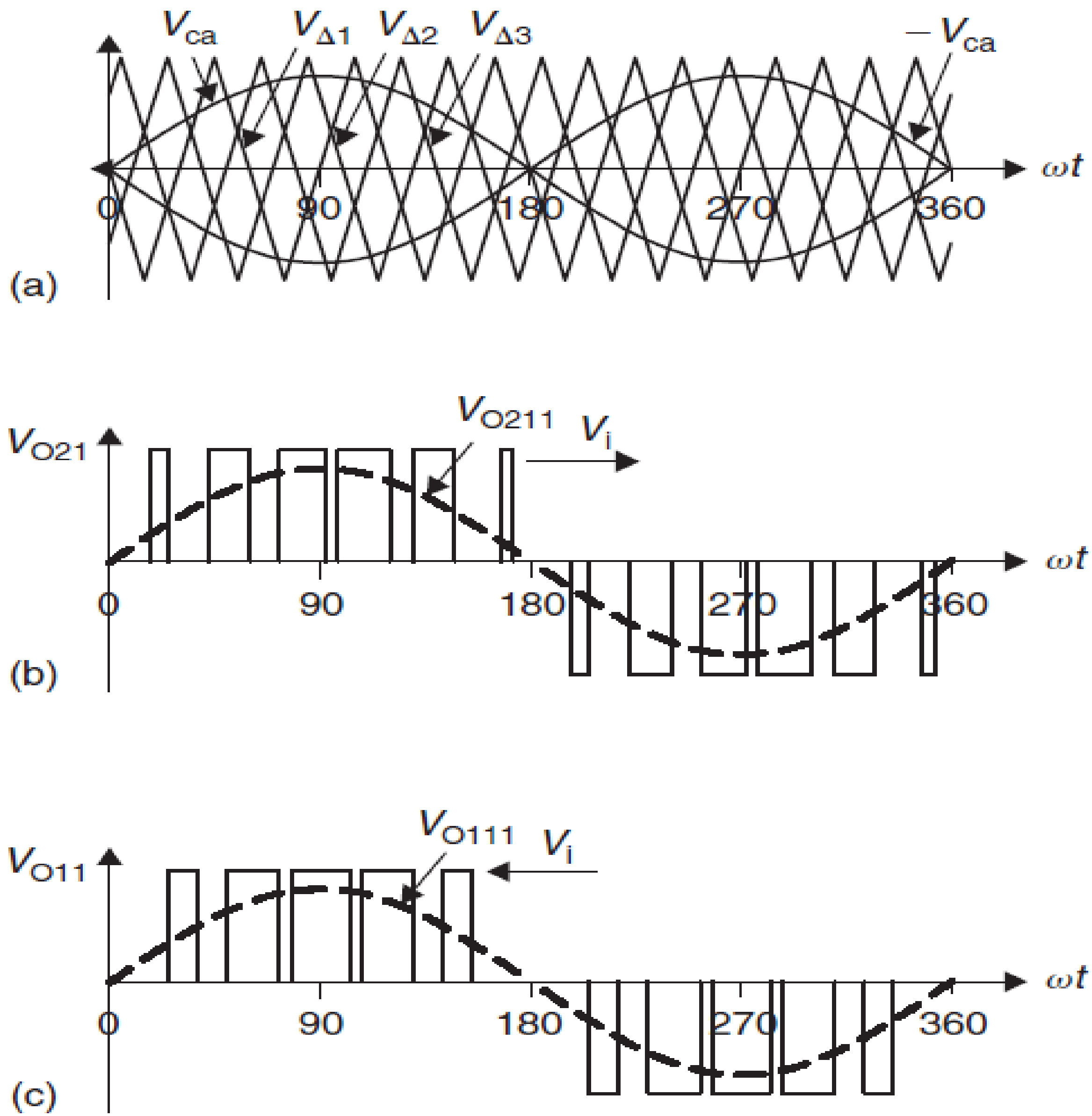
Three-phase input plus single-phase output VSI

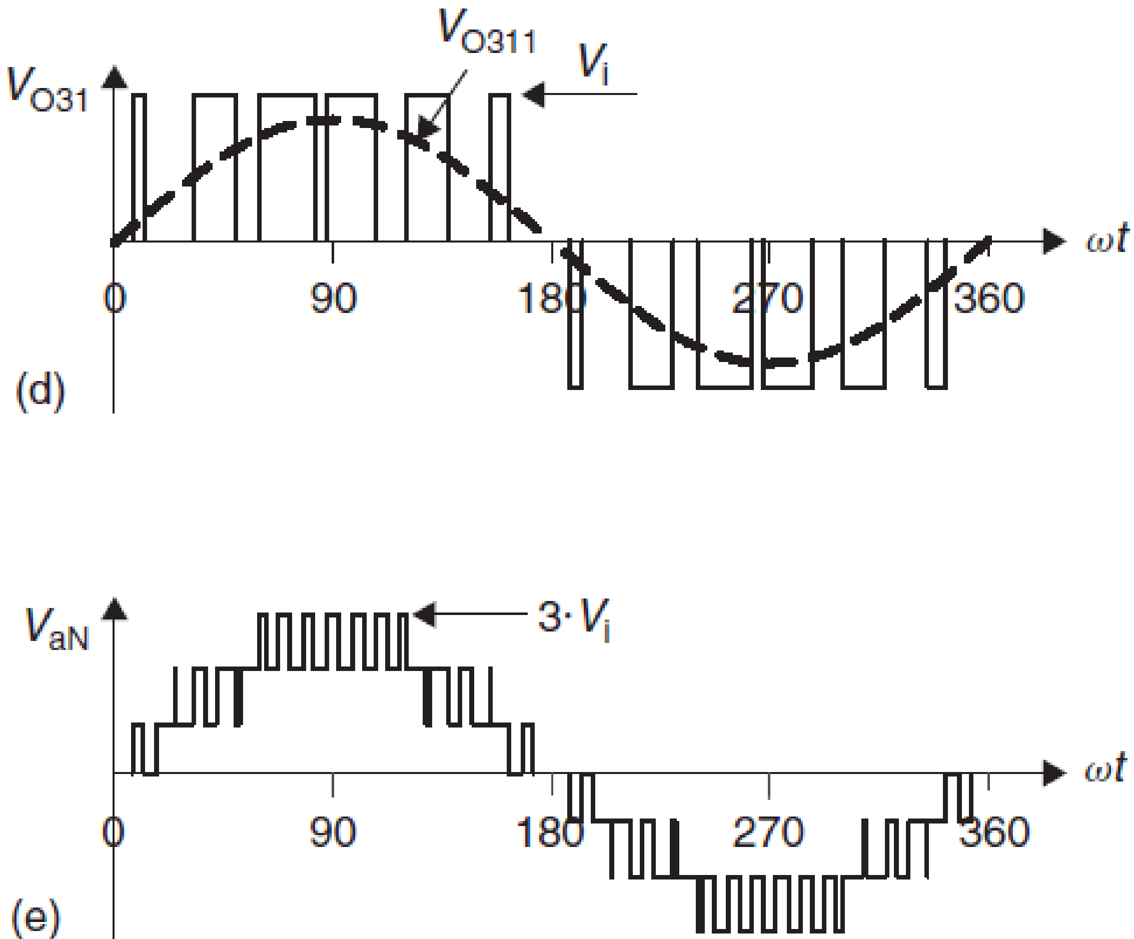
- Multistage PWM inverter consists of many cells. Each cell can be a single- or three phase input plus single-phase output VSI, which is shown in Figure



Multistage converter based on a multicell arrangement

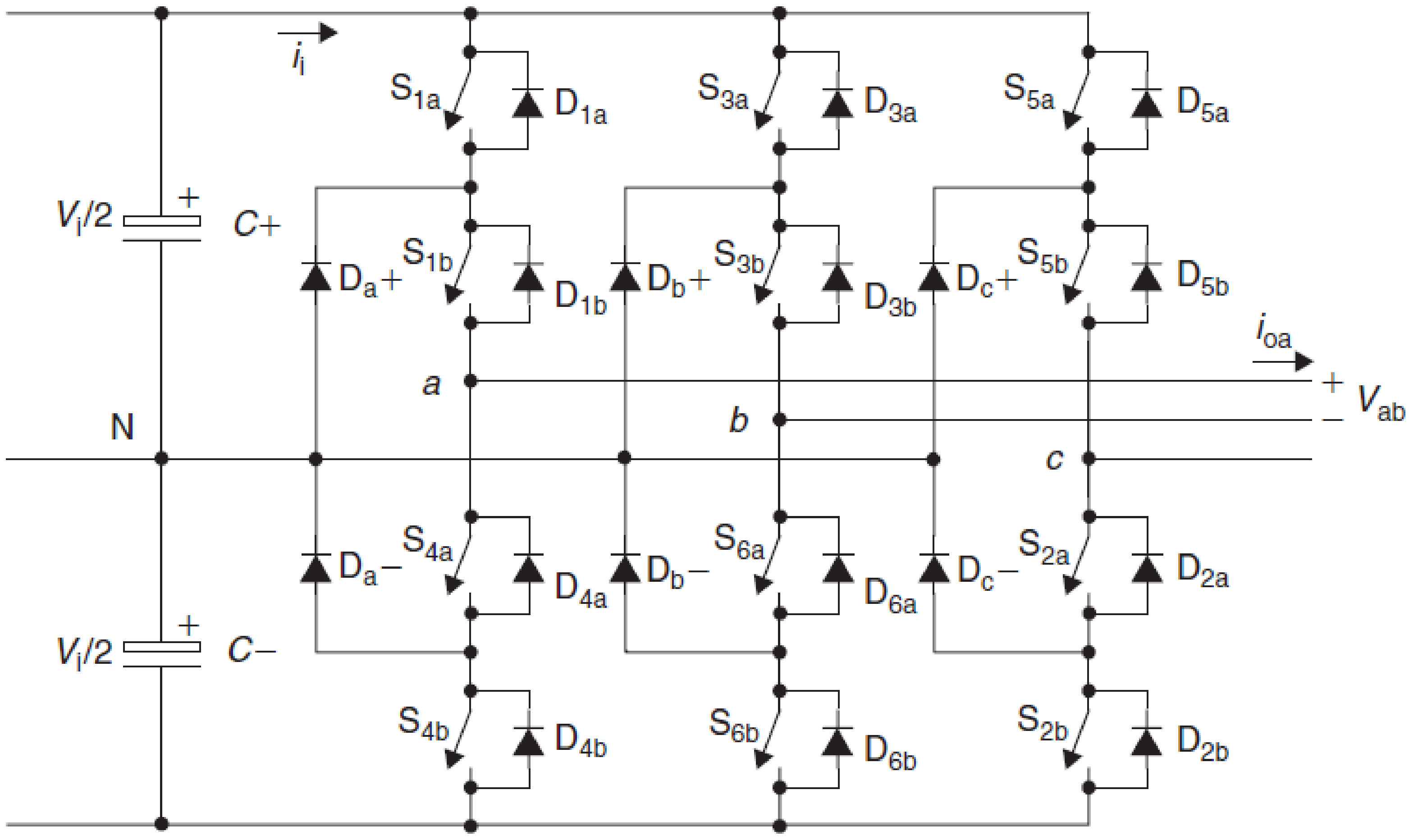
- If the three-phase AC supply is a secondary winding of a main transformer, it is floating and isolated from other cells and common ground point.
- Therefore, all cells can be linked in series or parallel manner.
- Each phase consist of three cells with difference phase-angle shift by 20◦ each other.
- The carrier-based PWM technique is applied in this three-phase multistage PWM inverter.


V_{ca}
$V_{\Delta 1}$
$V_{\Delta 2}$
$V_{\Delta 3}$
$-V_{ca}$
ωt
0
90
180
270
360
(a)
V_{O21}
V_{O211}
V_i
ωt
0
90
180
270
360
(b)
V_{O11}
V_{O111}
V_i
ωt
0
90
180
270
360
(c)

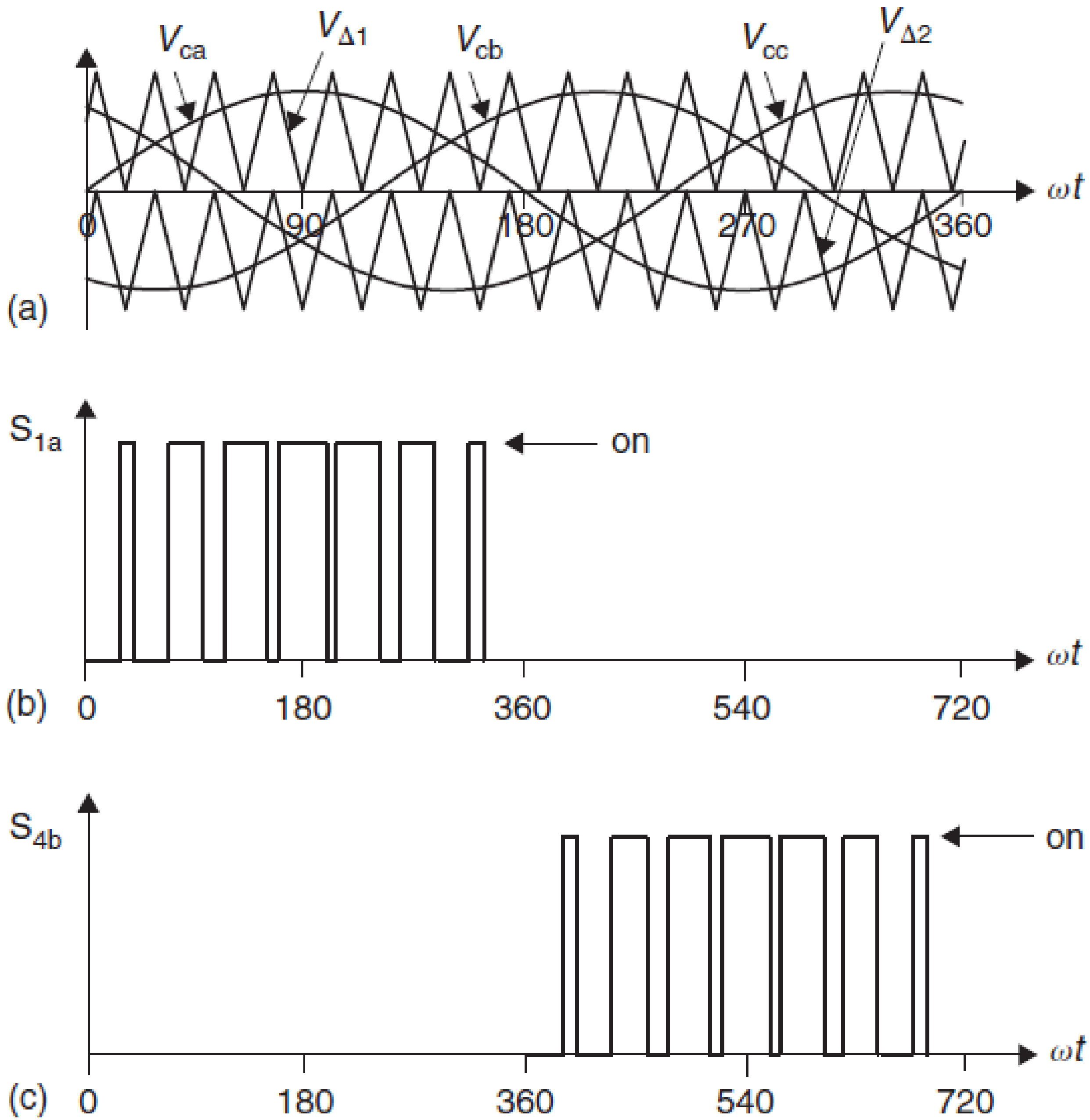


Ideal waveforms associated with the multicell PWM inverter (three stages, m_a=0.8, m_f=6). (a) Carrier and modulating signals, (b) cell c_{11} AC output voltage, (c) cell c_{21} AC output voltage, (d) cell c_{31} AC output voltage and (e) phase a load voltage

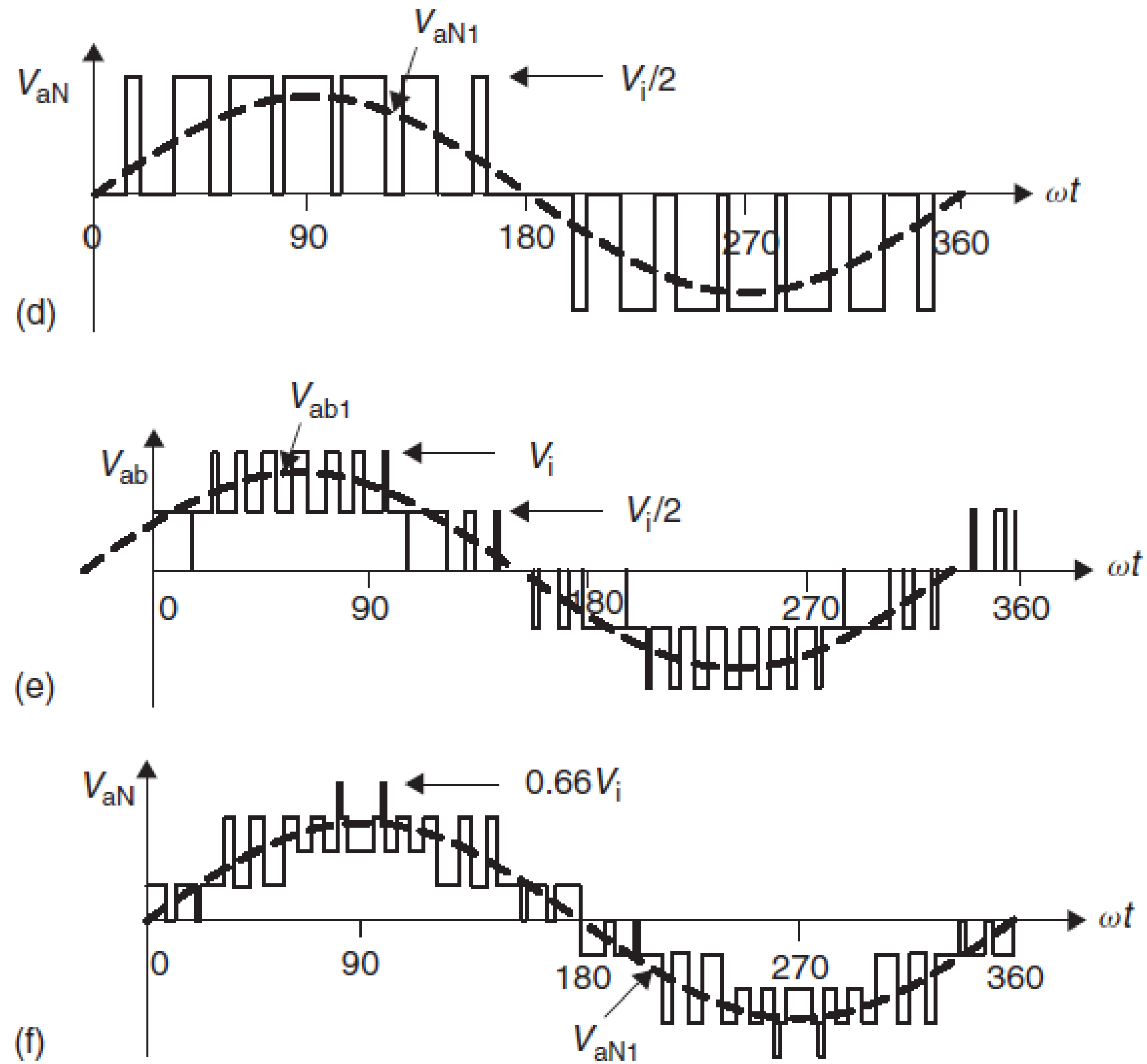
Multilevel PWM Inverter



Three-phase three-level PWM VSI



V_{ca}
$V_{\Delta 1}$
V_{cb}
V_{cc}
$V_{\Delta 2}$
ωt
0
90
180
270
360
(a)
S_{1a}
on
ωt
(b)
0
180
360
540
720
S_{4b}
on
ωt
(c)
0
180
360
540
720



Ideal waveforms associated with three-phase three-level VSI (three levels, *m*a =0.8, *m*f =15). (a) Carrier and modulating signals, (b) switch S1a status, (c) switch S4bstatus, (d) inverter phase aN voltage, (e)AC output line voltage and (f)AC output phase voltage

MATHEMATICAL MODELING FOR DC/AC PWM INVERTERS

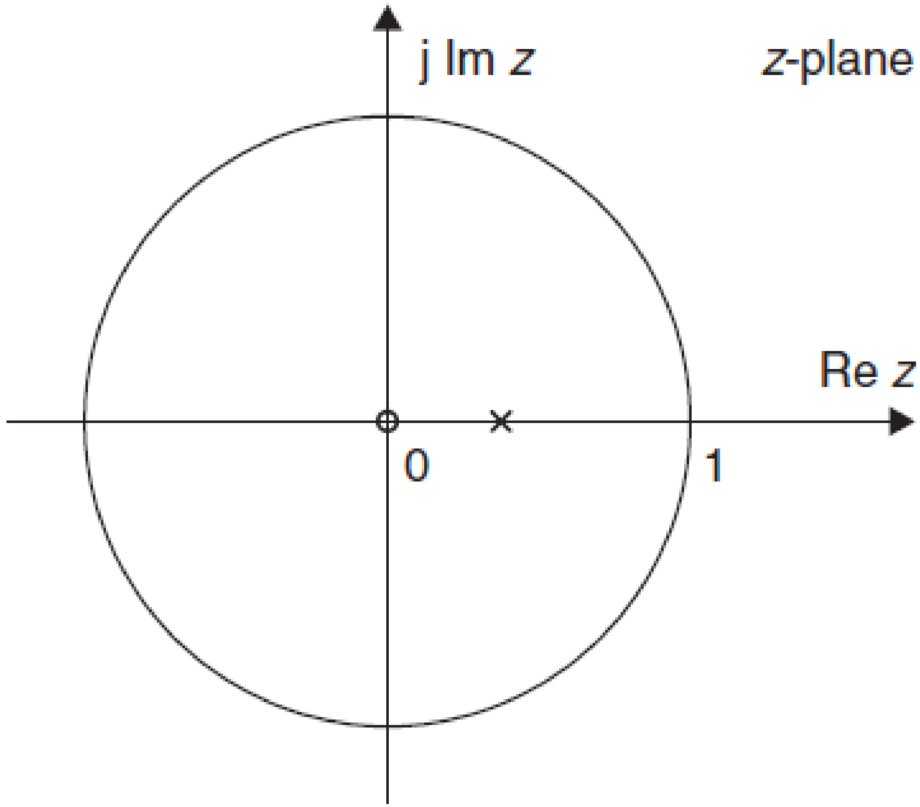
- By per-unit system the voltage transfer gain is unity. The transfer function in the time domain is an exponential function, and it has the following form in the *s*-domain

$$G(s) = \frac{1}{1 + sT}$$

- In digital control system, all DC/AC PWM inverters are treated as an FOH has the transfer function in the *z*-domain:

$$G(z) = \frac{z}{z - 1/e}$$

- It means the DC/AC PWM inverter is the first-order-element that possesses one zero at $z=0$ and one pole at $z=1/e$, which is located on the unit-cycle.
- The zero and pole in the *z*-plane are shown in Figure (Next slide)



Zero and pole of the FOH in the *z*-plane

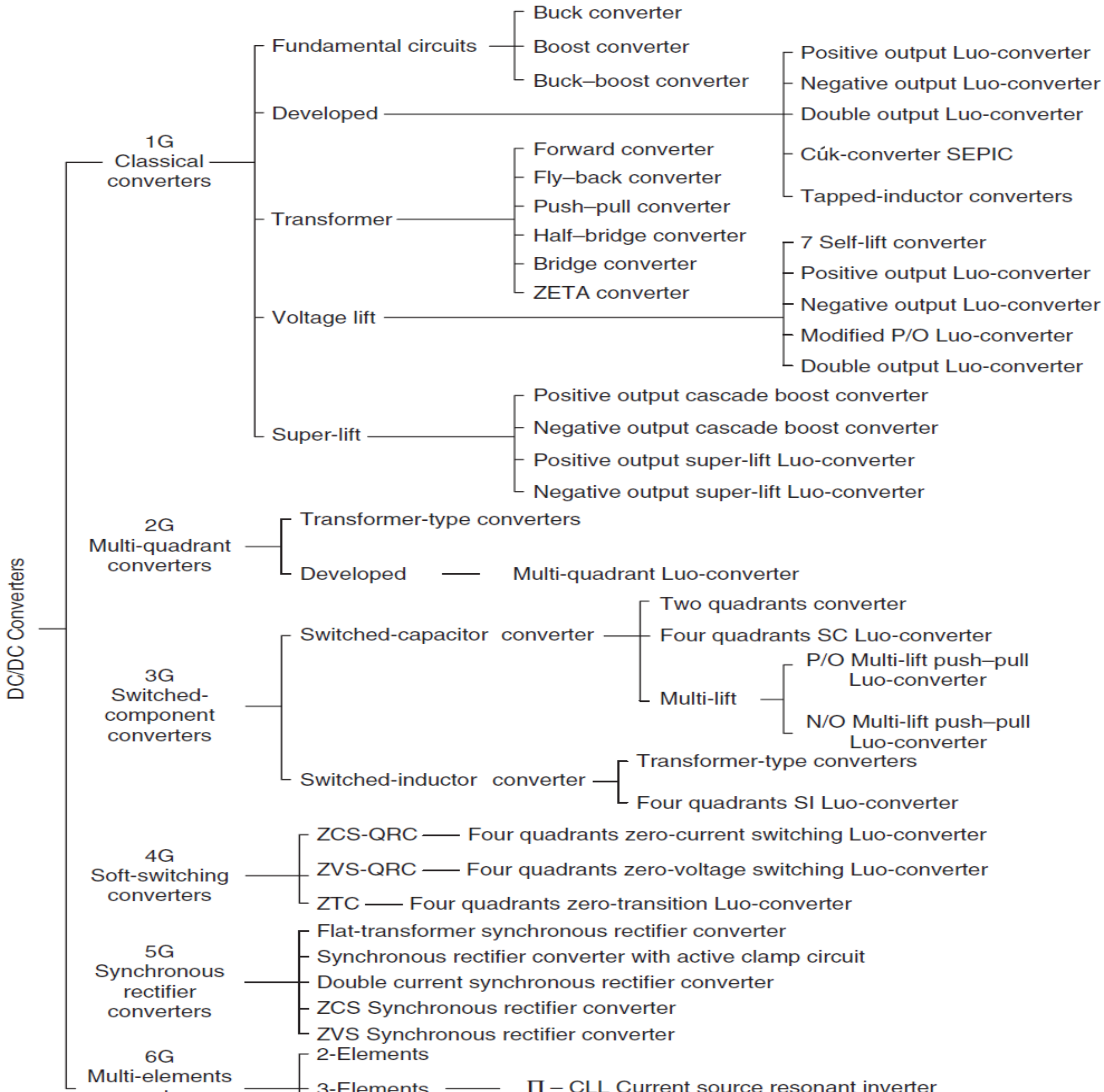
Unit-III

Digitally Controlled DC/DC Converters
&
Digitally Controlled AC/AC Converters

- Power DC/DC converters have plenty of topologies
- By an uncompleted statistics, there are more than 500 topologies of power DC/DC converters existing.
- Dr. F. L. Luo and Dr. H.Ye have firstly categorized all existing prototypes of the power DC/DC converters into six generations theoretically and evolutionarily since 2001

- First-generation (classical/traditional) converters
- Second-generation (multi-quadrant) converters
- Third-generation (switched-component) converters
- Fourth-generation (soft-switching) converters
- Fifth-generation (synchronous rectifier) converters
- Sixth-generation (multiple energy-storage elements resonant) converters

DC/DC converter family tree



The First-Generation Converters

- The first-generation converters perform in a single-quadrant mode and in low power range (up to around 100 W).
- Five categories
- Fundamental converters
- •Transformer-type converters
- Developed converters
- Voltage-lift converters
- Super-lift converters

Fundamental converters

- Three types of fundamental DC/DC topologies were constructed,
- which are **Buck** converter, **Boost** converter and **Buck–Boost** converter.
- Derived from single-quadrant operation choppers. For example, buck converter was derived from A-type chopper.

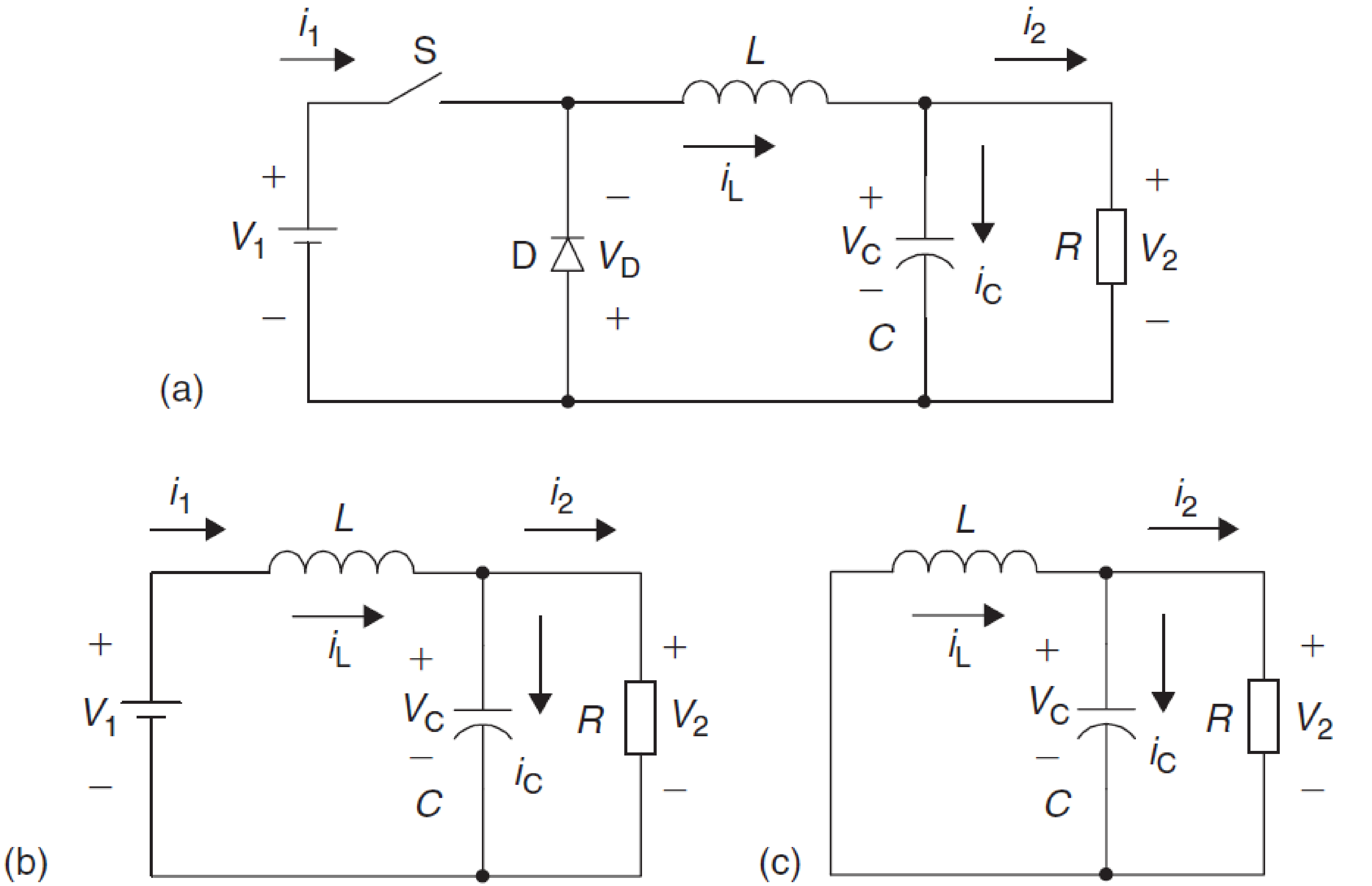
Two main problems: linkage between input and output, and very large output voltage ripple

Buck converter

- Buck converter is a step-down DC/DC converter. It works in the first-quadrant operation.
- It can be derived from Quadrant I chopper. Its circuit diagram, and switch-on and switch-off equivalent circuit are shown in Figure
- The output voltage is calculated by the formula:

$$V_O = \frac{t_{on}}{T} V_{in} = k V_{in}$$

- where T is the repeating period ($T = 1/f$), in which f is the chopping frequency; $t$on is the switch-on time and k is the conduction duty cycle ($k = t$on$/T$)



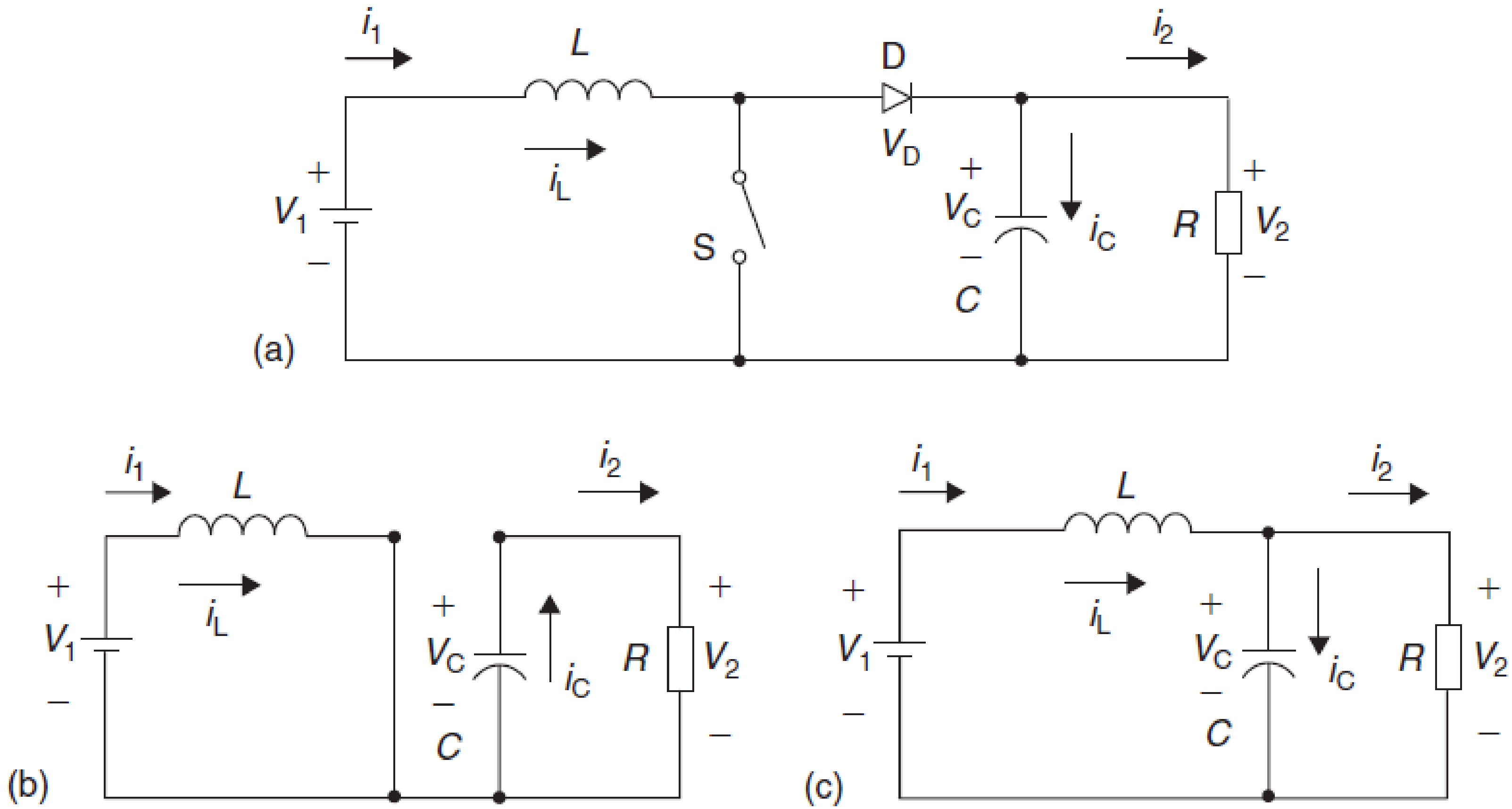
Buck converter. (a) Circuit diagram, (b) switch-on and (c) switch-off

Boost converter

- Boost converter is a step-up DC/DC converter.
- It works in the second-quadrant operation.
- It can be derived from Quadrant II chopper.
- The output voltage is calculated by the formula:

$$V_O = \frac{T}{T - t_{on}} V_{in} = \frac{1}{1 - k} V_{in}$$

- where T is the repeating period ($T = 1/f$), in which f is the chopping frequency; t_{on} is the switch-on time and k is the conduction duty cycle ($k = t_{on}/T$)



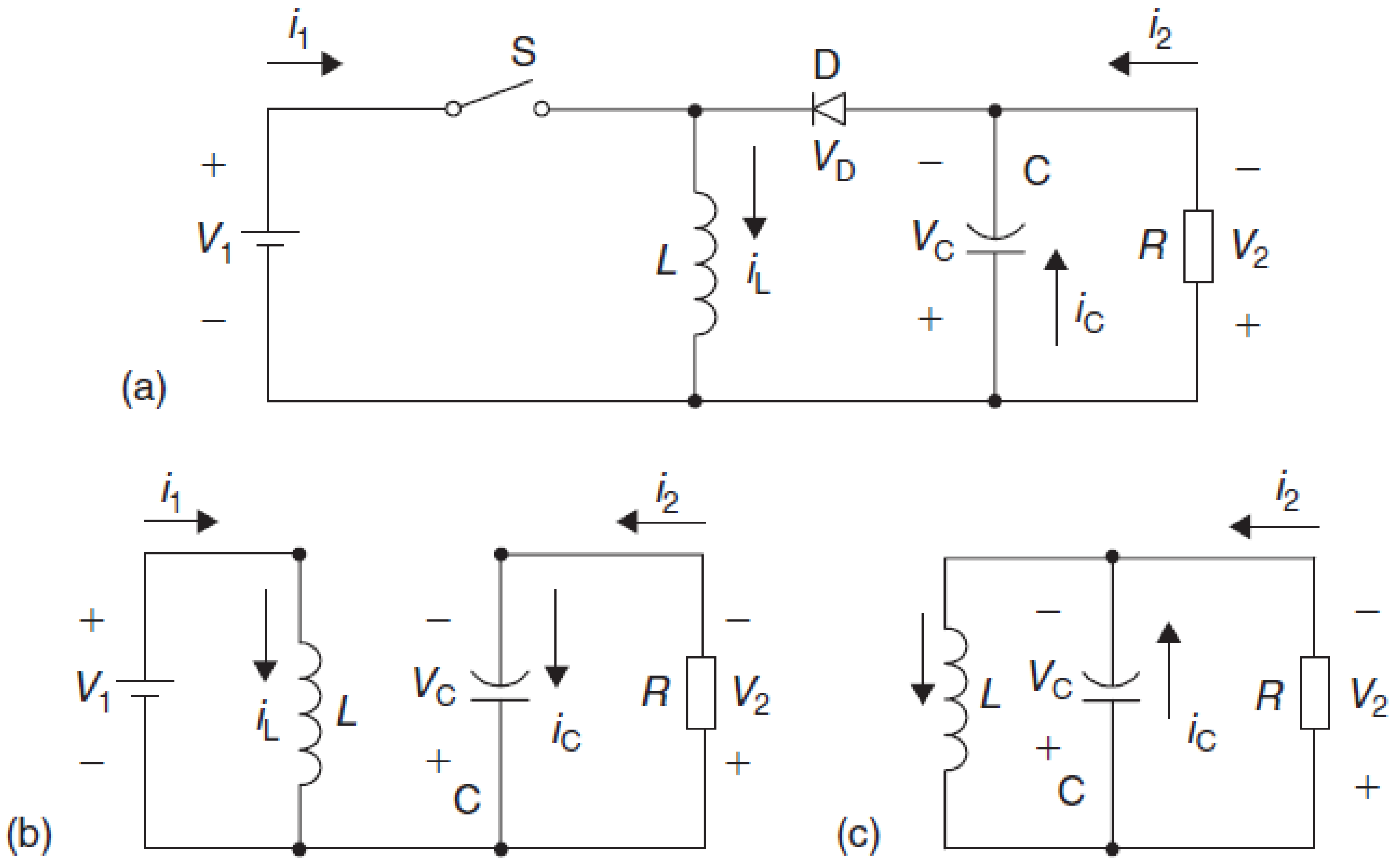
Boost converter. (a) Circuit diagram, (b) switch-on and (c) switch-off

Buck–Boost converter

- Buck–boost converter is a step-down/up DC/DC converter.
- It works in the third quadrant operation.
- The output voltage is calculated by the formula:

$$V_O = \frac{t_{on}}{T - t_{on}} V_{in} = \frac{k}{1-k} V_{in}$$

- where T is the repeating period ($T = 1/f$), in which f is the chopping frequency; t_{on} is the switch-on time and k is the conduction duty cycle ($k = t_{on}/T$)



Buck–boost converter. (a) Circuit diagram, (b) switch-on and (c) switch-off

Developed Converters

- This converters overcome the second fault of the fundamental DC/DC converters.
- They are derived from fundamental converters with adding a low-pass filter.
- Typical prototypes converters are

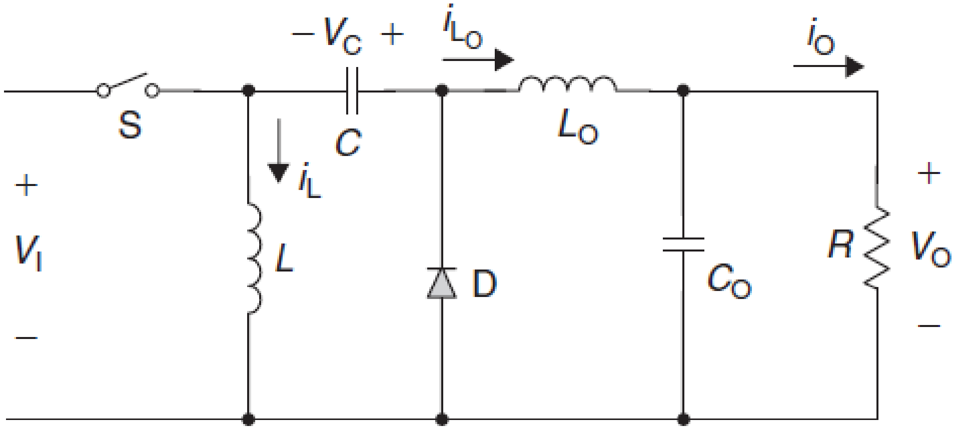
➢ positive output (P/O) **Luo**-converter,
➢ negative output (N/O) **Luo**-converter,
➢ double output (D/O) **Luo**-converter,
➢ **Cúk**-converter,
➢ single-ended primary inductance converter (**SEPIC**) and
➢ Watkins–Johnson converters.

- The output voltage ripple of all developed-type converters is usually small, which can be lower than 2%.
- In order to obtain the random output voltage, which can be higher or lower input voltage
- All developed converters provide very great convenience for industrial applications.
- Therefore, the output voltage gain of all developed converters is:

$$V_O = \frac{k}{1-k} V_{in}$$

P/O Luo-Converter

- It can be derived from buck–boost converter. Its circuit diagram is shown in Figure

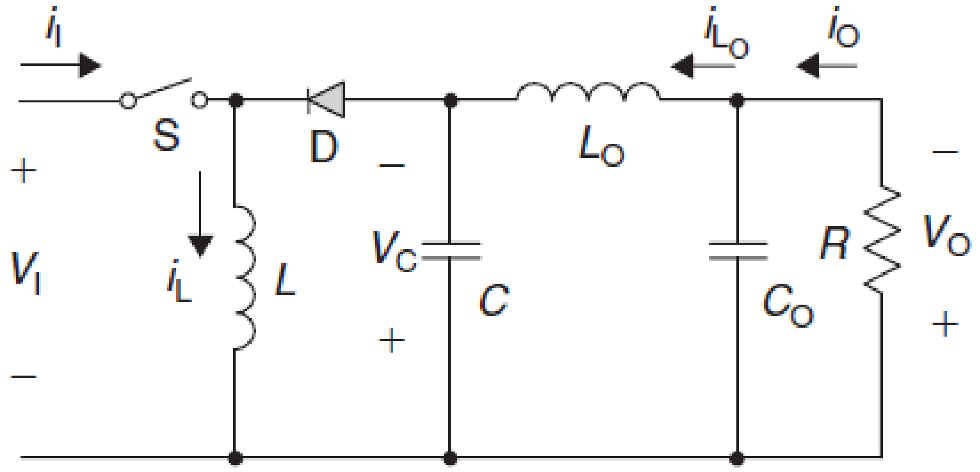


- The output voltage is calculated by the formula

$$V_O = \frac{k}{1-k} V_{in}$$

N/O Luo-Converter

- It can also be derived from buck–boost converter



- The output voltage is calculated by the formula as in P/O Luo Converter.

D/O Luo-Converter

- In order to obtain mirror symmetrical P/O and N/O voltage D/O **Luo-**converter was constructed.
- D/O **Luo-**converter is the elementary circuit of the series “D/O **Luo**converters”.
- It can also be derived from buck–boost converter.
- Its circuit diagram is shown in next slide
- The output voltage is calculated by the formula

$$V_O = \frac{k}{1-k} V_{in}$$

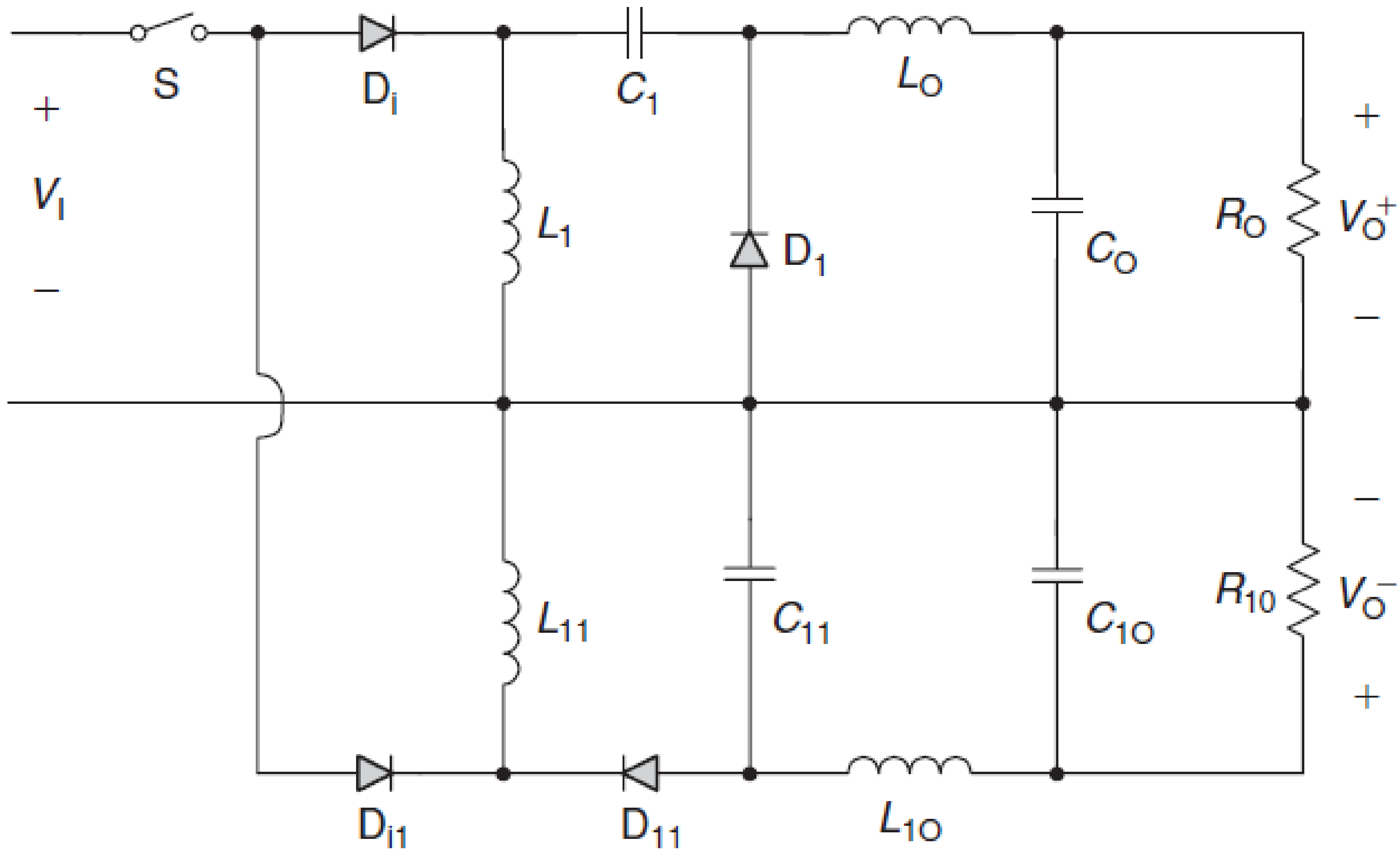
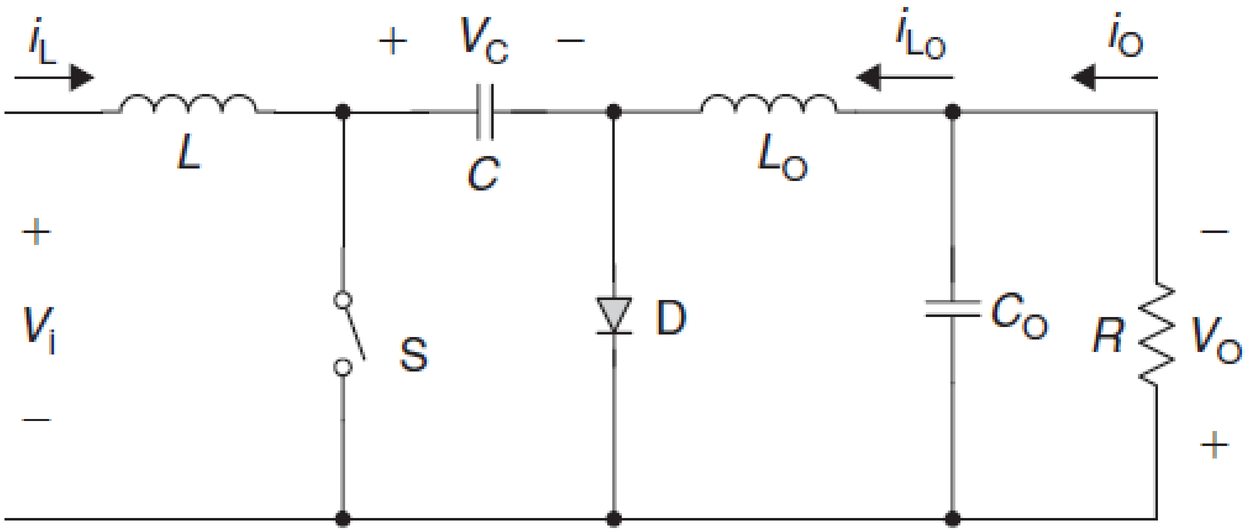


Fig. D/O Luo-converter

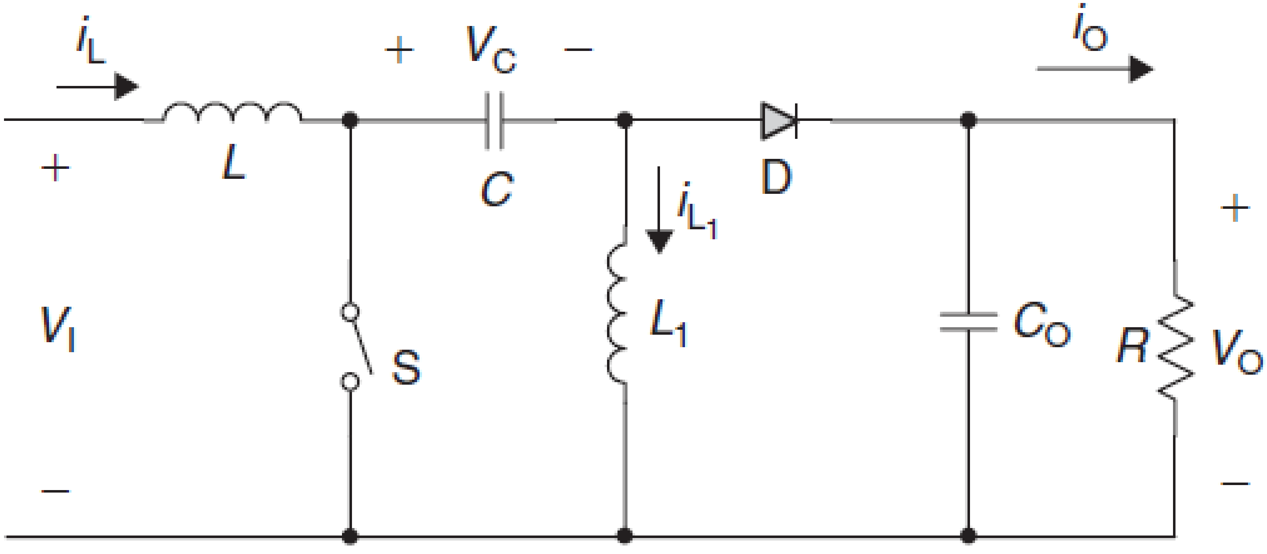
Cúk-Converter

- Cúk-converter is derived from boost converter.
- The output voltage is same as P/O Luo and N/O Luo converters



SEPIC

- The **SEPIC** is derived from boost converter.
- The output voltage is calculated by the formula as in previous converter



Fourth-Generation Converters/Soft Switching Converters

- Fourth-generation DC/DC converters are called soft-switching converters.
- There are four types of soft-switching methods:

- Resonant-switch converters
- Load-resonant converters
- Resonant-DC-link converters
- High-frequency-link integral-half-cycle converters

- Till now only resonant-switch conversion method has been paid more attention.
- There are three main categories,
  - zero-current-switching (ZCS),
  - zero-voltage-switching (ZVS) and
  - zero-transition (ZT) converters.

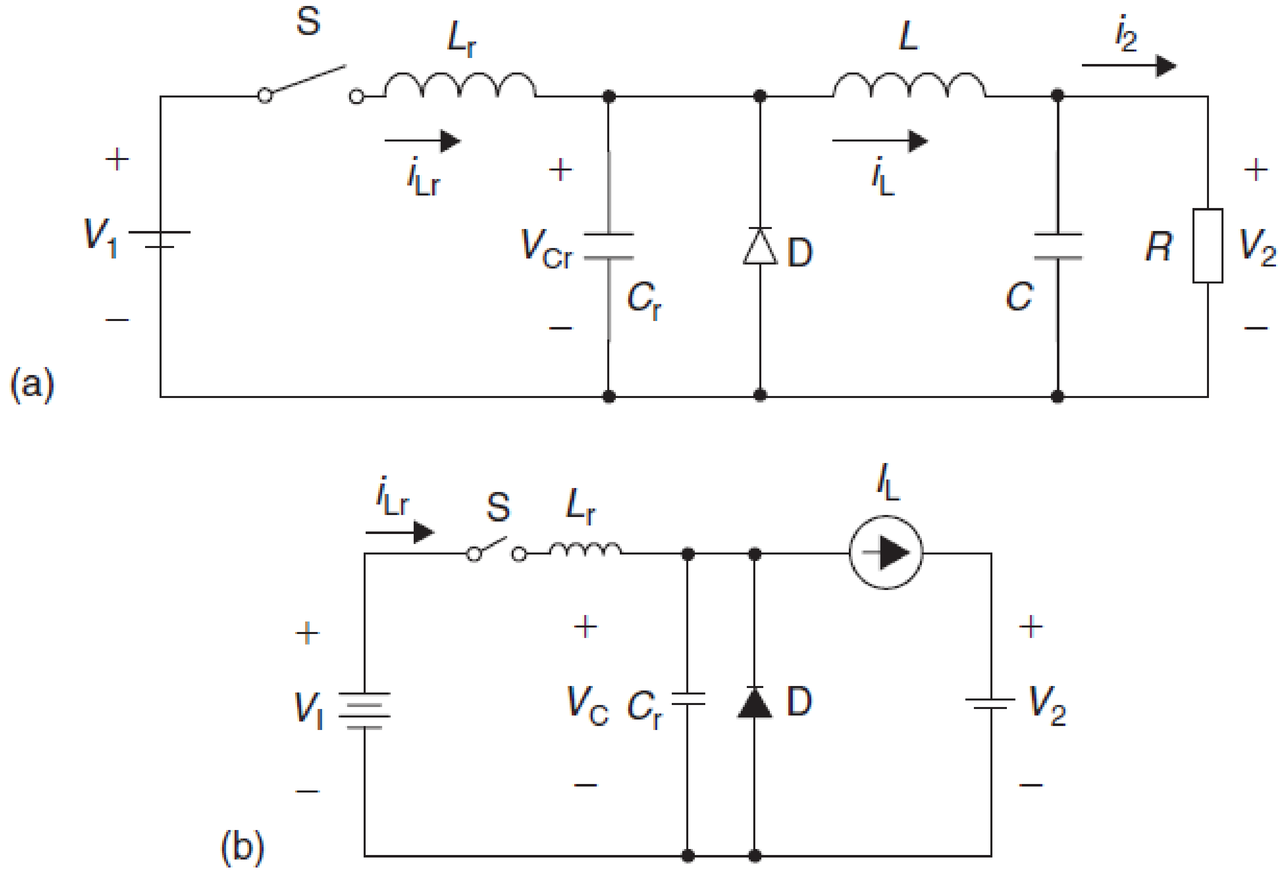
- These converters can perform in two- and four quadrant operation with high-output power range (say several thousand watts (w)).

- According to the transferred power becomes large, the power losses increase largely.
- Main power losses are produced during the switch-on and switch-off period.
- How to reduce the power losses across the switches is the clue to increase the power transfer efficiency.
- Soft-switching technique successfully solved this problem.
- Prof. Fred C. Lee is the pioneer of the soft switching technique.

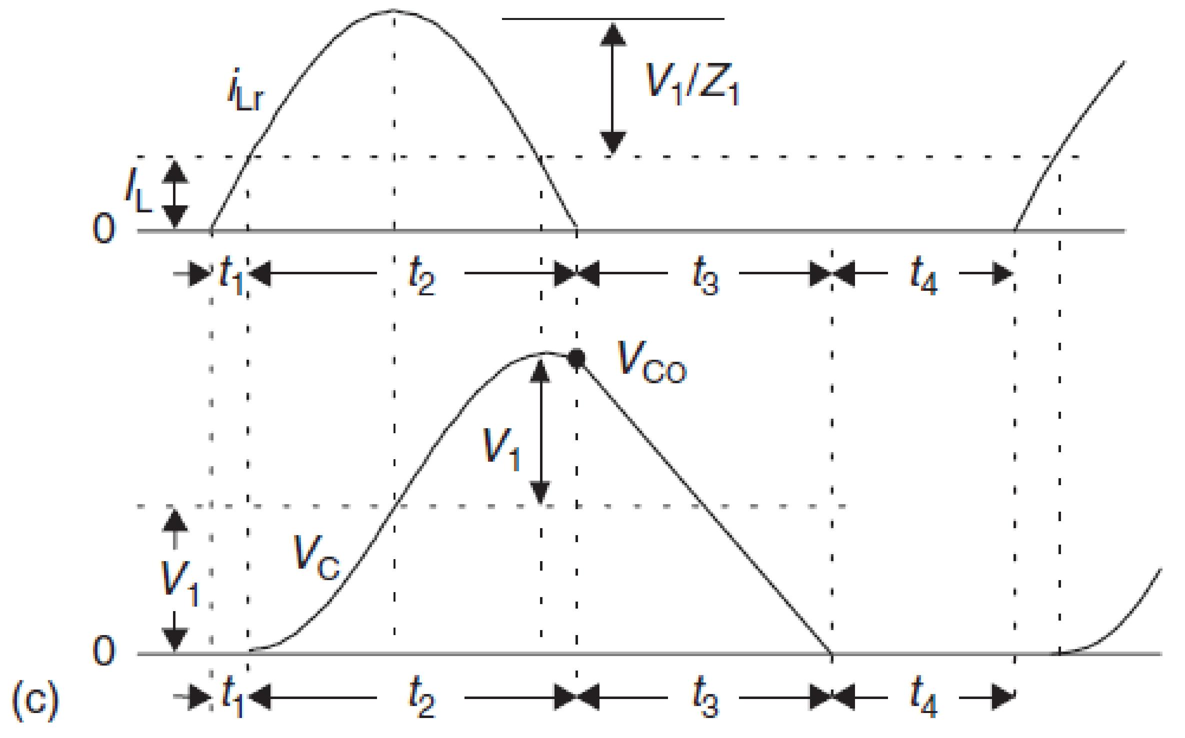
- ZCS and ZVS converters have three resonant states:
  - over resonance (completed resonance);
  - optimum resonance (critical resonance) and
  - quasi-resonance (sub-resonance).
- Only quasi-resonance state has two clear cross-zero points as a repeating period.

Zero-Current-Switching Quasi-Resonant Converters

- ZCS-QRC equips resonant circuit in the switch side to keep the switch-on and switch-off at zero-current condition.
- There are two states: full- and half-wave state.
- Most of the engineers enjoy the half-wave state.
- This technique has half-wave current resonance waveform with two zero-cross points.



A ZCS QR DC/DC converter. (a) Circuit diagram, (b) equivalent circuit diagram

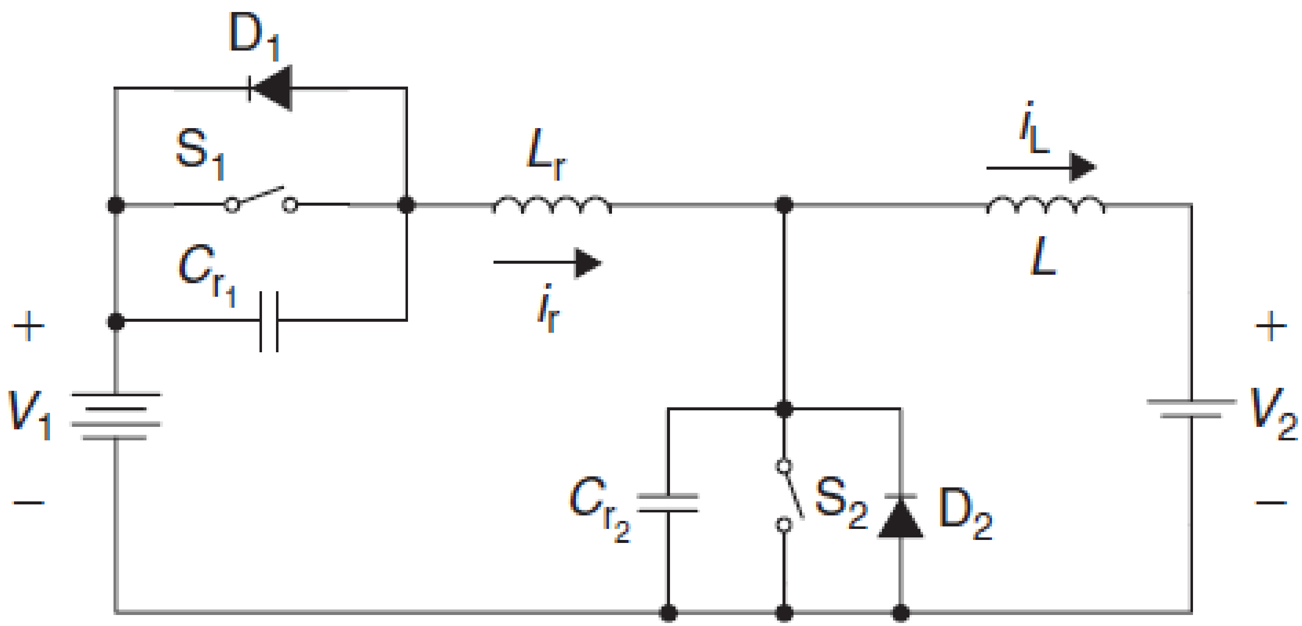


A ZCS QR DC/DC converter. (c) current and voltage waveforms

- The input source voltage V_1 =50V and output load voltage V_2 =30V. The load R=3 ohm and load current I_2 =10A. The circuit diagram is shown in Figure (a)
- To simplify the analysis and calculation, the load current is assumed as a constant value.
- The equivalent circuit is shown in Figure (b), and the corresponding waveforms of the resonant current $i_{Lr}(t)$ and resonant voltage $v_{Cr}(t)$ are shown in Figure (c).
- Since the power losses are very low, the energy transfer efficiency (η) can be very high.
- The transferred power is 300W, and the power density is about 15 W/in.^{3} with the converter's volume (size: 2×2.5×4 in.^{3}) to be 20in.^{3}

Zero-Voltage-Switching Quasi-Resonant Converters

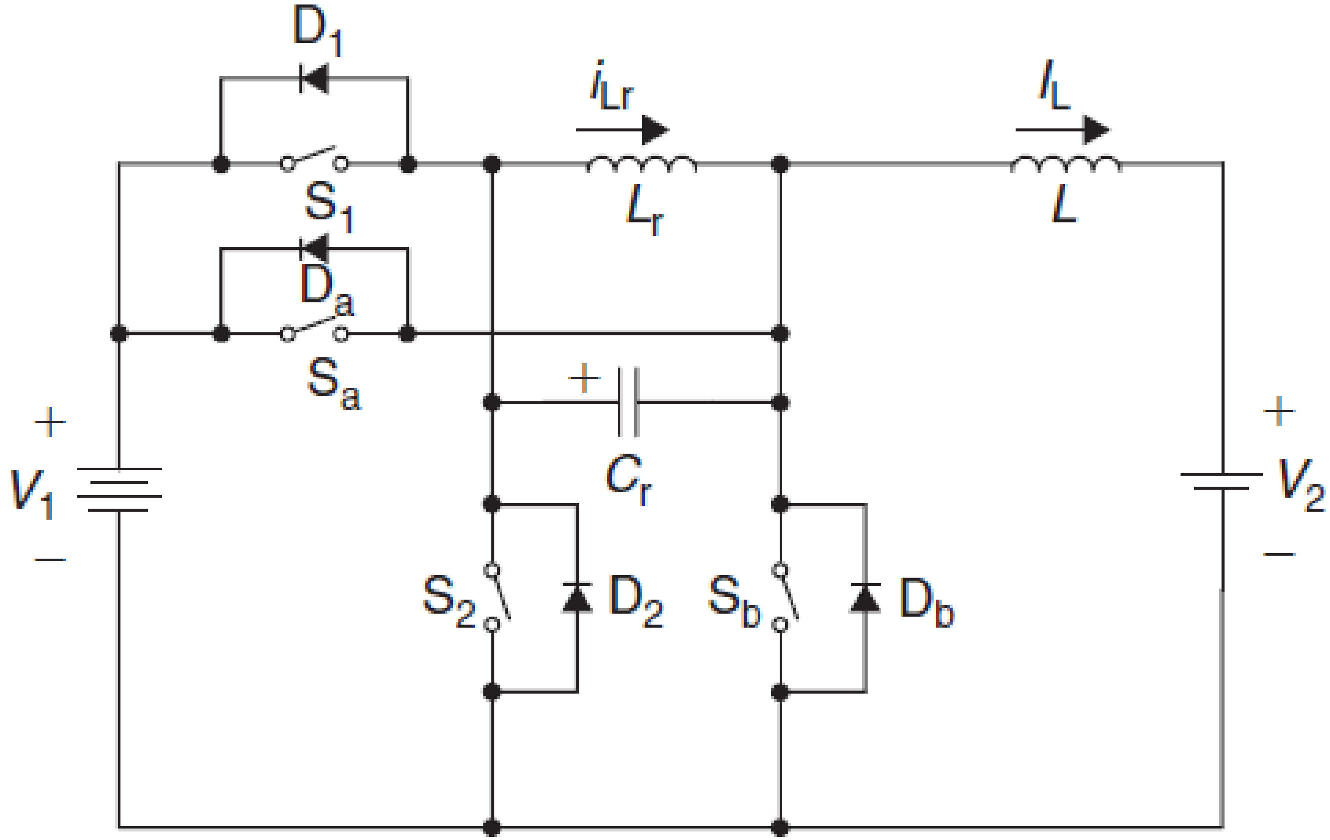
- ZVS-QRC equips resonant circuit in the switch side to keep the switch-on and switch-off at zero-voltage condition.
- There are two states: full- and half-wave state.
- Most of engineers enjoy the half-wave state.
- This technique has half-wave voltage resonance waveform with two zero-cross points



- The input source voltage is 14V and output load voltage is 42V. The size of this converter has the volume in 40 in.^{3} and the transfer power is 700W. Therefore, the power density is up to 17.6 W/in.^{3}

Zero-Transition Converters

- Using ZCS-QRC and ZVS-QRC largely reduce the power losses across the switches.
- Consequently, the switch device power rates become lower and converter power efficiency is increased. However, ZCS-QRC and ZVS-QRC have large current and voltage stresses.
- Therefore the device's current and voltage peak rates usually are 3–5 times higher than the working current and voltage.
- It is not only costly, but also ineffectively.
- ZT technique overcomes this fault.
- It implements zero-voltage plus ZCS (ZV-ZCS) technique without significant current and voltage stresses.

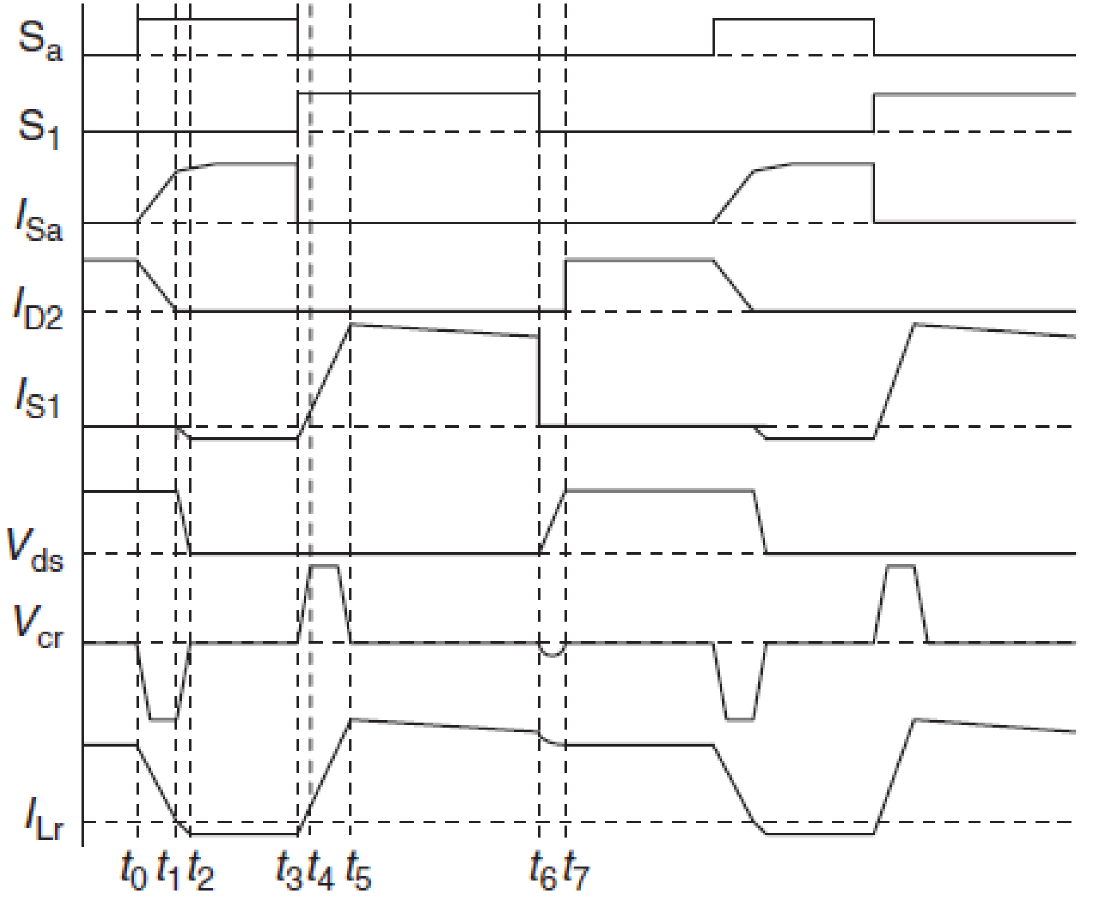


Two-quadrant operation ZT DC/DC converter

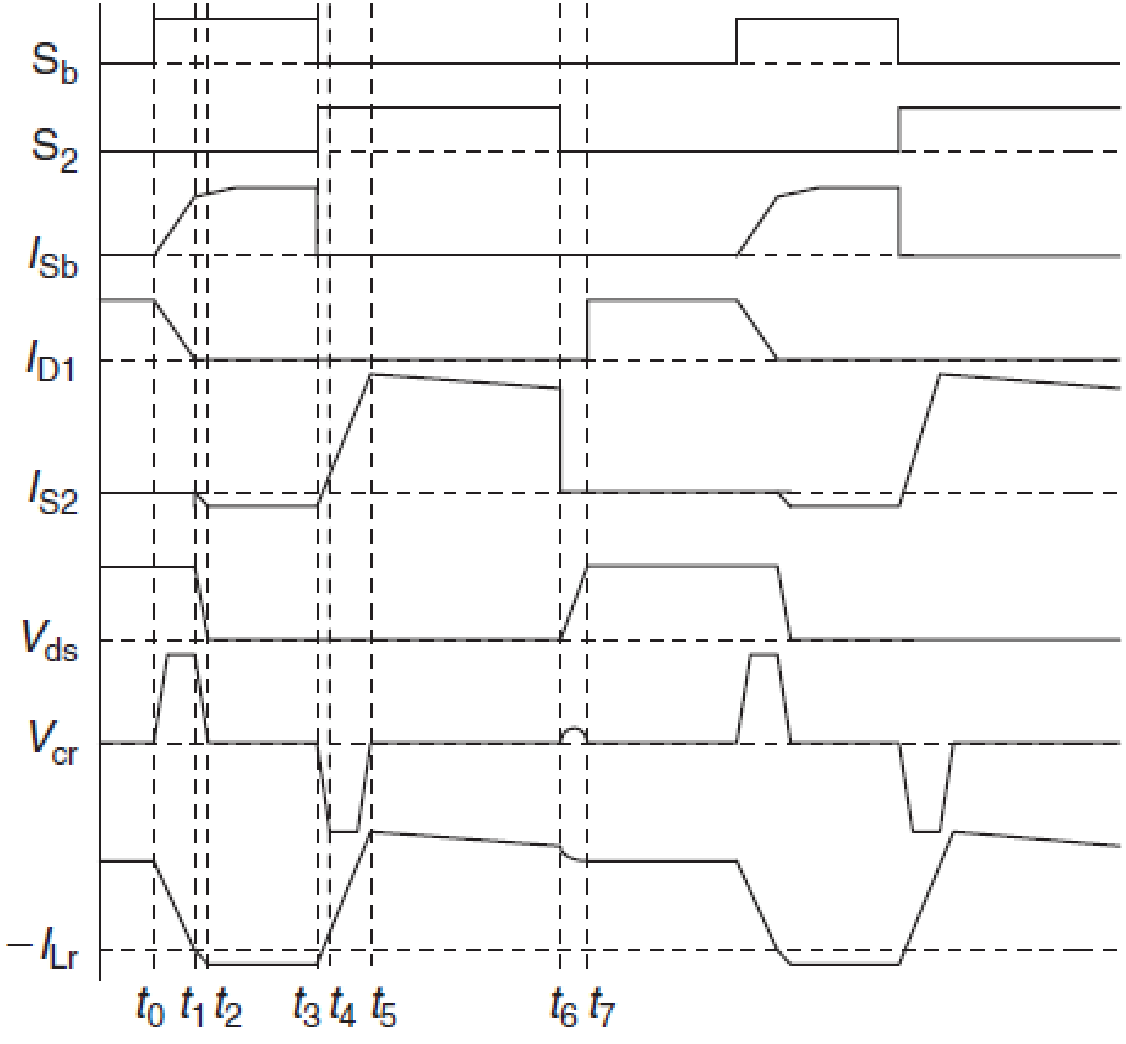
- The input source voltage is 14V and output load voltage is 42V. The operation state and switch/diode status are shown in Table

Switches (S) and diodes' (D) status (the blank status means off).

S&D	Mode A (Q_I)								Mode B (Q_{II})							
	Δt_1	Δt_2	Δt_3	Δt_4	Δt_5	Δt_6	Δt_7	Δt_8	Δt_1	Δt_2	Δt_3	Δt_4	Δt_5	Δt_6	Δt_7	Δt_8
S_1				ON	ON	ON										
D_1									ON							ON
S_a	ON	ON	ON													
D_a															ON	ON
S_2												ON	ON	ON		
D_2	ON							ON								
S_b									ON	ON	ON					
D_b							ON	ON								



Waveforms of Quadrant I operation of the ZT DC/DC converter



Waveforms of Quadrant II operation of the ZT DC/DC converter

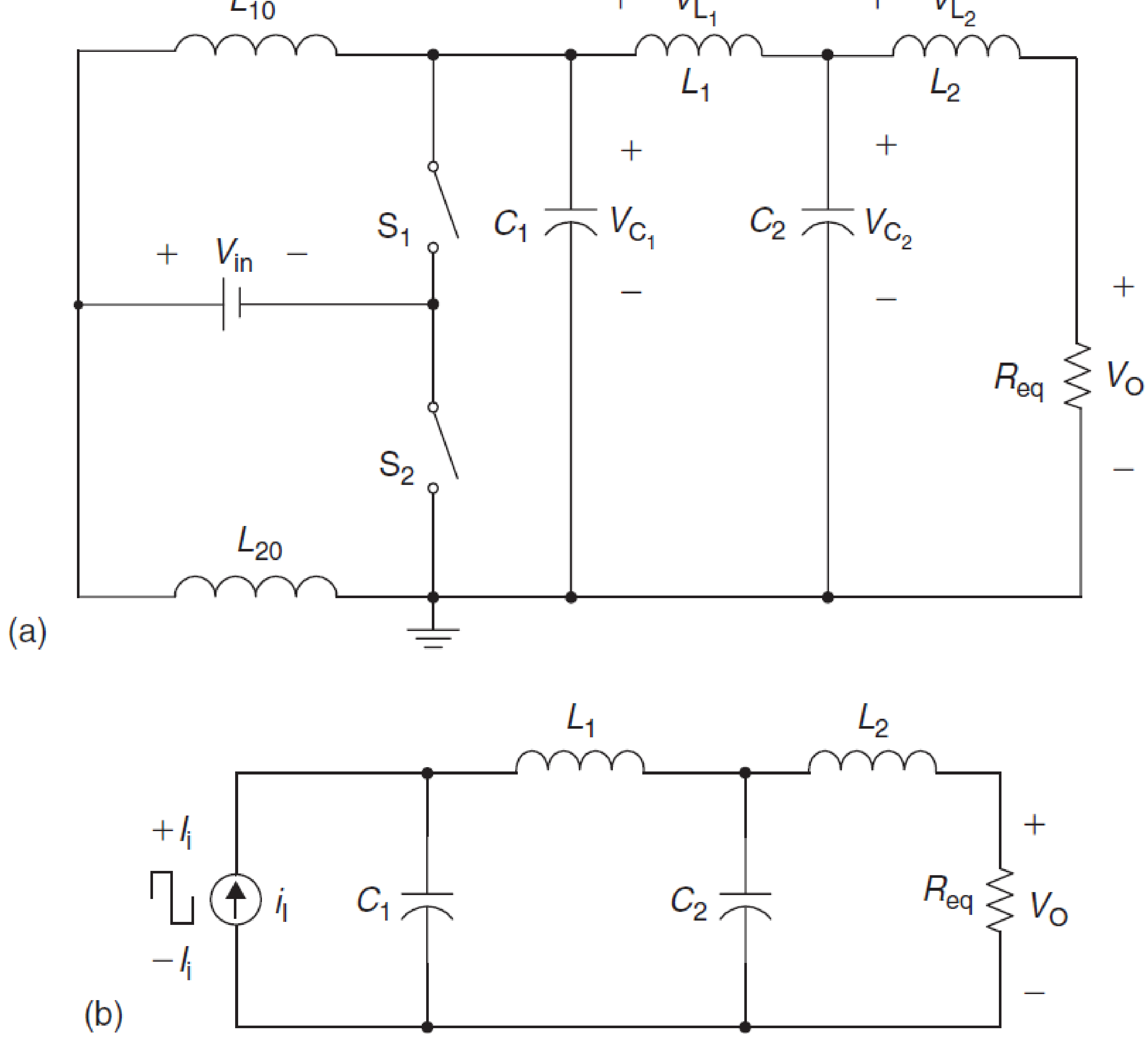
The Sixth-Generation Converters / MER power converters

- The sixth-generation converters are called multiple energy-storage (MER) elements resonant power converters (RPC).
- Current source resonant inverters (CSRIs) are the heart of many systems and equipment, e.g. uninterruptible power supply (UPS) and high-frequency annealing (HFA) apparatus.

- Many topologies shown in open literature are the series resonant converters (SRC) and parallel resonant converters (PRC) that consist of two, three or four energy-storage elements.
- However, they have a lot of the limitations.
- These limitations of two-, three- or/and four-element resonant topologies can be overcome by special design.
- These converters have sorted into three main categories:

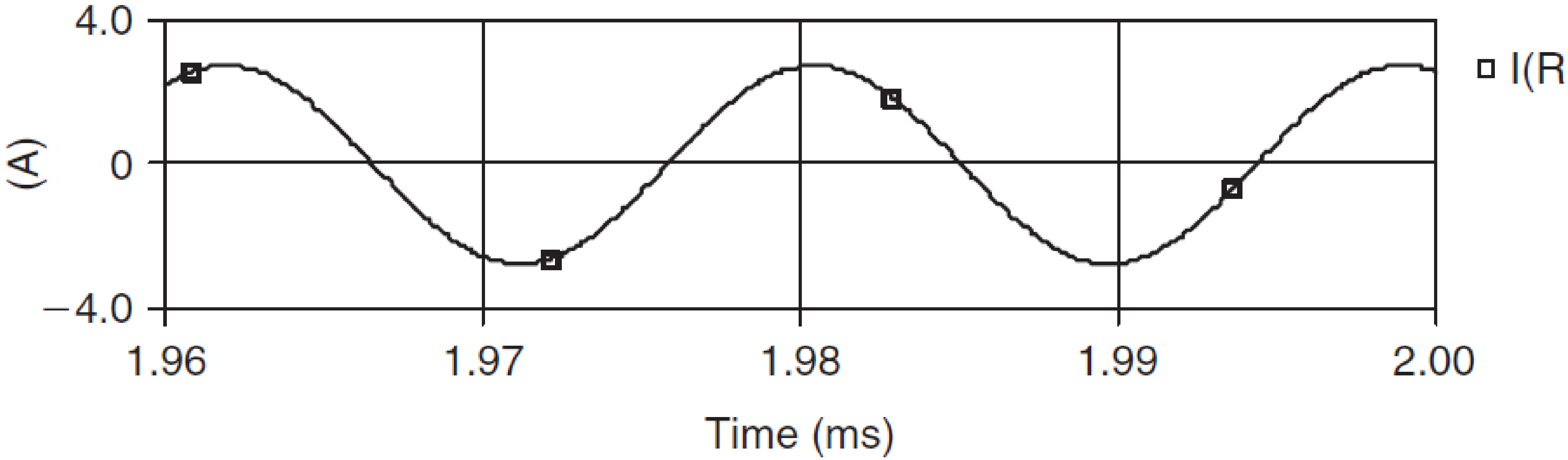
  - Two energy-storage elements resonant DC/AC and DC/AC/DC converters;
  - Three energy-storage elements resonant DC/AC and DC/AC/DC converters;
  - Four energy-storage elements (2L–2C) resonant DC/AC and DC/AC/DC converters.

- By mathematical calculation there are **8** prototypes of 2-element converters, **38** prototypes of 3-element converters and **98** prototypes of 4-element (2L–2C) converters.
- Carefully analyzing these prototypes we can find out that not so many circuits can be realized.
- If we keep the output in low-pass bandwidth, the series components must be inductors and shunt components must be capacitors.
- Furthermore analysis, the first component of the resonant-filter network can be an inductor in series, or a capacitor in shunt.
- In the first case, only alternative (square wave) voltage source can be applied to the network.
- In the second case, only alternative (square wave) current source can be applied to the network.

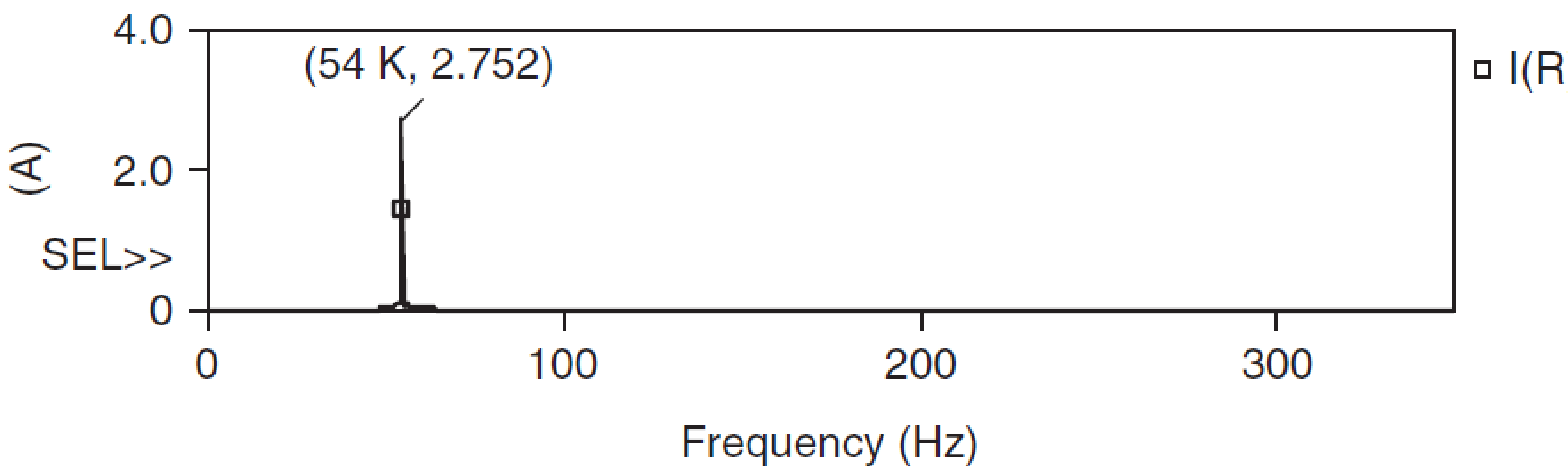


Cascade double Γ–CL current source resonant inverter. (a) Circuit diagram and (b) equivalent circuit.

- Figure (a) shows a cascade double **Γ**–CL current source resonant inverter.
- It consists of four energy-storage elements, the double **Γ**–CL: *C*1–*L*1 and *C*2–*L*2. Its equivalent diagram is shown in Figure (b).
- The energy source is a DC voltage V_{in} chopped by two main switches S1 and S2 to construct a bipolar current source, $i_i = \pm I_i$.
- The pump inductors L_{10} and L_{20} are equal to each other, and are large enough to keep the source current nearly constant during operation.
- The real load absorbs the delivered energy, its equivalent load should be proposed resistive, *R*eq.



Output current waveform of the cascade double Γ–CL CSRI



The FFT spectrum of the output current of the cascade double Γ–CL CSRI

- The input source voltage is V_{in} =30V, L_{10} =L_{20} =20 mH, I_{in}=±1A, Req =10, C_1 =C_2 =C =0.22μF, and L_1 =L_2 =L=100μH.
- The output current waveform is nearly pure sinusoidal function shown in Figure previous slide.
- The corresponding fast Fourier transformation (FFT) spectrum is shown in Figure previous slide and
- The total harmonic distortion (THD) is mostly a 0.

MATHEMATICAL MODELING FOR POWER DC/DC CONVERTERS

- Since the output voltage of a power DC/DC converter is out of control in a period T once the duty cycle k is applied, therefore, it is the element to keep the output voltage in a period $T = 1/f$
- By per-unit system, the voltage transfer gain is unity (1) in a sampling interval

- A power DC/DC converter is a second order element, and its transfer function is:

$$G(s) = \frac{V_O}{V_I}\Big|_{\text{per-unit}} = \frac{1}{1 + s\tau + s^2\tau\tau_d}$$

- ………..(1)
- where τ is the time constant and τ_d is the damping time constant
- In general situation, τ_d is smaller than the critical value $\tau/4$, there are two real poles $-\sigma_1$ and $-\sigma_2$ located in the left-hand half-plane in the s-plane.

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d} = \frac{1/\tau\tau_d}{(s+\sigma_1)(s+\sigma_2)}$$

$$\sigma_1 = \frac{\tau + \sqrt{\tau^2 - 4\tau\tau_\mathrm{d}}}{2\tau\tau_\mathrm{d}} \quad \text{and} \quad \sigma_2 = \frac{\tau - \sqrt{\tau^2 - 4\tau\tau_\mathrm{d}}}{2\tau\tau_\mathrm{d}}$$

- Correspondingly, a power DC/DC converter is an single-order hold (SOH) in the *z*-domain

$$G(z) = \mathbb{Z}[G(s)] = \mathbb{Z}\left[\frac{1/\tau\tau_\mathrm{d}}{(s+\sigma_1)(s+\sigma_2)}\right] = \frac{1}{\tau\tau_\mathrm{d}(\sigma_2 - \sigma_1)}\left(\frac{z}{z - \mathrm{e}^{-T\sigma_1}} - \frac{z}{z - \mathrm{e}^{-T\sigma_2}}\right)$$

- Expanding and simplifying the above Equation

$$G(z) = \frac{M}{\sqrt{\tau^2 - 4\tau\tau_d}}\left[\frac{z}{z - e^{-\sigma_1 T}} - \frac{z}{z - e^{-\sigma_2 T}}\right]$$

$$= \frac{Mz}{\sqrt{\tau^2 - 4\tau\tau_d}}\left[\frac{e^{-\sigma_1 T} - e^{-\sigma_2 T}}{(z - e^{-\sigma_1 T})(z - e^{-\sigma_2 T})}\right]$$

$$= \frac{Mz\left(e^{-\left(\frac{\tau - \sqrt{\tau^2 - 4\tau\tau_d}}{2\tau\tau_d}\right)T} - e^{-\left(\frac{\tau + \sqrt{\tau^2 - 4\tau\tau_d}}{2\tau\tau_d}\right)T}\right)}{\sqrt{\tau^2 - 4\tau\tau_d}\left(z - e^{-\left(\frac{\tau - \sqrt{\tau^2 - 4\tau\tau_d}}{2\tau\tau_d}\right)T}\right)\left(z - e^{-\left(\frac{\tau + \sqrt{\tau^2 - 4\tau\tau_d}}{2\tau\tau_d}\right)T}\right)}$$

- As

$$\sigma_1 - \sigma_2 = \frac{\sqrt{\tau^2 - 4\tau\tau_d}}{\tau\tau_d}$$

- It means that the DC/DC converter performs a second-order response without oscillation

- In some applications, τ_d is greater than the critical value $\tau/4$, there are a couple of conjugating poles $-s_1$ and $-s_2$ located in the left-hand half-plane in the s-plane.
- As discussed earlier, Equation (1) is rewritten as:

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d} = \frac{1/\tau\tau_d}{(s + s_1)(s + s_2)}$$

where $s_1 = \sigma + j\omega$ and $s_2 = \sigma - j\omega$

$$\sigma = \frac{1}{2\tau_d} \quad \text{and} \quad \omega = \frac{\sqrt{4\tau\tau_d - \tau^2}}{2\tau\tau_d}$$

- Correspondingly, the power DC/DC converter is an SOH in the *s*-domain and is rewritten as:

$$G(s) = \frac{M/\tau\tau_d}{(s+\sigma+j\omega)(s+\sigma-j\omega)} = \frac{M/\tau\tau_d}{(s+\sigma)^2+\omega^2} = \frac{M}{\tau\tau_d\omega} \times \frac{\omega}{(s+\sigma)^2+\omega^2}$$

$$= \frac{2M}{\sqrt{4\tau\tau_d-\tau^2}} \times \frac{\omega}{(s+\sigma)^2+\omega^2}$$

- Applying Z transformation, the mathematical modeling for the SOH for large damping time constant is:

$$G(z) = \frac{2M}{\sqrt{4\tau\tau_d-\tau^2}} \frac{z e^{-aT}\sin\omega T}{z^2 - 2z e^{-aT}\cos\omega T + e^{-2aT}}$$

where $\sigma = a = 1/2\tau_d$

- Expanding and simplifying the above Equation

$$G(z) = \frac{2Mz\mathrm{e}^{-aT}\sin\omega T}{\sqrt{4\tau\tau_\mathrm{d} - \tau^2}(z^2 - 2z\mathrm{e}^{-aT}\cos\omega T + \mathrm{e}^{-2aT})}$$

$$= \frac{2Mz\mathrm{e}^{-T/2\tau_\mathrm{d}}\sin\left(\frac{\sqrt{4\tau\tau_\mathrm{d}-\tau^2}}{2\tau\tau_\mathrm{d}} \times T\right)}{\sqrt{4\tau\tau_\mathrm{d} - \tau^2}\left(z^2 - 2z\mathrm{e}^{-T/2\tau_\mathrm{d}}\cos\left(\frac{\sqrt{4\tau\tau_\mathrm{d}-\tau^2}}{2\tau\tau_\mathrm{d}}\right) + \mathrm{e}^{-T/\tau_\mathrm{d}}\right)}$$

- It means that the DC/DC converter performs a second-order response with oscillation in one-step delay (*T*) in a digital control system

MATHEMATICAL MODELING OF FUNDAMENTAL DC/DC CONVERTER

- Fundamental DC/DC converters such as buck, boost and buck–boost converters consist of one capacitor and one inductor; therefore, the modeling is simple
- In most industrial applications, power DC/DC converters work in the continuous conduction mode (CCM), and perform in the case with small damping time constant.
- For example, the inductor L is in mH and capacitor C is in μF.
- Usually, the time constant τ is large enough, and damping time constant τ_d is smaller than the critical value $\tau/4$.

- Question
- Refer to the buck converter discussed earlier, assume the following conditions.
- V_1 =40V, L=1 mH, C =40μF, f =20 kHz (T =50μs), k =0.4 and R=1 ohm power losses are ignored. We get V_2 =16V, I_2 =I_L =16A, I_1 =6.4A.

- The mathematical model components are:

$$PE = V_1 I_1 T = 40 \times 6.4 \times 50\mu = 12.8\,\text{mJ}$$

$$W_\text{L} = \frac{1}{2} L I_\text{L}^2 = \frac{1}{2} 1m \times 16^2 = 128\,\text{mJ}$$

$$W_\text{C} = \frac{1}{2} C V_\text{C}^2 = \frac{1}{2} 40\mu \times 16^2 = 5.12\,\text{mJ}$$

$$SE = W_\text{L} + W_\text{C} = 128 + 5.12 = 133.12\,\text{mJ}$$

$$EF = \frac{SE}{PE} = \frac{133.12}{12.8} = 10.4$$

$$CIR = \frac{W_C}{W_L} = \frac{5.12}{128} = 0.04$$

since $EL = 0$, efficiency $(\eta) = 1$.

$$\tau = \frac{2T \times EF}{1 + CIR} = \frac{100\mu \times 10.4}{1.04} = 1\,\text{ms}$$

$$\tau_\text{d} = \frac{2T \times EF}{1 + CIR} CIR = \frac{100\mu \times 10.4 \times 0.04}{1.04} = 40\,\mu\text{s}$$

$$\xi = \frac{\tau_\text{d}}{\tau} = CIR = 0.04 < 0.25$$

$$\sigma_1 = \frac{\tau + \sqrt{\tau^2 - 4\tau\tau_\text{d}}}{2\tau\tau_\text{d}} = \frac{1m + \sqrt{1\mu - 160n}}{80n} = \frac{1 + 0.9165}{80\mu}$$

$$= \frac{1}{0.0000417} = 23.96\,\text{kHz}$$

$$\sigma_2 = \frac{\tau - \sqrt{\tau^2 - 4\tau\tau_\mathrm{d}}}{2\tau\tau_\mathrm{d}} = \frac{1m - \sqrt{1\mu - 160n}}{80n} = \frac{1 - 0.9165}{80\mu}$$

$$= \frac{1}{0.000958} = 1.044\,\mathrm{kHz}$$

- The corresponding transfer function in per-unit system is:

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_\mathrm{d}} = \frac{1/\tau\tau_\mathrm{d}}{(s+\sigma_1)(s+\sigma_2)}$$

- We know that σ_1 is much larger than σ_2, so that the term $e^{-\sigma 1t}$ is much smaller than the term $e^{-\sigma 2t}$. It is reasonable to ignore the expression involving the term $e^{-\sigma 1t}$.
- The unit-step response is:

$$v_2(t) = 16(1 + K_1 e^{-\sigma_1 t} + K_2 e^{-\sigma_2 t}) = 16(1 + 0.0455 e^{-\frac{t}{0.0000417}} - 1.0455 e^{-\frac{t}{0.000958}})$$

where:

$$K_1 = -\frac{1}{2} + \frac{\tau}{2\sqrt{\tau^2 - 4\tau\tau_d}} = -0.5 + \frac{1}{2\sqrt{1^2 - 0.16}} = -0.5 + 0.5455 = 0.0455$$

$$K_1 = -\frac{1}{2} + \frac{\tau}{2\sqrt{\tau^2 - 4\tau\tau_d}} = -0.5 - \frac{1}{2\sqrt{1^2 - 0.16}} = -0.5 - 0.5455 = -1.0455$$

or

$$v_2(t) \approx 16(1 - \mathrm{e}^{-\frac{t}{0.000958}})$$

The impulse response is:

$$\Delta v_2(t) = \frac{U}{\sqrt{1 - 4\tau_\mathrm{d}/\tau}}(\mathrm{e}^{-\sigma_2 t} - \mathrm{e}^{-\sigma_1 t}) = 1.0911U(\mathrm{e}^{-\frac{t}{0.000958}} - \mathrm{e}^{-\frac{t}{0.0000417}})$$

or

$$\Delta v_2(t) \approx U\mathrm{e}^{-\frac{t}{0.000958}}$$

- Where U is the interference. From the above analysis and calculation, the corresponding transfer function in per-unit system in the *s*-domain can be approximately written as:

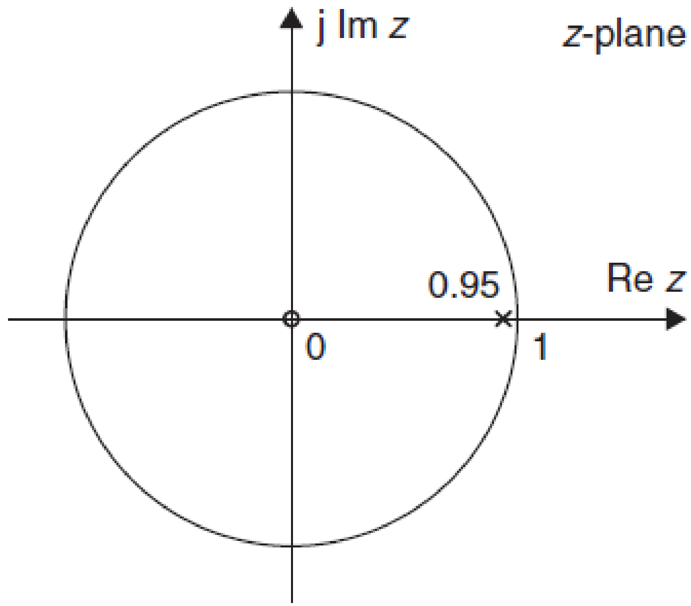
$$G(s) \approx \frac{1}{1 + s\tau_e}$$

- where τe is the equivalent time constant τ_e =0.000958 s ≈ 1ms=τ.
- The corresponding transfer function in per-unit system in the *z*-domain can be approximately written as:

$$G(z) \approx \frac{z}{z - e^{-T/\tau_e}}$$

- where T is the sampling interval (T =50μs). Since T/τ_e is very small nearly 0.05, so that:

$$G(z) \approx \frac{z}{z - e^{-T/\tau_e}} \approx \frac{z}{z - 1 + T/\tau_e} \approx \frac{z}{z - 0.95}$$



The zero's and pole's locations of a buck converter

- The transfer function has one pole and one zero. The pole is at z =0.95 inside the unity-cycle, the zero is at z =0 at the original point.
- Therefore, this converter is stable element. The zero's and pole's locations of this buck converter are shown in previous slide.

MATHEMATICAL MODELING OF DEVELOPED DC/DC CONVERTERS

- Most power DC/DC converters consist of multiple (more than two) passive energy stored components.
- In traditional method, they have higher-order transfer function.
- For example, the developed DC/DC converters such as positive/negative output Luo-converters, Cúk converter and SEPIC consist of two capacitors and two inductors.

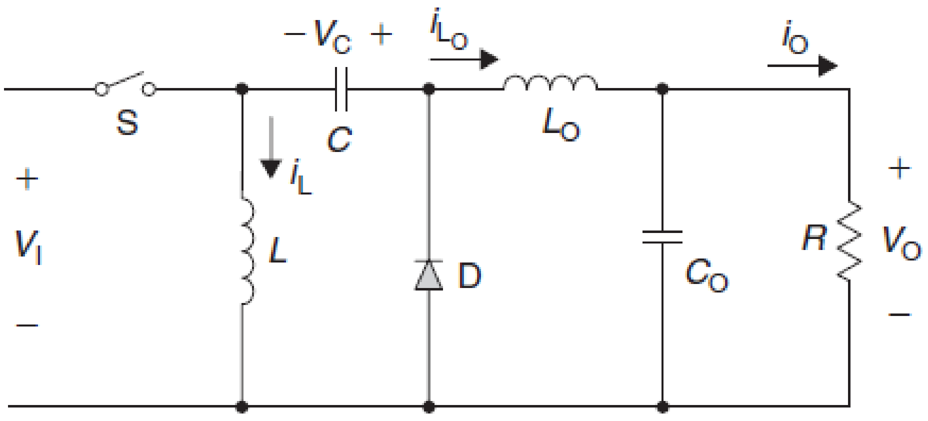


Fig: P/O Luo-converter

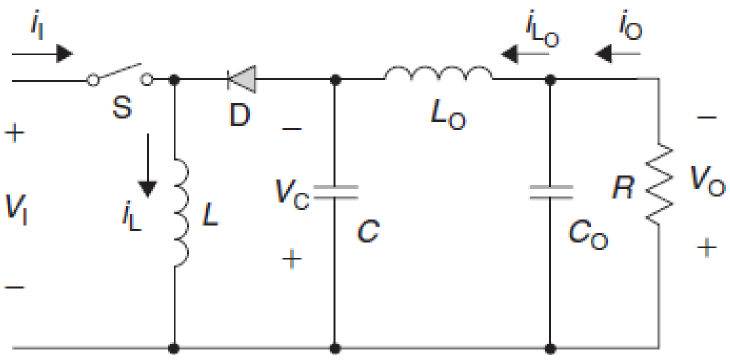


Fig: N/O Luo-converter

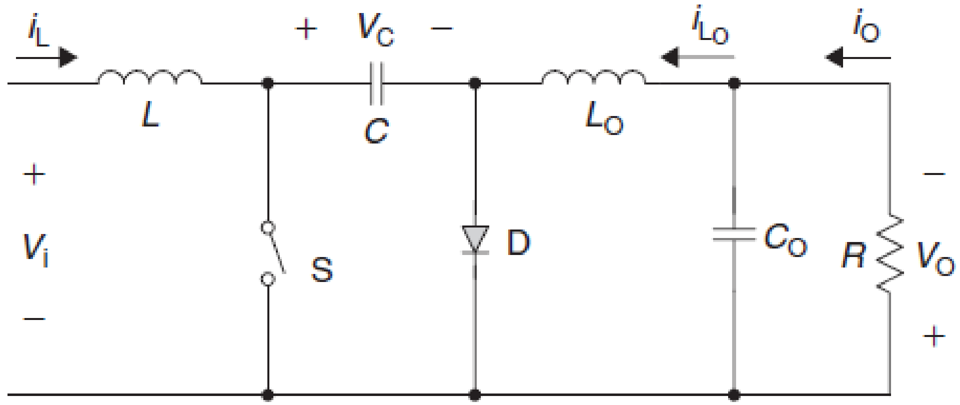


Fig: Cuk converter

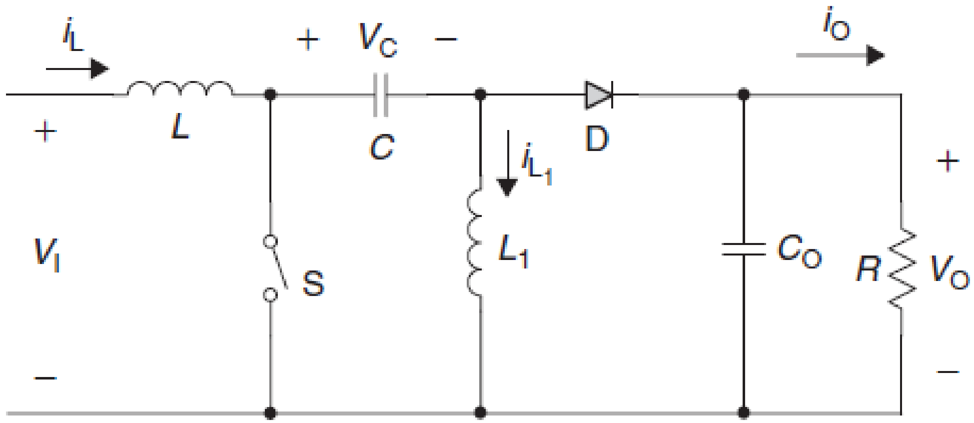


Fig: SEPIC

- In most industrial applications, power DC/DC converters work in the CCM, and perform in the case with small damping time constant.
- For example, the inductor, *L*, is in mH and capacitor, *C*, is in μF. Usually, the time constant τ is large enough, and damping time constant τd is smaller than the critical value $\tau/4$

Question:

- Refer to the N/O Luo-converter shown in Figure Assume the following conditions

  V_1=40V, L=L_O=5 mH, C =C_O=20μF, f =20 kHz (T =50μs), k =0.5 and

  R=2ohm power losses are ignored. We get V_O=40V,V_C=V_{CO} =40V, I_O=I_{LO}=20A, I_1=I_L=20A.

Find the transfer function of the converter and comment on the stability of the circuit.

- The mathematical model components are:

$$PE = V_1 I_1 T = 40 \times 20 \times 50\mu = 40\,\mathrm{mJ}$$

$$W_\mathrm{L} = \frac{1}{2} L I_\mathrm{L}^2 + \frac{1}{2} L_\mathrm{O} I_\mathrm{LO}^2 = 5m \times 20^2 = 2\,\mathrm{J}$$

$$W_\mathrm{C} = \frac{1}{2} C_\mathrm{O} V_\mathrm{CO}^2 + \frac{1}{2} C V_\mathrm{C}^2 = 20\mu \times 40^2 = 32\,\mathrm{mJ}$$

$$SE = W_\mathrm{L} + W_\mathrm{C} = 2000 + 32 = 2032\,\mathrm{mJ}$$

$$EF = \frac{SE}{PE} = \frac{2032}{40} = 50.8$$

$$CIR = \frac{W_C}{W_L} = \frac{32}{2000} = 0.016$$

since $EL = 0$, efficiency $(\eta) = 1$.

$$\tau = \frac{2T \times EF}{1 + CIR} = \frac{100\mu \times 50.8}{1.016} = 5\,\text{ms}$$

$$\tau_d = \frac{2T \times EF}{1 + CIR} CIR = \frac{100\mu \times 50.8 \times 0.016}{1.016} = 80\,\mu\text{s}$$

$$\xi = \frac{\tau_d}{\tau} = CIR = 0.016 << 0.25$$

- Since the damping time constant τd is much smaller than time constant τ, the corresponding transfer function in per-unit system is considered as:

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d} \approx \frac{1}{1 + s\tau} = \frac{1}{1 + 0.005s}$$

The unit-step response is:

$$v_O(t) = 40(1 - e^{-\frac{t}{\tau}}) = 40(1 - e^{-\frac{t}{0.005}})$$

The impulse response is:

$$\Delta v_O(t) = Ue^{-\frac{t}{\tau}} = Ue^{-\frac{t}{0.005}}$$

- where *U* is the interference. The corresponding transfer function in per-unit system in the *z*-domain can be approximately written as:

$$G(z) \approx \frac{z}{z - e^{-T/\tau}} = \frac{z}{z - e^{-50\mu/5m}} = \frac{z}{z - e^{-0.01}} = \frac{z}{z - 0.99}$$

- where T is the sampling interval (T =50µs) and τ is the time constant (τ =5 ms), so that T/τ is very small to be equal to 0.01. The transfer function has one pole and one zero.
- The pole is at z =0.99 inside the unity-cycle; therefore, this converter is stable circuit.

- The zero’s and pole’s locations of this converter are shown as

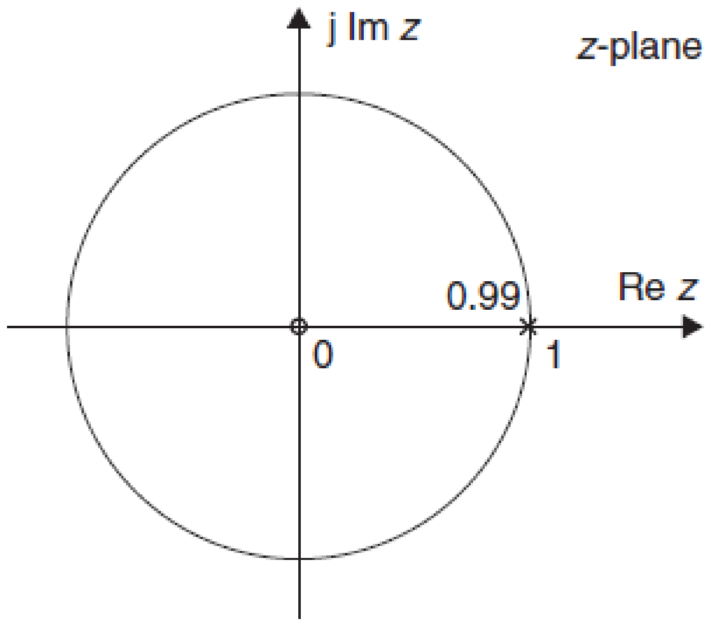


Fig: The zero’s and pole’s locations of a N/O Luo-converter

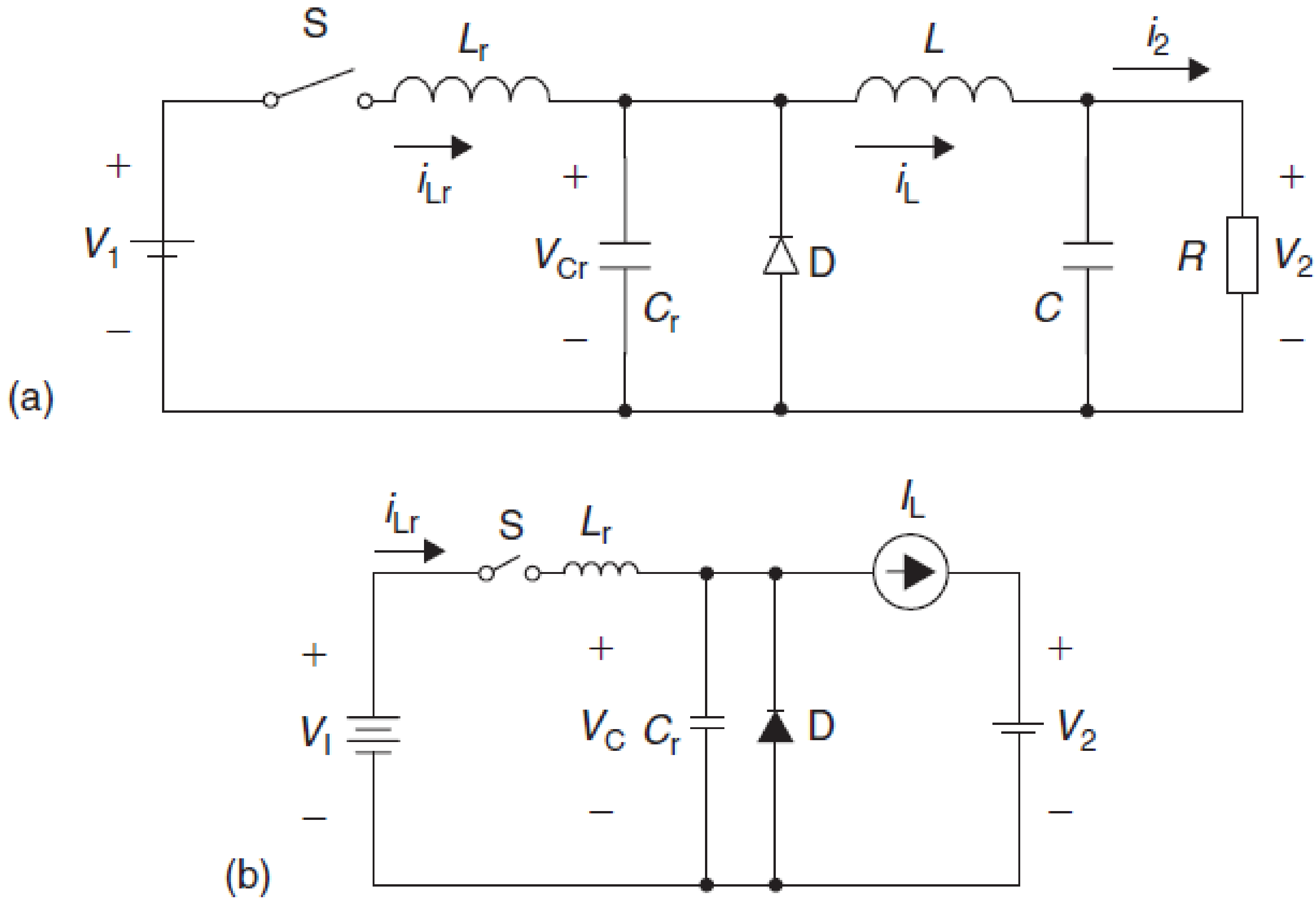
SOFT-SWITCHING CONVERTERS

- In order to reduce the power losses soft-switching technique has been applied in both research and industrial application
- Soft-switching converters are sorted in three categories:

❖ ZCS converters,

❖ ZVS converters,

❖ ZT converters.



A ZCS QR DC/DC converter. (a) Circuit diagram, (b) equivalent circuit diagram

- For high-accuracy consideration we can estimate the energy stored in a resonant circuit is:

$$E_{res} = W_{L_r} + W_{C_r} = \frac{1}{2}\int_{t_{res}} \left[L_r i_{L_r}^2(t) + C_r v_{C_r}^2(t)\right]dt$$

- where t_{res} is the resonant process time-length, i_{Lr} (t) is the resonant inductor instantaneous current in the resent process and v_{Cr} (t) is the resonant capacitor instantaneous voltage in the resent process.
- For a pure resonance period the functions i_{Lr} (t) and v_{Cr} (t) should be sinusoidal function.
- The energy stored in the inductor and capacitor is fully transferred to each other in a quarter cycles

$$i_{\mathrm{L_r}}(t) = I_{\mathrm{O}} \sin \omega_{\mathrm{r}} t$$

$$v_{\mathrm{C_r}}(t) = V \sin\left(\omega_{\mathrm{r}} t - \frac{\pi}{2}\right)$$

with

$$I_{\mathrm{O}} = \frac{V}{\sqrt{L_{\mathrm{r}}/C_{\mathrm{r}}}} \quad \text{and} \quad \omega_{\mathrm{r}} = \frac{1}{\sqrt{L_{\mathrm{r}} C_{\mathrm{r}}}}$$

- The average energy stored in the inductor is:

$$W_{\mathrm{Lr}} = \frac{1}{2} \int_{t_{\mathrm{res}}} L_{\mathrm{r}} i_{\mathrm{L_r}}^2(t) \mathrm{d}t = \frac{1}{2} L_{\mathrm{r}} \left(\frac{I_{\mathrm{O}}}{\sqrt{2}}\right)^2 = \frac{C_{\mathrm{r}}}{4} V^2$$

- The average energy stored in the capacitor is:

$$W_{\mathrm{Cr}} = \frac{1}{2}\int_{t_{\mathrm{res}}} C_{\mathrm{r}} v_{\mathrm{C_r}}^2(t)\mathrm{d}t = \frac{1}{2}C_{\mathrm{r}}\left(\frac{V}{\sqrt{2}}\right)^2 = \frac{C_{\mathrm{r}}}{4}V^2$$

- The average energy stored in whole resonant circuit is:

$$E_{\mathrm{r}} = W_{\mathrm{L_r}} + W_{\mathrm{C_r}} = \frac{1}{2}C_{\mathrm{r}}V^2$$

- The resonant inductor L_r is usually in μH that is much lower than the main inductor, and the capacitor C_r is usually in μF that maybe lower than the main capacitor.
- Therefore the stored energy in the resonant circuit can be ignored in brief calculation.

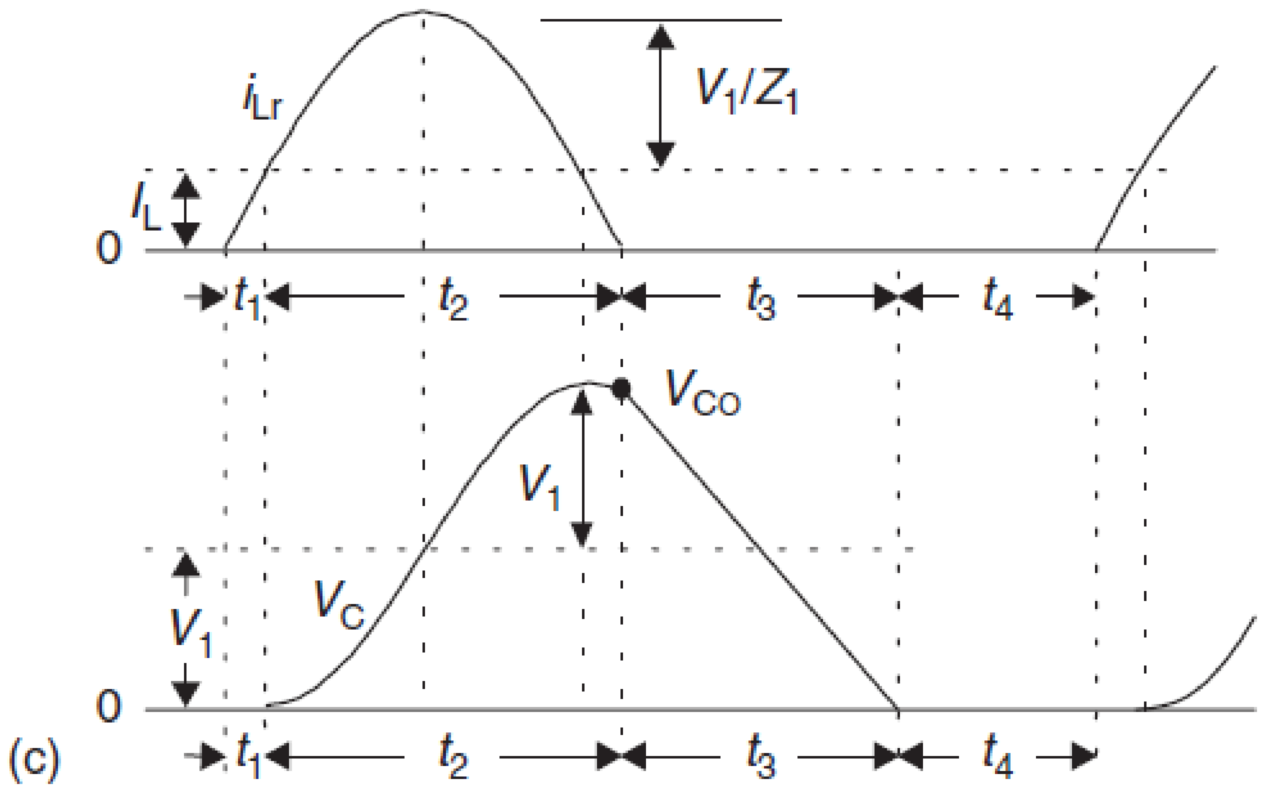
Question:

Consider a ZCS buck converter in which the components are: V_1 =50V, I_1 =6A, L=10 mH, C =60μF, L_r =4μH, C_r =1μF, output voltage V_2 =30V the load R=3 and I_2 =10A. Determine the dynamics of the converter and comment on stability.

$$\omega = \frac{1}{\sqrt{L_r C_r}} = \frac{1}{\sqrt{4\mu \times 1\mu}} = 500000\,\text{rad}$$

$$Z = \sqrt{\frac{L_r}{C_r}} = \sqrt{\frac{4\mu}{1\mu}} = 2\,\Omega$$

$$\alpha = \sin^{-1}\frac{ZI_2}{V_1} = \sin^{-1}\frac{2 \times 10}{50} = \sin^{-1} 0.4 = 0.41\,\text{rad}$$



(c) current and voltage waveforms

$$t_1 = \frac{L_r I_2}{V_1} = \frac{4 \times 10}{50} = 0.8\,\mu\text{s}$$

$$t_2 = \frac{\pi + \alpha}{\omega} = \frac{3.552}{500000} = 7.1\,\mu\text{s}$$

$$t_3 = \frac{V_1(1 + \cos\alpha)C_r}{I_2} = \frac{50 \times 1.9165 \times 1\mu}{10} = 4.58\,\mu\text{s}$$

$$t_4 = \frac{V_1(t_1 + t_2)}{V_2 I_2}\left(I_2 + \frac{V_1}{Z}\frac{2\cos\alpha}{\alpha + \pi/2}\right) - (t_1 + t_2 + t_3) = 5.05\,\mu\text{s}$$

$$T = t_1 + t_2 + t_3 + t_4 = 17.53\,\mu\text{s}$$

$$f = 1/T = \frac{1}{17.528} = 57\,\text{kHz}$$

$$k = \frac{t_1 + t_2}{T} = \frac{7.9}{17.53} = 0.45\,\mu\text{s}$$

The resonant stored energy is:

$$E_r = W_{L_r} + W_{C_r} = \frac{1}{2}C_r V_1^2 = 0.5\mu \times 50^2 = 1.25\,\text{mJ}$$

Other parameters are:

$$PE = V_1 I_1 T = 50 \times 6 \times 17.53\mu = 5.26\,\text{mJ}$$

$$W_\text{L} = \frac{1}{2} L I_\text{L}^2 = 5m \times 10^2 = 500\,\text{mJ}$$

$$W_\text{C} = \frac{1}{2} C V_\text{C}^2 = 30\mu \times 30^2 = 27\,\text{mJ}$$

$$SE = W_\text{L} + W_\text{C} + E_\text{r} = 500 + 27 + 1.25 = 528.25\,\text{mJ}$$

$$EF = \frac{SE}{PE} = \frac{528.25}{5.26} = 100.43$$

$$CIR = \frac{W_\text{C}}{W_\text{L}} = \frac{27}{500} = 0.054$$

since $EL = 0$, efficiency $\eta = 1$.

$$\tau = \frac{2T \times EF}{1 + CIR} = \frac{2 \times 17.53\mu \times 100.43}{1.054} = 3.34\,\text{ms}$$

$$\tau_\text{d} = \frac{2T \times EF}{1 + CIR} CIR = \frac{2 \times 17.53\mu \times 100.43 \times 0.054}{1.054} = 180\,\mu\text{s}$$

$$\xi = \frac{\tau_\text{d}}{\tau} = CIR = 0.054 \ll 0.25$$

- Since the damping time constant τ_d is much smaller than time constant τ, the corresponding transfer function in per-unit system is considered as:

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d} \approx \frac{1}{1 + s\tau} = \frac{1}{1 + 0.00334s}$$

The unit-step response is:

$$v_O(t) = 30(1 - e^{-\frac{t}{\tau}}) = 30(1 - e^{-\frac{t}{0.00334}})$$

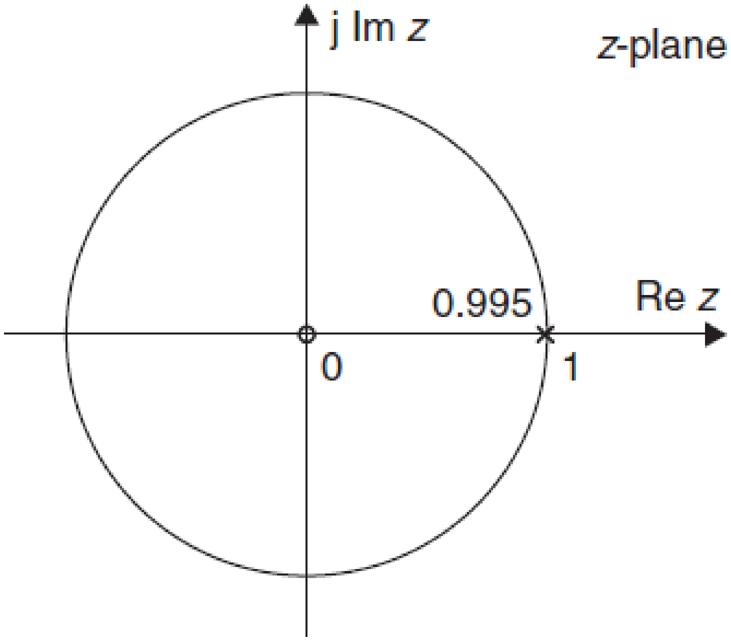
The impulse response is:

$$\Delta v_O(t) = Ue^{-\frac{t}{\tau}} = Ue^{-\frac{t}{0.00334}}$$

- where U is the interference. The corresponding transfer function in per-unit system in the z-domain can be approximately written as:

$$G(z) \approx \frac{z}{z - e^{-T/\tau}} = \frac{z}{z - e^{-17.53\mu/3.34m}} = \frac{z}{z - e^{-0.00525}} = \frac{z}{z - 0.995}$$

- where T is the sampling interval (T =17.53μs) and τ is the time constant (τ =3.34 ms), so that T/τ is very small to be equal to 0.00525.



- The transfer function has one pole and one zero. The pole is at z =0.995 inside the unity-cycle; therefore, this converter is stable circuit. The zero's and pole's locations of this ZCS QR DC/DC converter are shown in Figure

MULTI-ELEMENT RESONANT POWER CONVERTERS

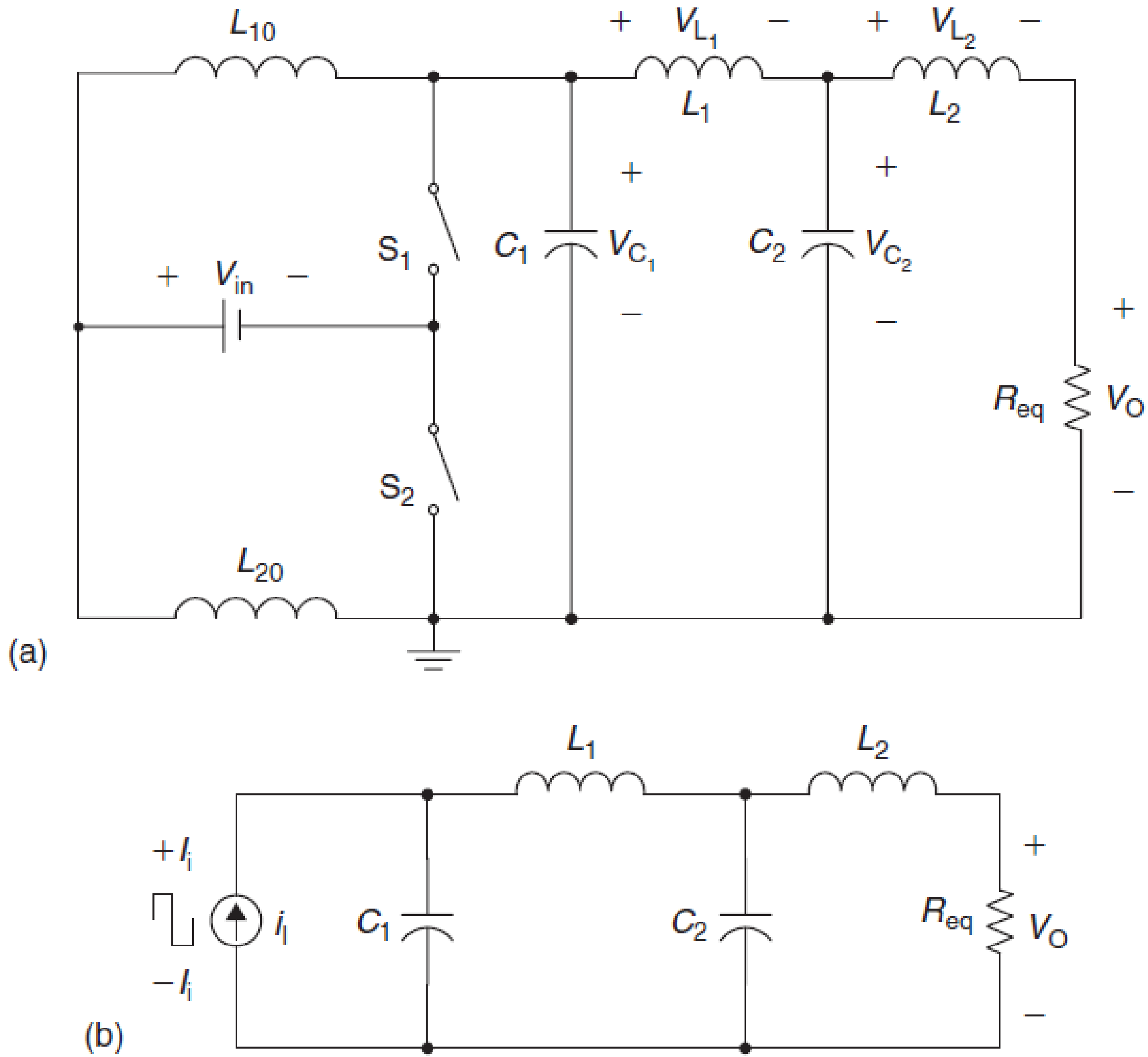
- The sixth-generation converters work in the resonant state to reduce the power losses.
- Depending on the number of the passive components there are few categories:

❖ Two-element RPC;

❖ Three-element RPC;

❖ Four-element (2L–2C) RPC

- All RPCs work in forced resonant state.
- It means that the applied frequency may not be equal to the natural circuit resonant frequency.
- The stored energy in the resonant circuit is AC form.
- A cascade double Γ–LC current source resonant inverter is shown in Figure



Cascade double –CL current source resonant inverter. (a) Circuit diagram and (b) equivalent circuit.

- From the equivalent circuit, the input current $i_i(t)$ is:

$$i_i(t) = \begin{cases} 1\text{ A} & nT \le t < (n+0.5)T \\ -1\text{ A} & (n+0.5)T \le t < (n+1)T \end{cases}$$

The input impedance is given by:

$$Z(\omega) = \frac{R_{\text{eq}}(1-\omega^2 L_1 C_2) + \text{j}\omega(L_1 + L_2 - \omega^2 L_1 L_2 C_2)}{1-\omega^2(L_1C_1 + L_2C_1 + L_2C_2) + \omega^4 L_1 L_2 C_1 C_2 + \text{j}\omega R_{\text{eq}}(C_1 + C_2 - \omega^2 L_1 C_1 C_2)}$$

or

$$Z(\omega) = \frac{R_{\text{eq}}(1-\omega^2 L_1 C_2) + \text{j}\omega(L_1 + L_2 - \omega^2 L_1 L_2 C_2)}{B(\omega)}$$

where

$$B(\omega) = 1-\omega^2(L_1C_1 + L_2C_1 + L_2C_2) + \omega^4 L_1 L_2 C_1 C_2 + \text{j}\omega R_{\text{eq}}(C_1 + C_2 - \omega^2 L_1 C_1 C_2)$$

Voltage and current on capacitor C_1:

$$\frac{V_{C_1}(\omega)}{I_i(\omega)} = \frac{R_{eq}(1-\omega^2 L_1 C_2) + j\omega(L_1 + L_2 - \omega^2 L_1 L_2 C_2)}{B(\omega)}$$

$$\frac{I_{C_1}(\omega)}{I_i(\omega)} = \frac{R_{eq}(1-\omega^2 L_1 C_2) + j\omega(L_1 + L_2 - \omega^2 L_1 L_2 C_2)}{B(\omega)/j\omega C_1}$$

Voltage and current on inductor L_1:

$$\frac{V_{L_1}(\omega)}{I_i(\omega)} = \frac{-R_{eq}\omega^2 L_1 C_2 + j\omega L_1(1-\omega^2 L_2 C_2)}{B(\omega)}$$

$$\frac{I_{L_1}(\omega)}{I_i(\omega)} = \frac{(1-\omega^2 L_2 C_2) + jR_{eq}\omega C_2}{B(\omega)}$$

Voltage and current on capacitor C_2:

$$\frac{V_{\mathrm{C}_2}(\omega)}{I_{\mathrm{i}}(\omega)} = \frac{R_{\mathrm{eq}} + \mathrm{j}\omega L_2}{B(\omega)}$$

$$\frac{I_{\mathrm{C}_2}(\omega)}{I_{\mathrm{i}}(\omega)} = \frac{-\omega^2 L_2 C_2 + \mathrm{j}R_{\mathrm{eq}}\omega C_2}{B(\omega)}$$

Voltage and current on inductor L_2:

$$\frac{V_{\mathrm{L}_2}(\omega)}{I_{\mathrm{i}}(\omega)} = \frac{\mathrm{j}\omega L_2}{B(\omega)}$$

$$\frac{I_{\mathrm{L}_2}(\omega)}{I_{\mathrm{i}}(\omega)} = \frac{1}{B(\omega)}$$

The output voltage and current on the resistor R_{eq}:

$$\frac{V_{\text{O}}(\omega)}{I_{\text{i}}(\omega)} = \frac{R_{\text{eq}}}{B(\omega)}$$

The current transfer gain is given by:

$$g(\omega) = \frac{I_{\text{O}}(\omega)}{I_{\text{i}}(\omega)} = \frac{1}{B(\omega)}$$

- Usually, the input impedance and output current gain draw more attention rather than all transfer functions listed in previous section.
- To simplify the operation, select:

$$L_1 = L_2 = L; \quad C_1 = C_2 = C; \quad \omega_0 = \frac{1}{\sqrt{LC}}$$

$$Z_0 = \sqrt{\frac{L}{C}}; \quad Q = \frac{Z_0}{R_{eq}} = \frac{\omega_0 L}{R_{eq}} = \frac{1}{\omega_0 C R_{eq}}; \quad \beta = \frac{\omega}{\omega_0}$$

Obtain

$$B(\beta) = 1 - 3\beta^2 + \beta^4 + \mathrm{j}\frac{2-\beta^2}{Q}\beta$$

Therefore:

$$Z(\beta) = \frac{(1-\beta^2) + \mathrm{j}Q(2-\beta^2)}{1 - 3\beta^2 + \beta^4 + \mathrm{j}\frac{2-\beta^2}{Q}\beta} R_{eq} = |Z|\angle\phi$$

where

$$|Z| = \frac{\sqrt{(1-\beta^2)^2 + Q^2(2-\beta^2)^2}}{\sqrt{(1-3\beta^2+\beta^4)^2 + \beta^2\left(\frac{2-\beta^2}{Q}\right)^2}} R_{\mathrm{eq}} \quad \text{and}$$

$$\phi = \tan^{-1}\frac{2-\beta^2}{1-\beta^2}Q - \tan^{-1}\frac{(2-\beta^2)\beta}{(1-3\beta^2+\beta^4)Q}$$

The current transfer gain becomes:

$$g(\beta) = \frac{1}{1-3\beta^2+\beta^4+\mathrm{j}\frac{2-\beta^2}{Q}\beta} = |g|\angle\theta$$

where

$$|g| = \frac{1}{\sqrt{(1-3\beta^2+\beta^4)^2 + \beta^2\left(\frac{2-\beta^2}{Q}\right)^2}}$$

and

$$\theta = -\tan^{-1}\frac{(2-\beta^2)\beta}{(1-3\beta^2+\beta^4)Q}$$

Therefore, the voltage and current on capacitor C_1:

$$\frac{V_{\mathrm{C_1}}(\beta)}{I_{\mathrm{i}}(\beta)} = \frac{(1-\beta^2)+\mathrm{j}\beta Q(2-\beta^2)}{B(\beta)} R_{\mathrm{eq}}$$

$$\frac{I_{\mathrm{C_1}}(\beta)}{I_{\mathrm{i}}(\beta)} = \mathrm{j}\frac{(1-\beta^2)+\mathrm{j}\beta Q(2-\beta^2)}{B(\beta)Q}$$

Voltage and current on inductor L_1:

$$\frac{V_{\mathrm{L_1}}(\beta)}{I_{\mathrm{i}}(\beta)} = \frac{-\beta^2+\mathrm{j}\beta Q(1-\beta^2)}{B(\beta)} R_{\mathrm{eq}}$$

$$\frac{I_{\mathrm{L_1}}(\beta)}{I_{\mathrm{i}}(\beta)} = \frac{(1-\beta^2)+\mathrm{j}\beta/Q}{B(\beta)}$$

Voltage and current on capacitor C_2:

$$\frac{V_{C_2}(\beta)}{I_i(\beta)} = \frac{1 + j\beta Q}{B(\beta)} R_{eq}$$

$$\frac{I_{C_2}(\beta)}{I_i(\beta)} = \frac{-\beta^2 + j\beta/Q}{B(\beta)}$$

Voltage and current on inductor L_2:

$$\frac{V_{L_2}(\beta)}{I_i(\beta)} = \frac{j\beta Q}{B(\beta)} R_{eq}$$

$$\frac{I_{L_2}(\omega)}{I_i(\omega)} = \frac{1}{B(\omega)}$$

The output voltage and current on the resistor R_{eq}:

$$\frac{V_o(\omega)}{I_i(\omega)} = \frac{R_{eq}}{B(\omega)}$$

The current transfer gain is given by:

$$g(\beta) = \frac{I_o(\beta)}{I_i(\beta)} = \frac{1}{B(\beta)}$$

- Calculate the energy stored in this resonant circuit as:

$$E_{res} = W_{Lr} + W_{Cr} = \frac{1}{2}\int_{t_{res}} \left[L_1 i_{L_1}^2(t) + L_2 i_{L_2}^2(t) + C_1 v_{C_2}^2(t) + C_2 v_{C_2}^2(t)\right] dt$$

- where t_{res} is the forced resonant process time-length $T = 1/f$, i_{L1} (t) and i_{L2} (t) are the resonant inductor instantaneous currents in the resent process, and v_{C1} (t) and v_{C2} (t) are the resonant capacitor instantaneous voltages in the resent process.

- The energy stored in the inductor and capacitor is fully transferred to each other in a quarter cycles:

$$i_L(t) = I_O \sin \omega t$$

$$v_C(t) = V \sin\left(\omega t - \frac{\pi}{2}\right)$$

where the natural resonant angular frequency is:

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

Question:

- The relevant frequency β is selected as β=1.59. V_{in} =30V, L_{10} =L_{20} =20 mH, I_{in}=±1A, R_{eq} =10, C_1 =C_2 =C =0.22μF and L_1 =L_2 =L=100μH. Therefore, Z_0 =21.32, Q=Z_0/R_{eq} =2.132. The applied frequency f =54 kHz, i.e. T =18.5μs. Find the transfer function of the given converter.

- we have the parameters below:

$$B(\beta) = 1 - 3\beta^2 + \beta^4 + \mathrm{j}\frac{2-\beta^2}{Q}\beta = 1 - 3 \times 1.59^2 + 1.59^4 + \mathrm{j}\frac{2-1.59^2}{2.132}1.59$$

$$|B(\beta)| = 0.4386 \quad \text{or} \quad |g| = \frac{1}{|B(\beta)|} = 2.28$$

$$V_{\mathrm{C}_1} = \frac{(1-\beta^2) + \mathrm{j}\beta Q(2-\beta^2)}{B(\beta)} R_{\mathrm{eq}}$$

$$= \frac{(1-1.59^2) + \mathrm{j} \times 1.59 \times 2.132(2-1.59^2)}{0.4386} \times 10 = 75.66\,\mathrm{V}$$

$$I_{\mathrm{L}_1} = \frac{(1-\beta^2) + \mathrm{j}\beta/Q}{B(\beta)} = \frac{(1-1.59^2) + \mathrm{j}(1.59/2.132)}{0.4386} = 3.88\,\mathrm{A}$$

$$V_{\mathrm{C}_2} = \frac{1 + \mathrm{j}\beta Q}{B(\beta)} R_{\mathrm{eq}} = \frac{1 + \mathrm{j} \times 1.59 \times 2.132}{0.4386} \times 10 = 80.6\,\mathrm{V}$$

$$I_{\mathrm{L}_2} = \frac{1}{B(\beta)} = 2.28\,\mathrm{A}$$

The stored energy as:

$$W_L = \frac{1}{2}LI_{L_1}^2 + \frac{1}{2}LI_{L_2}^2 = 50\mu \times (3.88^2 + 2.28^2) = 1012.6\,\mu\text{J}$$

$$W_C = \frac{1}{2}CV_{C_1}^2 + \frac{1}{2}CV_{C_2}^2 = 0.11\mu \times (75.66^2 + 80.6^2) = 1344.3\,\mu\text{J}$$

Other parameters are:

$$PE = V_1 I_1 T = 30 \times 1 \times 18.5\mu = 555\,\mu\text{J}$$

$$SE = W_L + W_C = 1012.6 + 1344.3 = 2356.9\,\mu\text{J}$$

$$EF = \frac{SE}{PE} = \frac{2356.9}{555} = 4.25$$

$$CIR = \frac{W_C}{W_L} = \frac{1344.3}{1012.6} = 1.33$$

since $EL = 0$, efficiency $\eta = 1$.

$$\tau = \frac{2T \times EF}{1 + CIR} = \frac{2 \times 18.5\mu \times 4.25}{2.33} = 67.5\,\mu\text{s}$$

$$\tau_{\text{d}} = \frac{2T \times EF}{1 + CIR} CIR = \frac{2 \times 18.5\mu \times 4.25 \times 1.33}{2.33} = 90\,\mu\text{s}$$

$$\xi = \frac{\tau_{\text{d}}}{\tau} = CIR = 1.33 > 0.25$$

- Since the damping time constant τ_d is greater than time constant τ, the corresponding transfer function in per-unit system is considered as:

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d} = \frac{1/\tau\tau_d}{(s+s_1)(s+s_2)}$$

where

$$s_1 = \sigma + j\omega \quad \text{and} \quad s_2 = \sigma - j\omega$$

$$\sigma = \frac{1}{2\tau_d} = \frac{1}{0.00018}\ \text{Hz} \quad \text{and} \quad \omega = \frac{\sqrt{4\tau\tau_d - \tau^2}}{2\tau\tau_d} = \frac{\sqrt{24.3n - 4.556n}}{12.15n}$$

$$= \frac{140.5\mu}{12.15n} = 11,565\ \text{rad/s}$$

The transfer function is rewritten as:

$$G(s) = \frac{1/\tau\tau_d}{(s+\sigma)^2+\omega^2} = \frac{2}{\sqrt{4\tau_d/\tau - 1}} \frac{\omega}{(s+\sigma)^2+\omega^2}$$

- The corresponding transfer function in per-unit system in the *z*-domain can be approximately written as:

$$G(z) = \frac{2}{\sqrt{4\tau_d/\tau - 1}} \frac{z e^{-aT} \sin \omega T}{z^2 - 2z e^{-aT} \cos \omega T + e^{-2aT}}$$

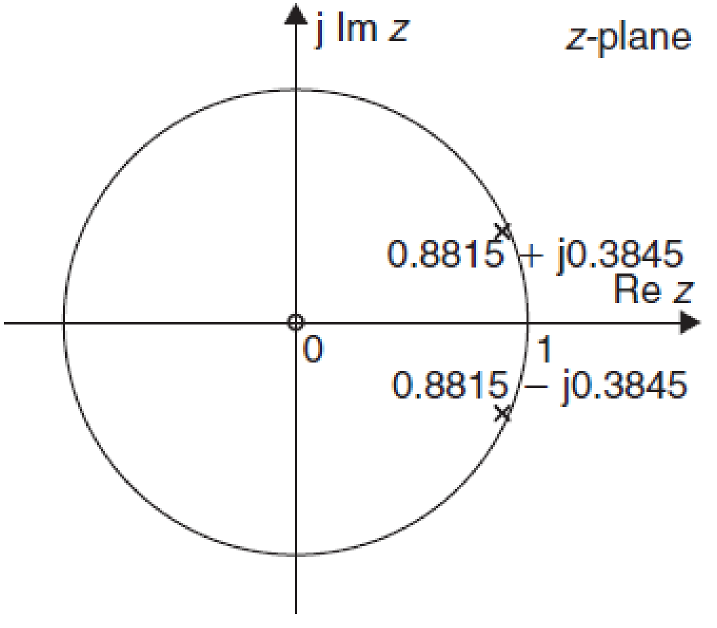
where $a = \sigma = \dfrac{1}{2\tau_d} = \dfrac{1}{180\ \mu s}$, $\omega = 11,565$ rad/s and $T = 18.5\ \mu s$

$$G(z) = \frac{2}{\sqrt{4\tau_d/\tau - 1}} \frac{z e^{-aT} \sin \omega T}{z^2 - 2z e^{-aT} \cos \omega T + e^{-2aT}}$$

$$= \frac{0.96 \times z e^{-0.103} \sin 0.214}{z^2 - 2z e^{-0.103} \cos 0.214 + e^{-0.206}}$$

$$\text{or } G(z) = \frac{0.96 \times z \times 0.902 \times 0.2124}{z^2 - 2z \times 0.902 \times 0.9772 + 0.814} = \frac{0.039065z}{z^2 - 1.763z + 0.814}$$

The transfer function has one zero and two poles. The poles are at $z = 0.8815 \pm j\,0.3845$ inside the unity-cycle; therefore, this converter is stable circuit. The zero's and pole's locations of this cascade double Γ–LC CSRI are shown in Figure 7.38.



Digitally Controlled AC/AC Converters

- AC/AC converters are used for converting one AC power source into another AC power application. They are generally used in following applications:

❖ single-phase AC/AC voltage controllers;

❖ three-phase AC/AC voltage controllers

❖ single-phase input single-phase output (SISO) cycloconverters;

❖ three-phase input single-phase output (TISO) cycloconverters;

❖ three-phase input three-phase output (TITO) cycloconverters;

❖ AC/DC/AC pulse width modulation (PWM) converters;

❖ matrix converters.

- All AC/AC voltage converters convert the voltage from an AC source with high voltage and frequency to the lower output voltage and frequency with little phase angle delayed.

- All AC/AC cycloconverters convert the voltage from an AC source with high voltage and frequency to the lower output voltage and frequency with little phase angle delayed

- All AC/DC/AC converters convert the voltage from an AC source via DC link, then invert to the output load with lower voltage and variable (higher or lower) frequency.

- All AC/AC matrix converters directly convert the voltage from an AC source to the output load with lower voltage and variable (higher or lower) frequency

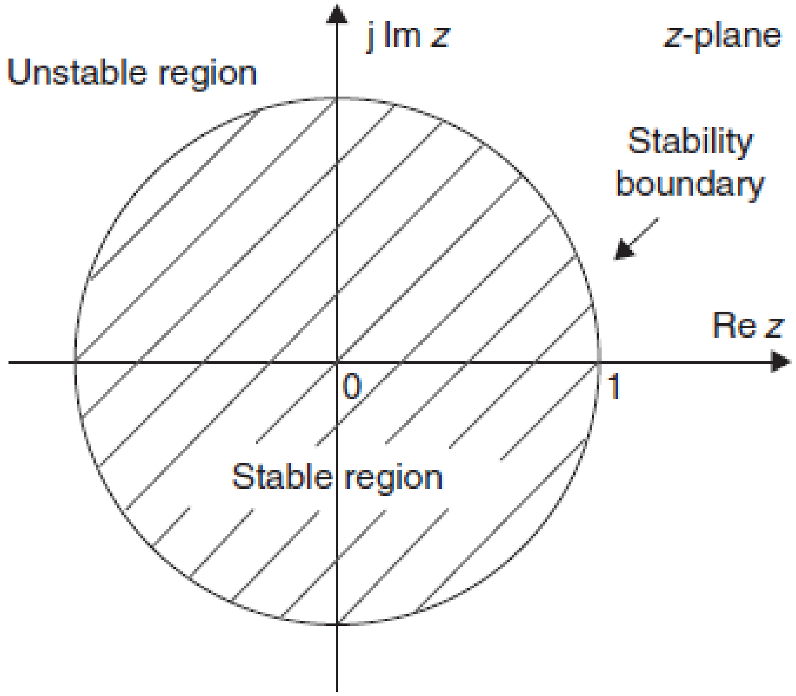
Unit-IV

Open-loop Control for Digital Power Electronics

- The fundamental problems in four main converters: AC/DC rectifiers, DC/AC inverters, DC/DC converters and AC/AC (and AC/DC/AC) converters.
- These problems are:
  - Stability analysis
  - Unity-step responses
  - Impulse (interference) responses

Stability Analysis

- Stability is one of the most important problems of the digital control systems.
- The fundamental stability criterion is zero-pole location adjustment.
- If a digital control system has all poles inside the unity-cycle in the *z*-plane, the system is stable.



Stable/unstable region in the *z*-plane.

- The stable region is inside the unity cycle and the unstable region is outside the unity-cycle.
- If the pole is located on the cycle, it is the critical state of the stability
- Stability of the digital control systems is also possibly adjusted in the *s*-domain. Considering the relation:

$$z = e^{Ts}$$

- Solving for *s*, we obtain:

$$s = \frac{1}{T} \ln z$$

where T is the sampling interval.

Converters Open-Loop Analysis

- We discussed the four typical converters in previous chapters.
- Their mathematical models are the typical elements:

➢ A zero-order-hold (ZOH) for AC/DC rectifiers.

➢ A first-order-hold (FOH) for DC/AC inverters and AC/AC (including AC/DC/AC) converters.

➢ A second-order-hold (SOH) for DC/DC converters.

- By digital control theory, the ZOH,FOH and SOH are considered stable in open-loop control although the ZOH has a pole at z =1 on the stability boundary

Analysis of Converters with a First-Order Load

- Typical first-order load can be an R–L circuit or an R–C circuit.
- Its transfer function in per-unit system in the *s*-domain is:

$$G_1(s) = \frac{1}{1 + s\tau_1}$$

- where $\tau 1$ is the time constant of the first-order load. That is, $\tau 1 = L/R$ for an R–L circuit or $\tau 1 = RC$ for an R–C circuit.

- Its transfer function in per-unit system in the *z*-domain is:

$$G_1(z) = \frac{z}{z - e^{-T/\tau_1}}$$

where T is the sampling interval. Definitely, $e^{-T/\tau_1} < 1$ since $T > 0$.

Analysis of Converters with a First-Order Load Plus an Integral Element

- The industrial applications of all converters have always required the converters to provide the power/energy to a first-order load plus an integral element such as a DC motor drive system.
- In the case we have to consider the extra integral element added in the system.
- Its transfer function in per-unit system in the *s*-domain is:

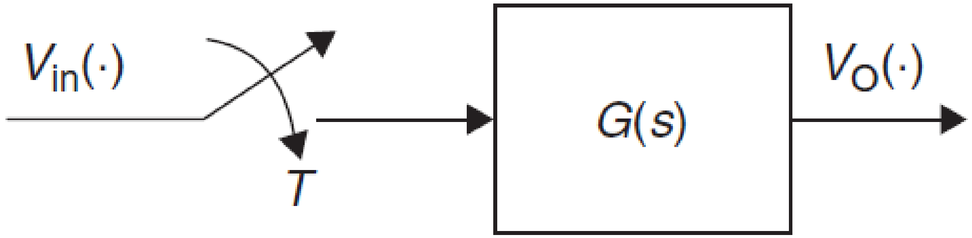
$$G_m(s) = \frac{1}{s\tau_m}$$

- where τ_m is the integral time constant, i.e. $\tau m = J = GD^2/375$ which is the rotor's inertia of a DC motor mechanical time constant. G is the rotor equivalent weight ($G = mg$), g is the gravitation acceleration (g =9.81 m/s2) and D is the rotor diameter.
- Its transfer function in per-unit system in the z-domain is:

$$G_m(z) = \frac{z}{z - T/\tau_m}$$

- where T is the sampling interval. Usually, the sampling interval T is smaller than the integral time constant τm, hence $T/\tau m < 1$

Unit-Step Responses



Open-loop control scheme.

- The control scheme is shown in Figure with the output parameter $v_O(t)$ and input step signal $v_{in}(t)$.
- The unit-step response is presented in the *s*-domain by the Laplace transform:

$$V_O(s) = G(s)V_{in}(s) = G(s)\frac{1}{s}$$

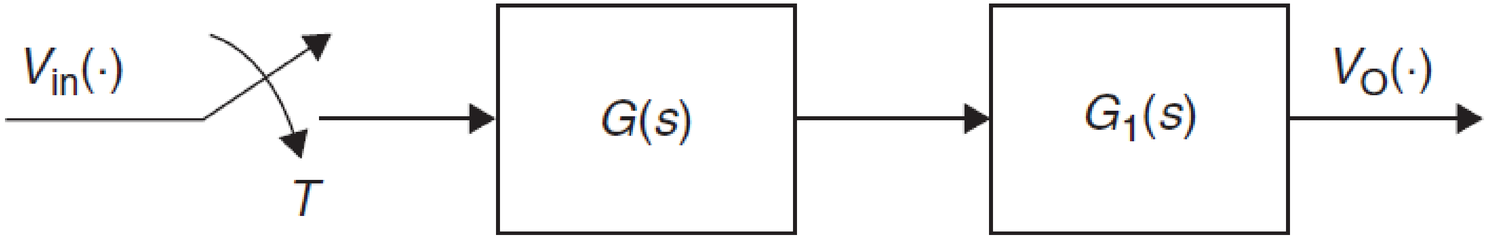
- where $G(s)$ is the converter transfer function and $V_{in}(s)$ is the Laplace transform function of the input unit-step function $V_{in}(s)=1/s$
- Its response in the z-domain is:

$$V_O(z) = G(z)V_{in}(z) = G(z)\frac{z}{z-1}$$

- where $G(z)$ is the converter transfer function and $V_{in}(z)$ is the Laplace transform function of the unit-step function $V_{in}(z)=z/(z-1)$

Unit step response analysis of Converters with a First-Order Load

- Unit-step response of the system consisting of converter with a first-order load is usually stable because the output from converter is stable.



Open-loop control of converter with a first-order load.

- The unit-step response is presented in the *s*-domain by Laplace transform:

$$V_O(s) = G(s)G_1(s)V_{in}(s) = G(s)\frac{1}{1+s\tau_1}\frac{1}{s}$$

- where *G*(*s*) is the converter transfer function, *G*1(*s*) is the first-order circuit transfer function and *V*in(*s*) is the Laplace transform function of the unit-step input signal *V*in(*s*)=1/*s*.
- Its response in the *z*-domain is:

$$V_O(z) = G(z)G_1(z)V_{in}(z) = G(z)\frac{z}{z-e^{-T/\tau_1}}\frac{z}{z-1}$$

- where $G(z)$ is the converter transfer function, $G_1(z)$ is the first-order circuit transfer function and $V_{in}(z)$ is the Laplace transform function of the unit-step function $V_{in}(z)=z/(z-1)$.

Unit step response Analysis of Converters with a First-Order Load Plus an Integral Element

- Unit-step response of the system consisting of converter with a first-order load plus an integral element is usually unstable because of the integral element

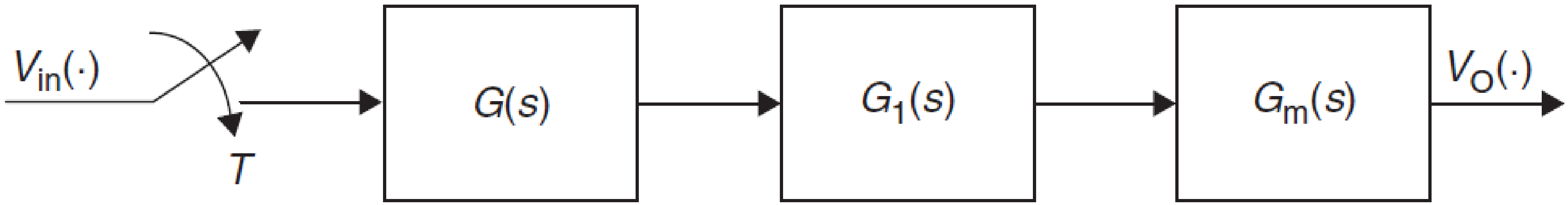


Figure 9.5 Open-loop control of converter with a first-order load plus an integral element.

- The unit-step response is presented in the *s*-domain by Laplace transform:

$$V_{\mathrm{O}}(s) = G(s)G_1(s)G_{\mathrm{m}}(s)V_{\mathrm{in}}(s) = G(s)\frac{1}{1+s\tau_1}\frac{1}{s\tau_{\mathrm{m}}}\frac{1}{s}$$

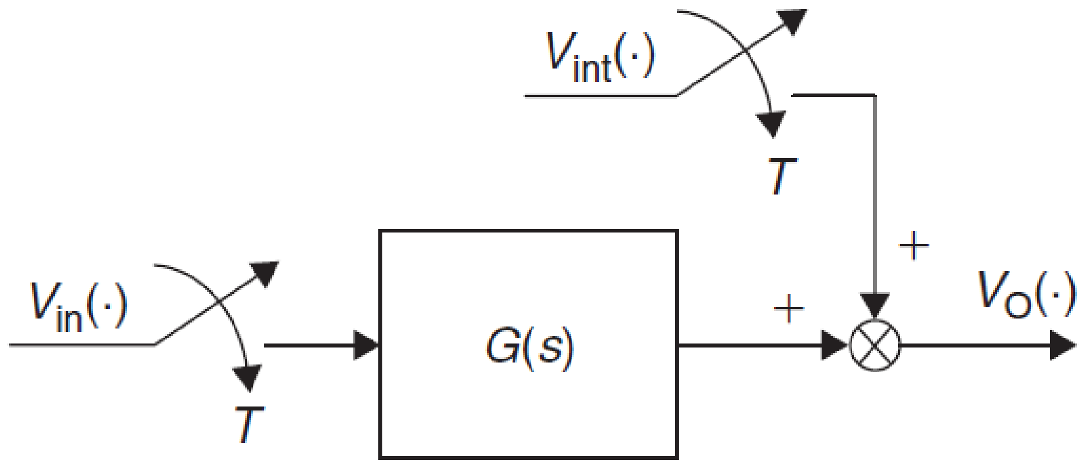
- where *G*(*s*) is the converter transfer function, *G*1(*s*) is the first-order circuit transfer function, *G*m(*s*) is the integral element transfer function and *V*in(*s*) is the Laplace transform function of the unit-step function *V*in(*s*)=1/*s*.
- Its response in the *z*-domain is:

$$V_{\mathrm{O}}(z) = G(z)G_1(z)G_{\mathrm{m}}(z)V_{\mathrm{in}}(z) = G(z)\frac{z}{z-\mathrm{e}^{-T/\tau_1}}\frac{z}{z-T/\tau_{\mathrm{m}}}\frac{z}{z-1}$$

- where $G(z)$ is the converter transfer function, $G1(z)$ is the first-order circuit transfer function, $Gm(z)$ is the integral element transfer function and $Vin(z)$ is the Laplace transform function of the unit-step function $Vin(z)=z/(z-1)$.

Impulse Responses

- Interference response usually called the impulse response is one of the most important problems of the digital control systems.
- The interference signal randomly perturbs to the system as an impulse signal disturb system output parameter.
- Generally, the interference signal is added in the output point of the converter just likely the load suddenly vibrated



Open-loop control of converter (with interference signal).

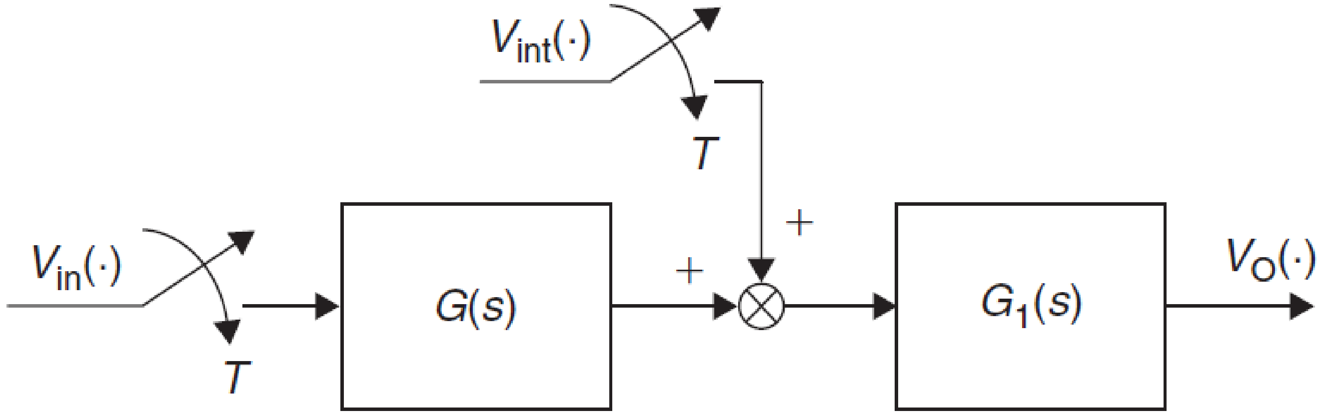
- the output parameter $V_O(t)$ and interference signal $V_{int}(t)=U\delta(t)$.
- The impulse response is presented in the *s*-domain by Laplace transform:

$$V_O(s) = V_{int}(s) = U$$

- where U is the interference signal.
- Its response in the *z*-domain is:

$$V_{\mathrm{O}}(z) = V_{\mathrm{int}}(z) = U$$

Analysis of Converters with a First-Order Load



Open-loop control of converter with a first-order load (with interference signal)

Impulse response of the system consisting of converter with a first-order load is usually stable because the first-order circuit is stable.

- The control scheme is shown in Figure with the output parameter is*VO*(*t*) and interference signal $V_{\mathrm{int}}(t)=U\delta(t)$.
- The impulse response is presented in the *s*-domain by Laplace transform

$$V_{\mathrm{O}}(s) = G_1(s)V_{\mathrm{int}}(s) = \frac{U}{1+s\tau_1}$$

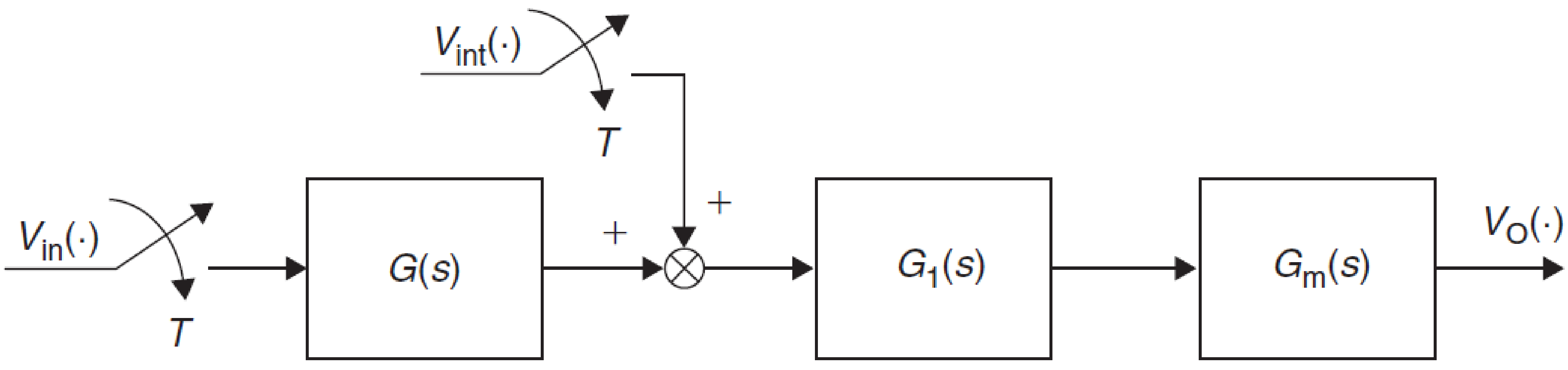
- where *G*1(*s*) is the first-order circuit transfer function, *V*int(*s*) is the Laplace transform function of the interference signal *V*int(*s*)=*U*.
- Its response in the *z*-domain is:

$$V_{\mathrm{O}}(z) = G_1(z)V_{\mathrm{int}}(z) = \frac{z}{z - \mathrm{e}^{-T/\tau_1}}U$$

Analysis of Converters with a First-Order Load Plus an Integral Element

- The impulse response is presented in the *s*-domain by Laplace transform:

$$V_O(s) = G_1(s)G_m(s)V_{int}(s) = \frac{U}{1+s\tau_1}\frac{1}{s\tau_m}$$



- Its response in the *z*-domain is:

$$V_O(z) = G_1(z)G_m(z)V_{int}(z) = \frac{z}{z - e^{-T/\tau_1}} \frac{z}{z - T/\tau_m} U$$

STABILITY ANALYSIS of AC/DC Rectifiers

- The mathematical model for power AC/DC Rectifiers is a ZOH. Its transfer function is assumed $u(t)$ in the time-domain, and that in the s-domain is:

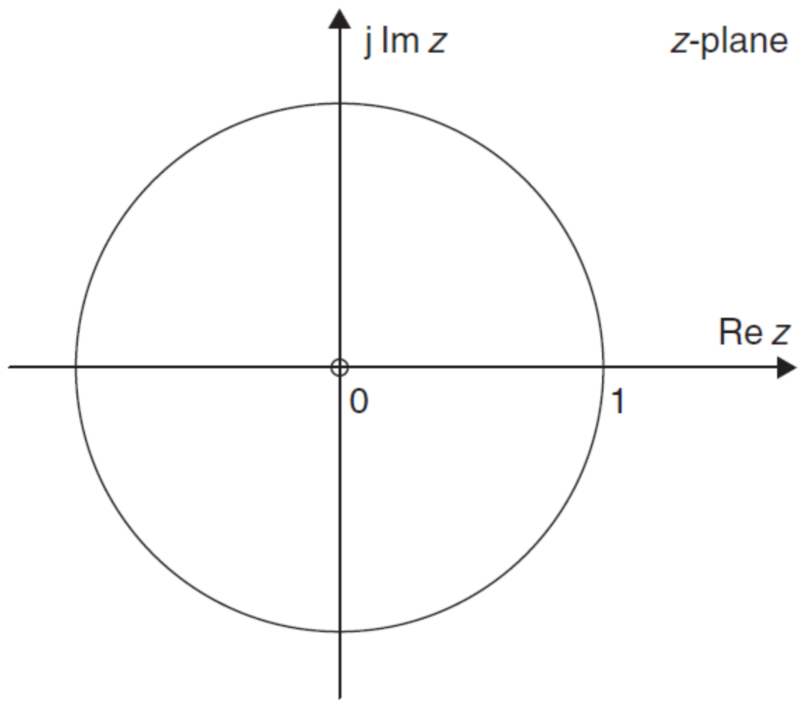
$$G(s) = \frac{1}{s}$$

- Its transfer function in the z-domain is:

$$G(z) = \frac{z}{z-1}$$

AC/DC Rectifiers Open-Loop Analysis

- all existing AC/DC rectifiers applied in industrial applications are stable although they have the pole located on the stability boundary



Analysis of AC/DC Rectifiers with a First-Order Load

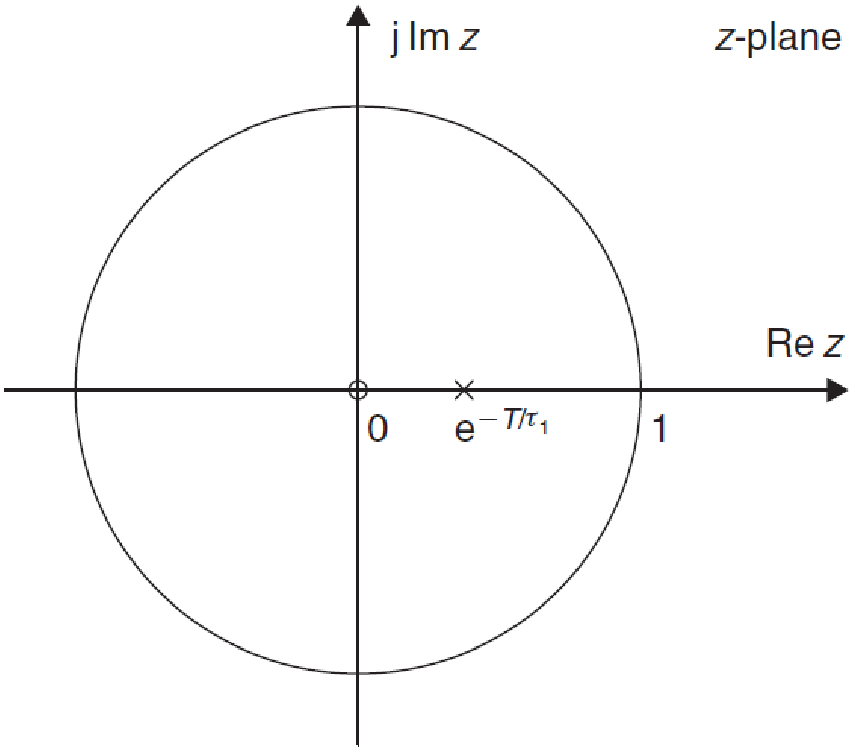
- The mathematical model for power AC/DC rectifiers is a ZOH.
- The system transfer function in the *s*-domain is:

$$G(s)G_1(s) = \frac{1}{s}\frac{1}{1+s\tau_1}$$

- Its transfer function in the *z*-domain is:

$$G(z)G_1(z) = \frac{z}{z-1}\frac{z}{z-e^{-T/\tau_1}}$$

- we have got two zeros at original point and two poles, one is inside the unity-cycle and another on the unity-cycle.
- Therefore, this open-loop control system is considered stable.



Open-loop control of power AC/DC rectifiers with a first-order load.

Analysis of Rectifiers with a First-Order Load Plus an Integral Element

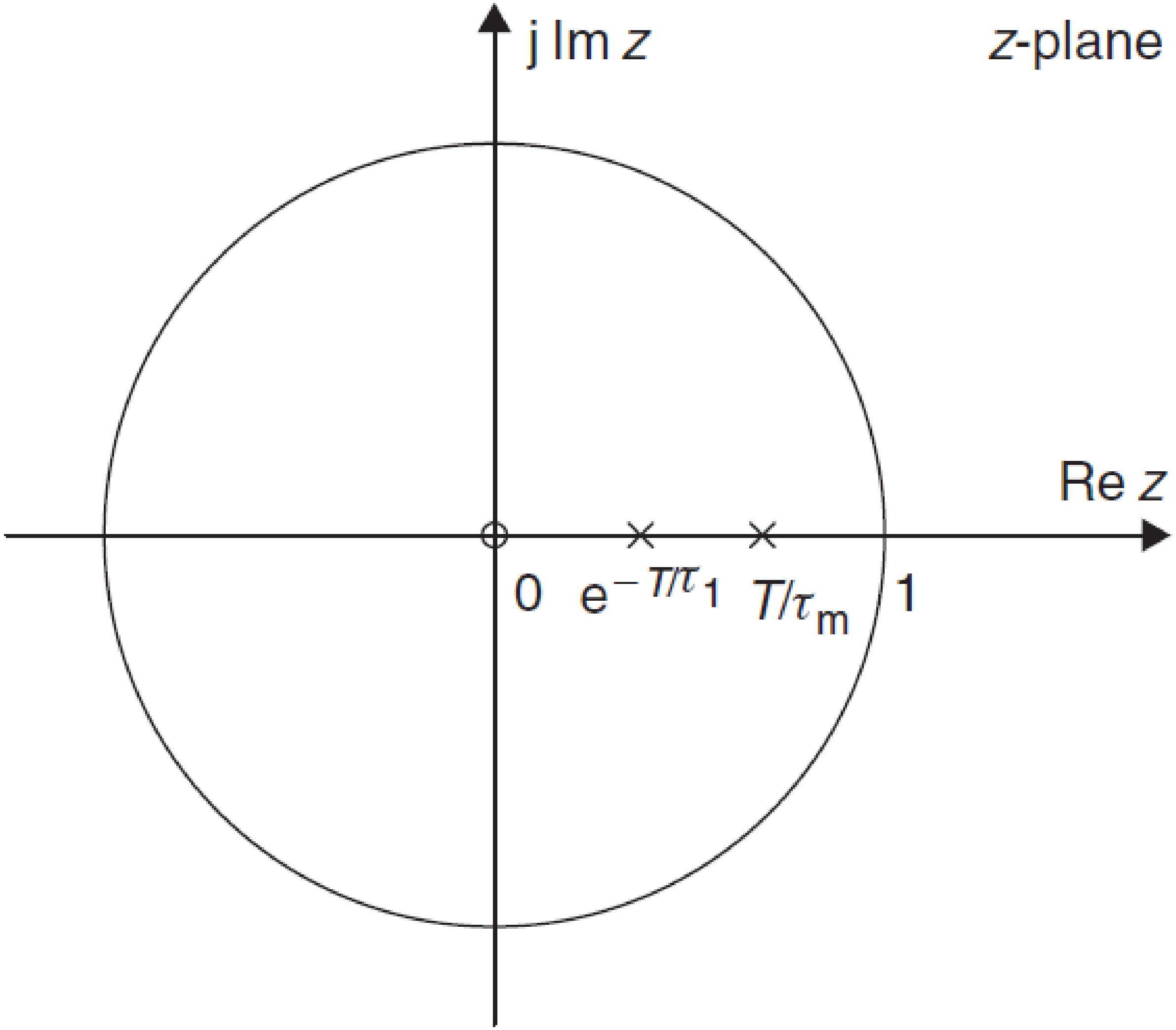
- The system transfer function in the *s*-domain is:

$$G(s)G_1(s)G_m(s) = \frac{1}{s}\frac{1}{1+s\tau_1}\frac{1}{s\tau_m} = \frac{1}{s^2\tau_m(1+s\tau_1)}$$

- Its transfer function in the *z*-domain is:

$$G(z)G_1(z)G_m(z) = \frac{z}{z-1}\frac{z}{z-T/\tau_m}\frac{z}{z-e^{-T/\tau_1}}$$

- we have got three zeros at original point and three poles. One pole is inside the unity-cycle and one on the unity-cycle, and another is uncertain.
- Therefore, this open-loop control system may be considered unstable.



Open-loop control of powerAC/DC rectifiers with a first-order load plus an integral element

DC/AC Inverters and AC/AC (AC/DC/AC) Converters

- The mathematical model for power DC/AC inverters and AC/AC (AC/DC/AC) converters to be an FOH
- Its transfer function in the *s*-domain is:

$$G(s) = \frac{1}{1 + sT}$$

- Its transfer function in the *z*-domain is:

$$G(z) = \frac{z}{z - 1/\mathrm{e}}$$

Open-Loop Stability Analysis for DC/AC Inverters andAC/AC (AC/DC/AC) Converters with a First-Order Load

- The open-loop control scheme for an FOH with a first-order load.
- The system transfer function in the *s*-domain is:

$$G(s)G_1(s) = \frac{1}{1+sT}\frac{1}{1+s\tau_1}$$

- Its transfer function in the *z*-domain is:

$$G(z)G_1(z) = \frac{z}{z-1/\mathrm{e}}\frac{z}{z-\mathrm{e}^{-T/\tau_1}}$$

- we have got two zeros at original point $z = 0$, and two poles at $z = 1/e$ and $z = e^{-T/\tau 1}$ inside the unity-cycle.
- Therefore, this open-loop control system is considered stable.

Open-Loop Stability Analysis for DC/AC Inverters andAC/AC (AC/DC/AC) Converters with a First-Order Load Plus an Integral Element

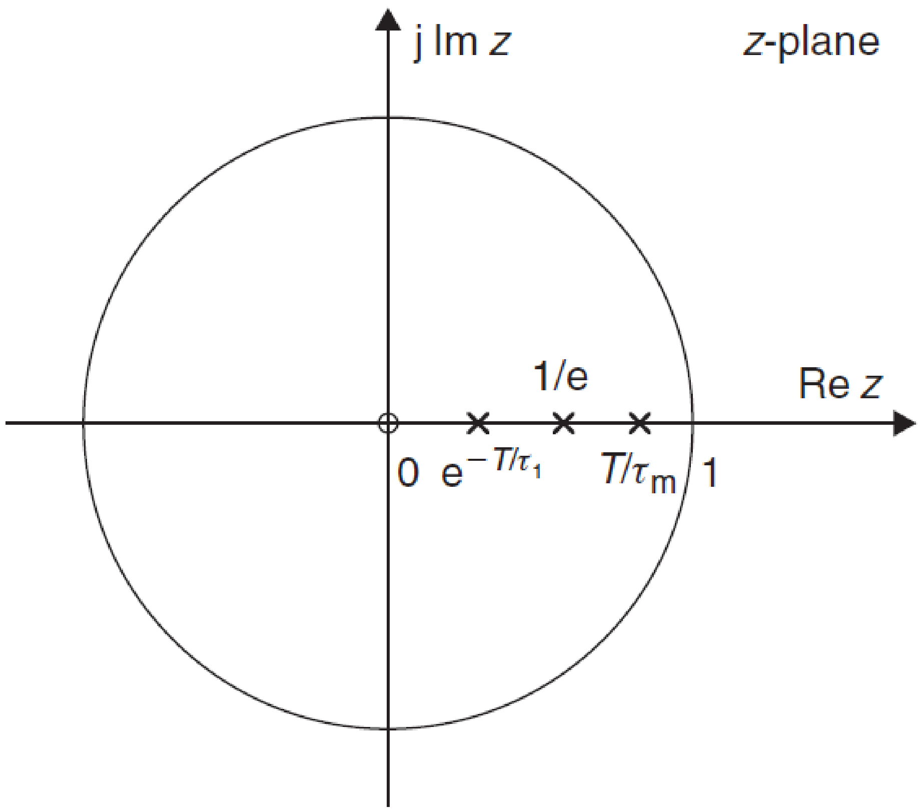
- The open-loop control scheme for an FOH with a first-order circuit plus an integral element

$$G(s)G_1(s)G_{\mathrm{m}}(s) = \frac{1}{1+sT}\frac{1}{1+s\tau_1}\frac{1}{s\tau_{\mathrm{m}}}$$

- Its transfer function in the *z*-domain is:

$$G(z)G_1(z)G_{\mathrm{m}}(z) = \frac{z}{z-1/\mathrm{e}}\frac{z}{z-T/\tau_{\mathrm{m}}}\frac{z}{z-\mathrm{e}^{-T/\tau_1}}$$

- we have got three zeros at original point and three poles. One pole is inside the unity-cycle and others are uncertain. Therefore, this open-loop control system may be considered unstable.



UNIT-STEP FUNCTION RESPONSES

- **AC/DC Rectifiers**
- The mathematical model for power AC/DC rectifiers is a ZOH. Its transfer function in the *s*-domain is:

$$G(s) = \frac{1}{s}$$

- Its transfer function in the *z*-domain is:

$$G(z) = \frac{z}{z-1}$$

AC/DC Rectifiers Open-Loop Analysis

- The block diagram is with $G(s)$ to be a ZOH. The unit-step function response in the s-domain is:

$$V_O(s) = G(s)V_{in}(s) = \frac{1}{s^2}$$

- The unit-step function response in the time domain is:

$$v_O(t) = t$$

- It is a linear rising line, so that it is not stable. The unit-step function response in the *z*-domain:

$$V_{\mathrm{O}}(z) = G(z)V_{\mathrm{in}}(z) = \frac{Tz}{(z-1)^2}$$

This unit-step function response is not stable.

Analysis of AC/DC Rectifiers with a First-Order Load

- The open-loop control scheme for a ZOH with a first-order load is shown in Figure
- The unit-step function response in the *s*-domain is:

$$V_O(s) = G(s)G_1(s)V_{in}(s) = \frac{1}{s^2}\frac{1}{1+s\tau_1}$$

- The unit-step function response in the time domain is:

$$v_O(t) = t - \tau_1(1 - e^{-t/\tau_1})$$

- It is nearly a linear rising line, so that it is not stable.

- The unit-step function response in the *z*-domain:

$$V_O(z) = G(z)G_1(z)V_{in}(z) = \frac{Tz}{(z-1)^2} - \frac{(1-e^{-T/\tau_1})z/\tau_1}{(z-1)(z-e^{-T/\tau_1})}$$

- This unit-step function response is not stable.

Analysis of Rectifiers with a First-Order Load Plus an Integral Element

- The open-loop control scheme for a ZOH with a first-order circuit plus an integral element is shown in Figure. The unit-step function response in the *s*-domain is:

$$V_O(s) = G(s)G_1(s)G_m(s)V_{in}(s) = \frac{1}{s^2}\frac{1}{1+s\tau_1}\frac{1}{s\tau_m}$$

- The unit-step function response in the time domain is:

$$v_O(t) = \frac{1}{2\tau_m}(t^2 - 2\tau_1 t + 2\tau_1^2 - 2\tau_1^2 e^{-t/\tau_1})$$

- It is nearly a linear rising line, so that it is not stable.
- The unit-step function response in the *z*-domain:

$$V_{\mathrm{O}}(z) = G(z)G_1(z)G_{\mathrm{m}}(z)V_{\mathrm{in}}(z) = \frac{Tz}{\tau_{\mathrm{m}}(z-1)^2}\left(\frac{T}{z-1} + \frac{T-2\tau_1}{2}\right)$$

- This unit-step function response is not stable

DC/AC Inverters and AC/AC (AC/DC/AC) Converters

- The mathematical model for power DC/AC inverters and AC/AC (AC/DC/AC) converters is an FOH. Its transfer function in the *s*-domain is:

$$G(s) = \frac{1}{1 + sT}$$

- Its transfer function in the *z*-domain is:

$$G(z) = \frac{z}{z - 1/\mathrm{e}}$$

Analysis of an FOH with a First-Order Load

- The open-loop control scheme for an FOH with a first-order load is shown in Figure . The unit-step function response in the *s*-domain is:

$$V_O(s) = G(s)G_1(s)V_{in}(s) = \frac{1}{s(1+sT)}\frac{1}{1+s\tau_1}$$

- The unit-step function response in the time domain is:

$$v_O(t) = 1 + \frac{T e^{-t/T} - \tau_1 e^{-t/\tau_1}}{\tau_1 - T}$$

- It is nearly an exponential function, so that it is stable.
- The unit-step function response in the *z*-domain:

$$V_{\mathrm{O}}(z) = G(z)G_1(z)V_{\mathrm{in}}(z) = \frac{z}{(z-1)} + \frac{z}{\tau_1 - T}\left(\frac{T}{z - 1/\mathrm{e}} - \frac{\tau_1}{z - \mathrm{e}^{-T/\tau_1}}\right)$$

- This unit-step function response is stable

Analysis of an FOH with a First-Order Load Plus an Integral Element

- The open-loop control scheme for an FOH with a first-order circuit plus an integral element is shown in Figure.
- The unit-step function response in the *s*-domain is:

$$V_O(s) = G(s)G_1(s)G_m(s)V_{in}(s) = \frac{1}{s(1+sT)}\frac{1}{1+s\tau_1}\frac{1}{s\tau_m}$$

- The unit-step function response in the time domain is:

$$v_O(t) = \frac{1}{\tau_m}\left[t - (\tau_1 + T) - \frac{(\tau_1 - T)e^{-t/T}}{\tau_1^2} + \frac{(\tau_1 - T)e^{-t/\tau_1}}{T^2}\right]$$

- It is nearly a linear rising line, so that it is not stable.
- The unit-step function response in the *z*-domain:

$$V_O(z) = G(z)G_1(z)G_m(z)V_{in}(z)$$

$$= \frac{1}{\tau_m}\left[-\frac{(\tau_1 + T)z}{z-1} + \frac{Tz}{(z-1)^2} - \frac{T^2 z}{(\tau_1 - T)(z - 1/e)} + \frac{\tau_1^2 z}{(\tau_1 - T)(z - e^{-T/\tau_1})}\right]$$

- This unit-step function response is not stable

Analysis of DC/DC converter

- The mathematical model for power DC/DC converters is an SOH. Its transfer function in the *s*-domain is

$$G(s) = \frac{1}{1 + s\tau + s^2\tau\tau_d}$$

- There are four conditions of the damping time constant τd related to the time constant τ

  - $\tau_d = 0$
  - $\tau_d < 0.25\tau$
  - $\tau_d = 0.25\tau$
  - $\tau_d > 0.25\tau$

- We list its transfer functions in the *s*-domain and in the *z*-domain below

$$G(s) = \frac{1}{1 + \tau s} \qquad \text{for } \tau_{\mathrm{d}} = 0$$

$$G(z) = \frac{z}{z - \mathrm{e}^{-T/\tau}} \qquad \text{for } \tau_{\mathrm{d}} = 0$$

$$G(s) = \frac{1/\tau\tau_{\mathrm{d}}}{(s + \sigma_1)(s + \sigma_2)} \qquad \text{for } \tau_{\mathrm{d}} < 0.25\tau$$

$$G(z) = \frac{1/\tau\tau_{\mathrm{d}}}{(\sigma_2 - \sigma_1)} \left(\frac{z}{z - \mathrm{e}^{-\sigma_1 T}} - \frac{z}{z - \mathrm{e}^{-\sigma_2 T}} \right) \qquad \text{for } \tau_{\mathrm{d}} < 0.25\tau$$

$$G(s) = \frac{1/\tau\tau_d}{(s+\sigma)^2} \qquad \text{for } \tau_d = 0.25\tau$$

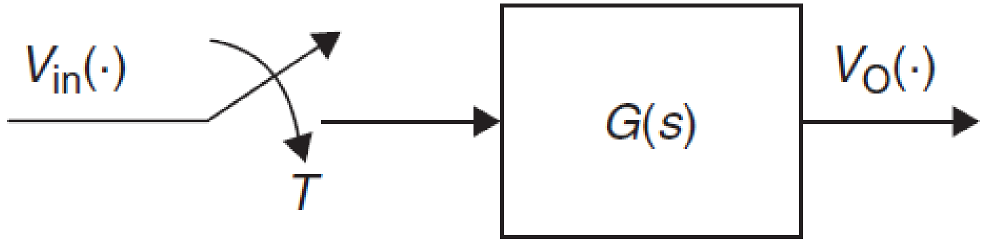
$$G(z) = \frac{4Tze^{(-2/\tau)T}}{(z - e^{(-2/\tau)T})^2} \qquad \text{for } \tau_d = 0.25\tau$$

$$G(s) = \frac{1/\tau\tau_d}{(s+\sigma)^2 + \omega^2} \qquad \text{for } \tau_d > 0.25\tau$$

$$G(z) = \frac{2}{\sqrt{4\tau_d/\tau - 1}} \frac{ze^{-aT} \sin \omega T}{z^2 - 2ze^{-aT} \cos \omega T + e^{-2aT}} \qquad \text{for } \tau_d > 0.25\tau$$

Converters Open-Loop Analysis

- The block diagram is shown in Figure with $G(\cdot)$ to be an SOH.



The Condition of τd =0

- The unit-step function responses in the *s*-domain and in the *z*-domain for the condition of τd =0 are:

$$V_O(s) = G(s)V_{in}(s) = \frac{1}{s(1 + s\tau)} \qquad \text{for } \tau_d = 0$$

$$V_O(z) = G(z)V_{in}(z) = \frac{z(1 - e^{-T/\tau})}{(z - 1)(z - e^{-T/\tau})} \qquad \text{for } \tau_d = 0$$

The unit-step response in the time domain is:

$$v_O(t) = 1 - e^{-t/\tau}$$

This is an exponential function, which is stable.

The Condition of τd <0.25τ

- The unit-step function response in the *s*-domain and in the *z*-domain for the condition of τd <0.25τ are

$$V_O(s) = G(s)V_{in}(s) = \frac{1/\tau\tau_d}{s(s+\sigma_1)(s+\sigma_2)} \quad \text{for } \tau_d < 0.25\tau$$

$$V_O(z) = G(z)V_{in}(z)$$

$$= \frac{z}{(z-1)} + \frac{\sigma_2 z}{(\sigma_1 - \sigma_2)(z - e^{-\sigma_1 T})} - \frac{\sigma_1 z}{(\sigma_1 - \sigma_2)(z - e^{-\sigma_2 T})} \quad \text{for } \tau_d < 0.25\tau$$

The unit-step response in the time domain is:

$$v_O(t) = 1 + \frac{\sigma_2 e^{-\sigma_1 t}}{\sigma_1 - \sigma_2} - \frac{\sigma_1 e^{-\sigma_2 t}}{\sigma_1 - \sigma_2}$$

This is an exponential function, which is stable.

The Condition of τd >0.25τ

- The unit-step function response in the *s*-domain and in the *z*-domain for the condition of τd >0.25τ are:

$$V_O(s) = G(s)V_{in}(s) = \frac{1/\tau\tau_d}{s[(s+\sigma)^2+\omega^2]} \quad \text{for } \tau_d > 0.25\tau$$

$$V_O(z) = G(z)V_{in}(z) = \frac{z}{z-1} - \frac{z^2 - ze^{-aT}\sec\phi\cos(\omega T+\phi)}{z^2 - 2ze^{-aT}\cos\omega T + e^{-2aT}} \quad \text{for } \tau_d > 0.25\tau$$

where $\phi = \tan^{-1}(-a/\omega)$. The unit-step response in the time domain is:

$$v_O(t) = 1 - e^{-at}\sec\phi\cos(\omega t - \phi)$$

This is an exponential function, which is stable.

Analysis of DC/DC Converters with a First-Order Load

IMPULSE RESPONSES

- **Impulse Response of the Converter Open-Loop Systems**
- The impulse responses in the *s*-domain and in the *z*-domain are:

$$V_{\mathrm{O}}(s) = V_{\mathrm{int}}(s) = U$$

$$V_{\mathrm{O}}(z) = V_{\mathrm{int}}(z) = U$$

- Its transfer function in the time domain is:

$$v_{\mathrm{O}}(t) = U\delta(t)$$

Impulse Response of the Converter with a First-Order Circuit

- The impulse responses in the *s*-domain and in the *z*-domain are:

$$V_O(s) = V_{int}(s)G_1(s) = \frac{U}{1 + s\tau_1}$$

$$V_O(z) = V_{int}(z)G_1(z) = \frac{Uz}{z - e^{-T/\tau_1}}$$

- Its transfer function in the time domain is:

$$v_O(t) = U e^{-t/\tau_1}$$

Impulse Response of the Converter with a First-Order Circuit Plus an Integral Element

- The impulse responses in the *s*-domain and in the *z*-domain are:

$$V_{\mathrm{O}}(s) = V_{\mathrm{int}}(s)G_1(s)G_{\mathrm{m}}(s) = \frac{U}{(1+s\tau_1)s\tau_{\mathrm{m}}}$$

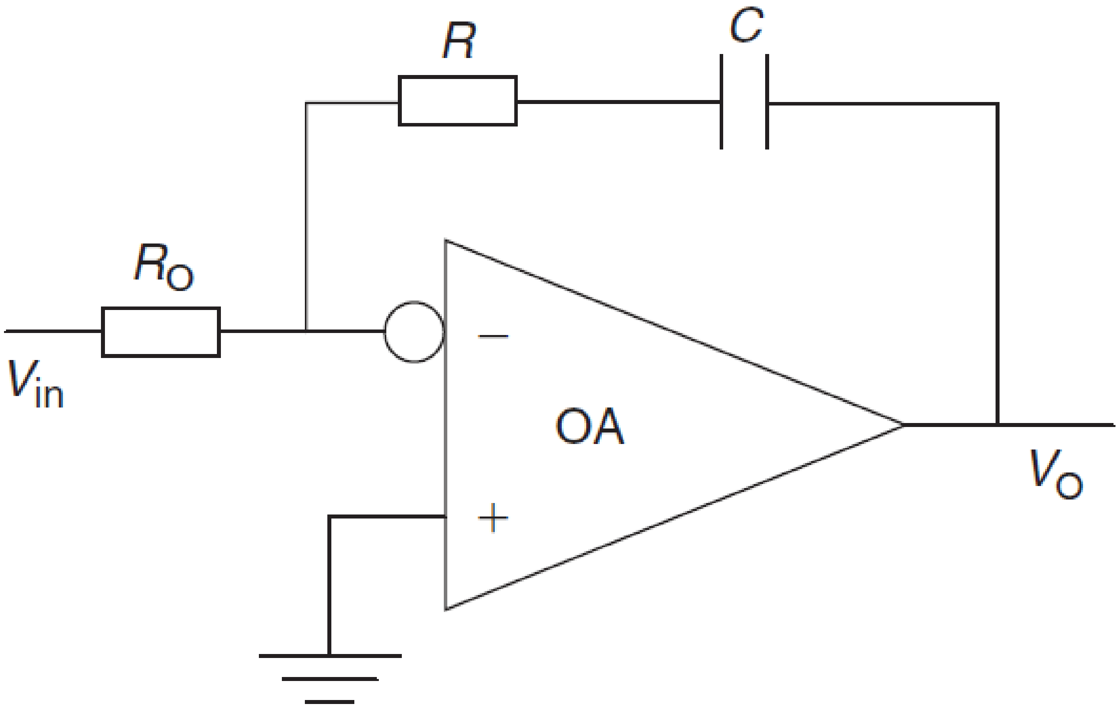
$$V_{\mathrm{O}}(z) = G_1(z)G_{\mathrm{m}}(z)V_{\mathrm{int}}(z) = \frac{Uz(1-\mathrm{e}^{-T/\tau_1})}{\tau_{\mathrm{m}}(z-1)(z-\mathrm{e}^{-T/\tau_1})}$$

- Its transfer function in the time domain is:

$$v_{\mathrm{O}}(t) = \frac{U}{\tau_{\mathrm{m}}}(1-\mathrm{e}^{-t/\tau_1})$$

Closed-Loop Control for Digital Power Electronics

PI Controller



Analog PI controller using OA.

- Its transfer function in time domain is:

$$\frac{v_O(t)}{v_{in}(t)} = \frac{R + \frac{1}{j\omega C}}{R_0} = \frac{R}{R_0}\left(1 + \frac{1}{j\omega RC}\right) = \frac{R}{R_0}\frac{1 + j\omega RC}{j\omega RC}$$

- Its transfer function in the *s*-domain is:

$$G_{pi}(s) = \frac{V_O(s)}{V_{in}(s)} = \frac{R}{R_0}\frac{1 + sRC}{sRC} = p\frac{1 + s\tau}{s\tau}$$

- where *p* is the proportional transfer gain, $p = R/R0$, and τ is the integral time constant, τi $= RC$

- The transfer function in the *s*-domain can be written in two items as:

$$G_{\mathrm{pi}}(s) = p + \frac{p}{s\tau_{\mathrm{i}}} = p + \frac{p_{\mathrm{i}}}{s}$$

- The transfer function in the *z*-domain can be written in two items as well:

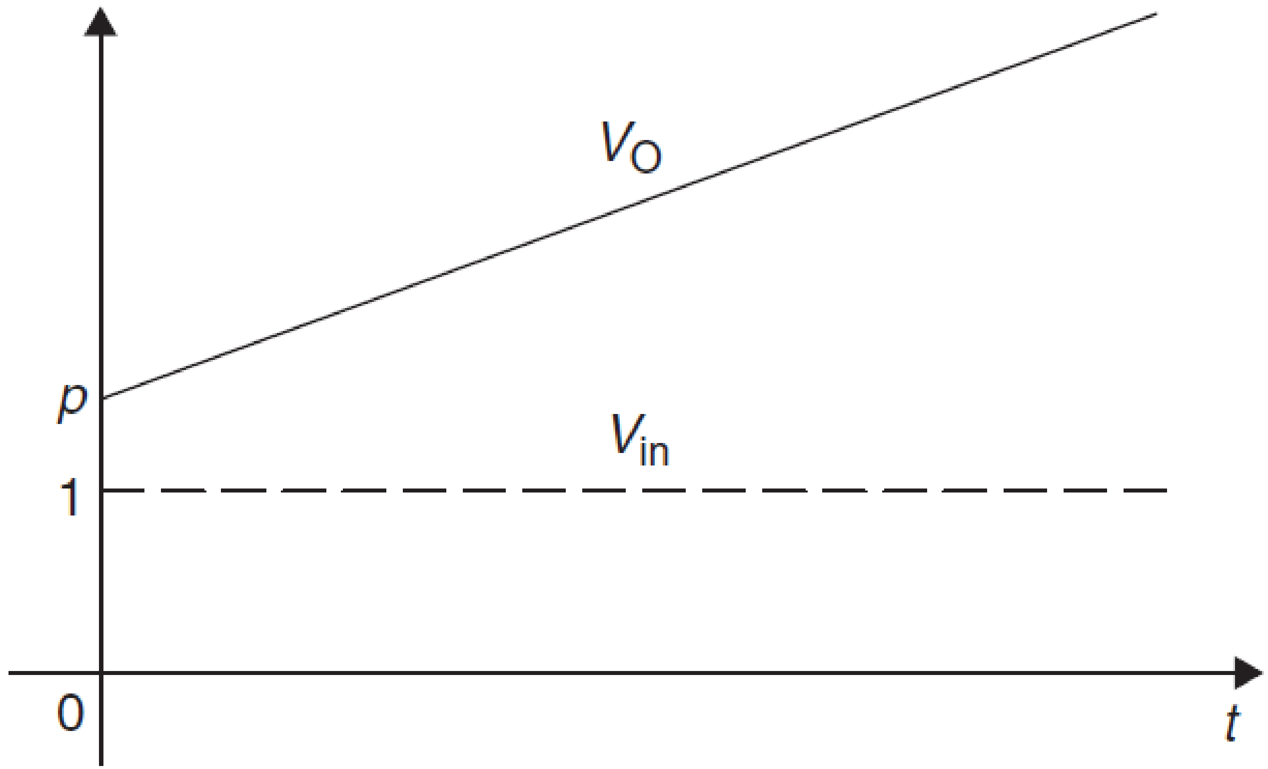
$$G_{\mathrm{pi}}(z) = p + p_{\mathrm{i}}\frac{z}{z-1}$$

Stability Analysis

- From the transfer functions, we can recognize that the PI controller is an unstable element with the pole on the stability boundary in the *s*-plane, and on the unity-cycle in the *z*-plane.
- Usually, the pole on the stability boundary in the *s*-plane can be treated as in the right-hand-half-plane (RHHP) in the *s*-domain.

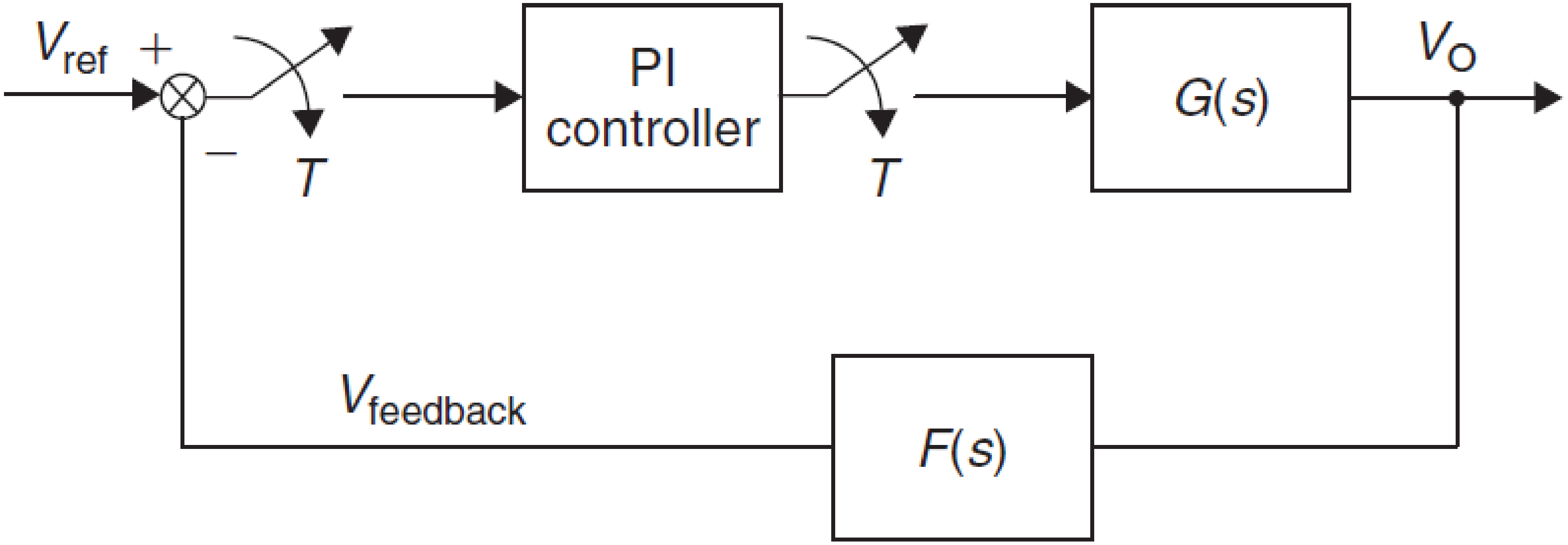
Unit-Step-Function Responses

- We can split the waveform in two parts: proportional part and integral part.
- The proportional part is a constant value which is equal to *p* at any time. The integral part is a linear line proportional to the time.



Input and output signals of PI controller in the time domain.

Closed-Loop Control

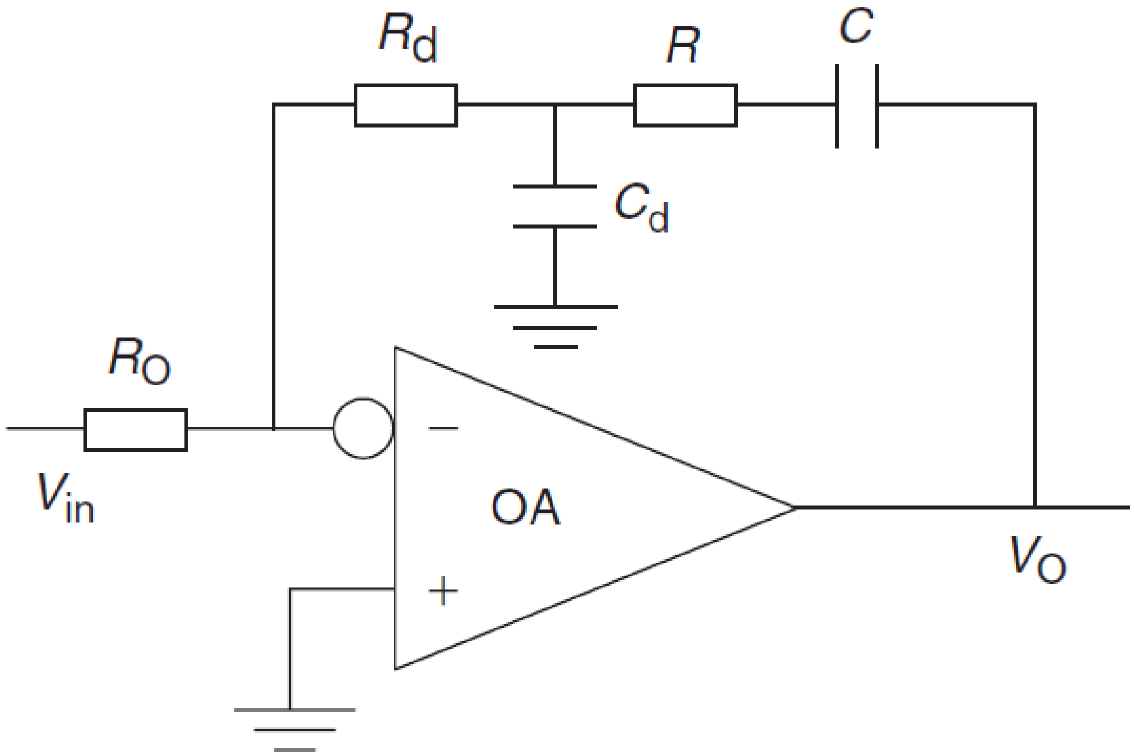


Closed-loop control system with a PI controller.

- The closed-loop transfer function of the whole system is:

$$G_C(s) = \frac{G_{pi}(s)G(s)}{1 + G_{pi}(s)G(s)F(s)}$$

Proportional-Plus-Integral-Plus-Differential Controller



Analog PID controller using OA.

- Its transfer function in time domain is:

$$G_{\mathrm{pid}}(t) = \frac{v_{\mathrm{O}}(t)}{v_{\mathrm{in}}(t)} = \frac{R}{R_0}\frac{(1+\mathrm{j}\omega RC)(1+\mathrm{j}\omega R_{\mathrm{d}}C_{\mathrm{d}})+\mathrm{j}\omega R_{\mathrm{d}}C}{\mathrm{j}\omega RC}$$

- If the differential resistant *R*d is small, i.e. *R*d<<*R*, we can have following expression

$$G_{\mathrm{pid}}(t) = \frac{v_{\mathrm{O}}(t)}{v_{\mathrm{in}}(t)} = \frac{R}{R_0}\frac{(1+\mathrm{j}\omega RC)(1+\mathrm{j}\omega R_{\mathrm{d}}C_{\mathrm{d}})}{\mathrm{j}\omega RC}$$

- Its transfer function in the *s*-domain is:

$$G_{\mathrm{pid}}(s) = \frac{V_{\mathrm{O}}(s)}{V_{\mathrm{in}}(s)} = \frac{R}{R_0}\frac{(1+sRC)(1+sR_{\mathrm{d}}C_{\mathrm{d}})}{sRC} = p\frac{(1+s\tau_{\mathrm{i}})(1+s\tau_{\mathrm{d}})}{s\tau_{\mathrm{i}}}$$

- We can rewrite the transfer function in the *s*-domain in three items as:

$$G_{\mathrm{pid}}(s) = p\frac{1 + s\tau_{\mathrm{i}} + s^2\tau_{\mathrm{i}}\tau_{\mathrm{d}}}{s\tau_{\mathrm{i}}}$$

- We can write it in three items as well:

$$G_{\mathrm{pid}}(s) = p + \frac{p_{\mathrm{i}}}{s} + p_{\mathrm{d}}s$$

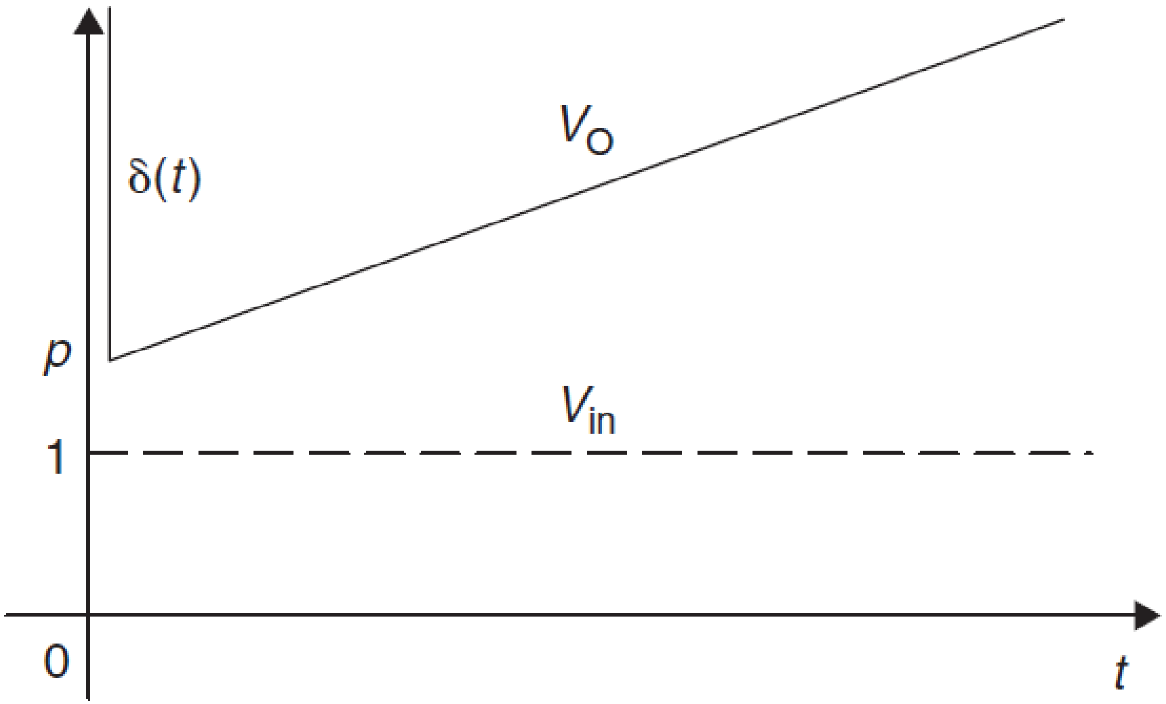
- The transfer function in the *z*-domain can be written in two items as well:

$$G(z) = p + p_{\mathrm{i}}\frac{z}{z-1} + p_{\mathrm{d}}\frac{z-1}{z}$$

Stability Analysis

- From the transfer functions, we can recognize that the PID controller is an unstable element with the pole is on the stability boundary in the *s*-domain and is on the unity-cycle in the *z*-domain

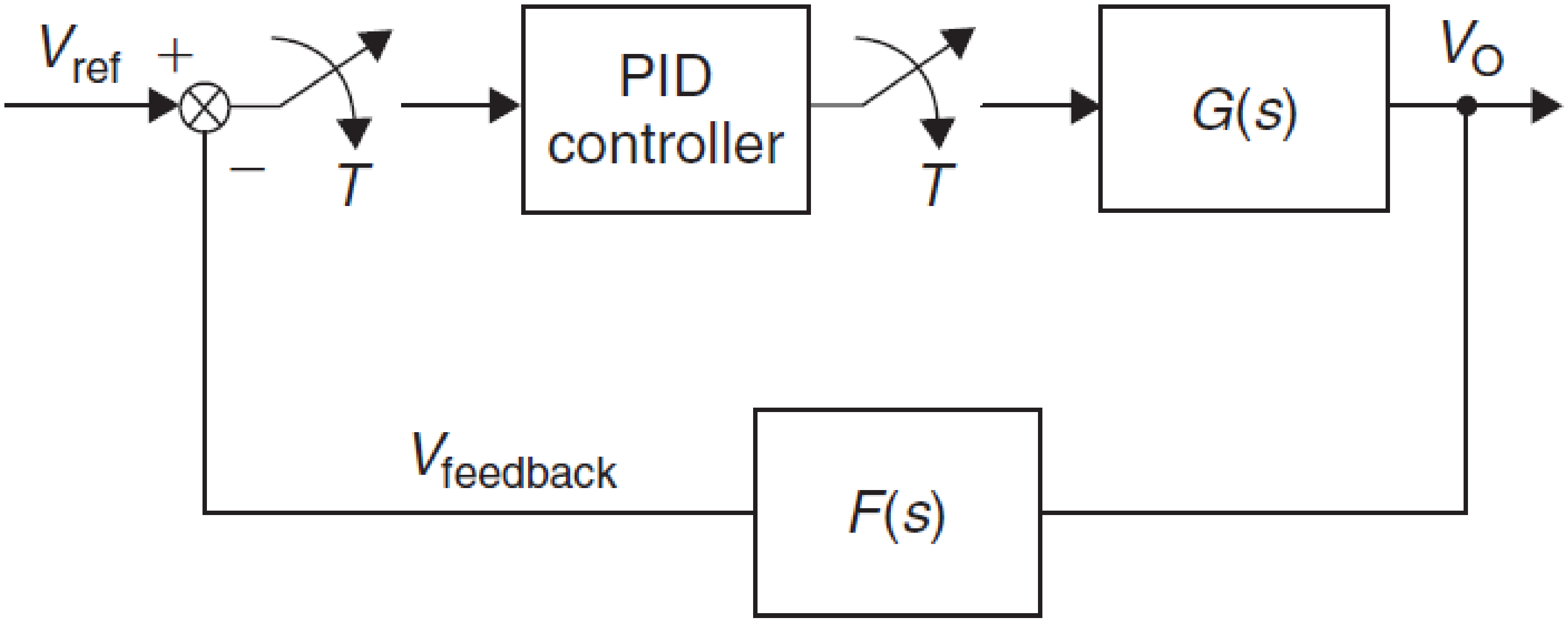
Unit-Step-Function Responses



Input and output signals of PID controller in the time domain.

- The PID controller has the step-function response in the time domain and is shown in Figure.
- We can split the waveform into three parts: proportional part, integral part and differential part.
- The proportional part is a constant value which is equal to *p* at any time. The integral part is a linear line proportional to the time. The differential part is a delta function in the time response

Closed-Loop Control

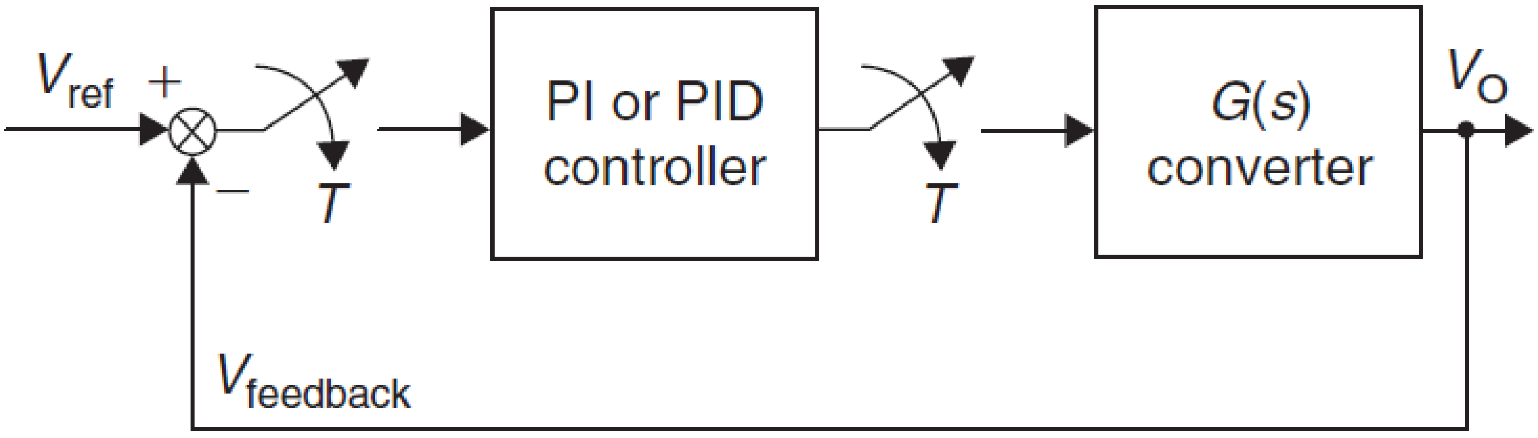


- The PID controller has the main role in a closed-loop control system. The block diagram

  is shown in Figure.
- The regulated converter has its transfer function *G*(*s*) and the feedback element with transfer function *F*(*s*). The closed-loop transfer function of the whole system is:

$$G_C(s) = \frac{G_{\text{pid}}(s)G(s)}{1 + G_{\text{pid}}(s)G(s)F(s)}$$

PI CONTROL FOR AC/DC RECTIFIERS



PI/PID controlled closed-loop control system of a converter.

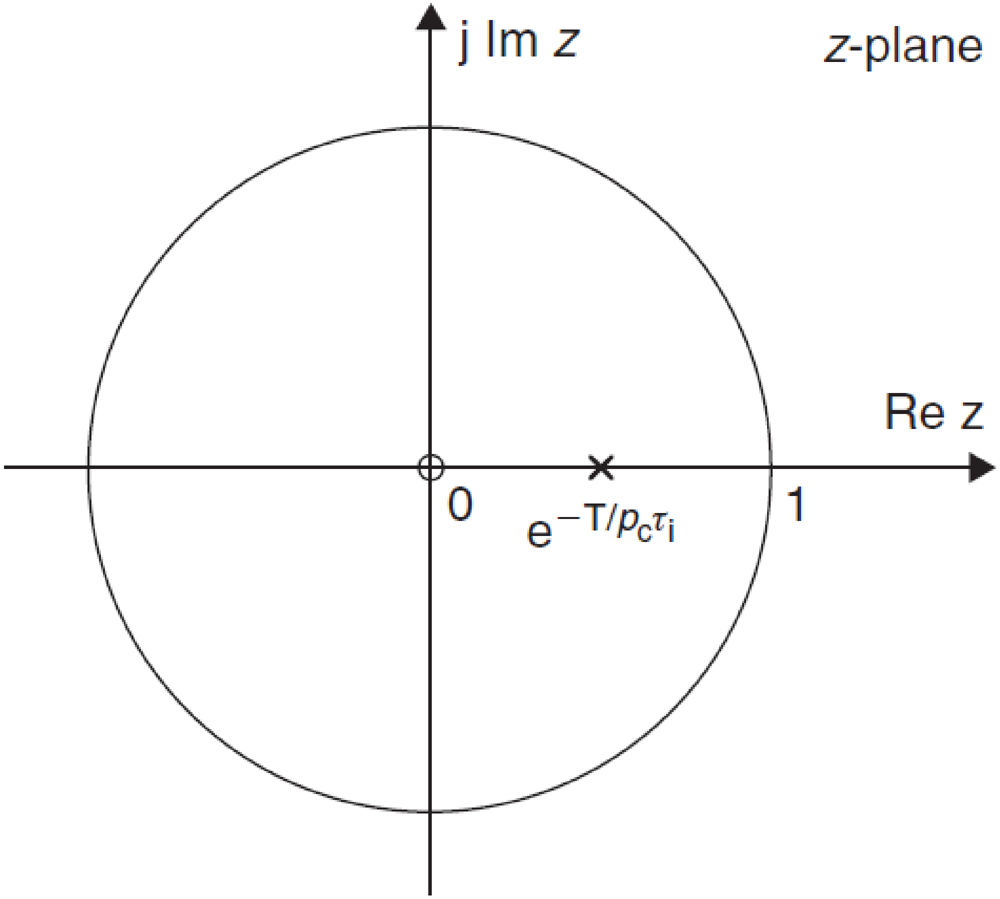
- The converter $G(s)$ is a zero-order hold (ZOH) simulating AC/DC rectifiers.
- The feedback network is assumed as a unity element.
- The system closed-loop transfer function in the *s*-domain is:

$$G_C(s) = \frac{G_{pi}(s)G(s)}{1 + G_{pi}(s)G(s)} = \frac{p\frac{1+s\tau_i}{s\tau_i}}{1 + p\frac{1+s\tau_i}{s\tau_i}} = \frac{1 + s\tau_i}{1 + p_C s\tau_i}$$

- The system closed-loop transfer function in the *z*-domain is:

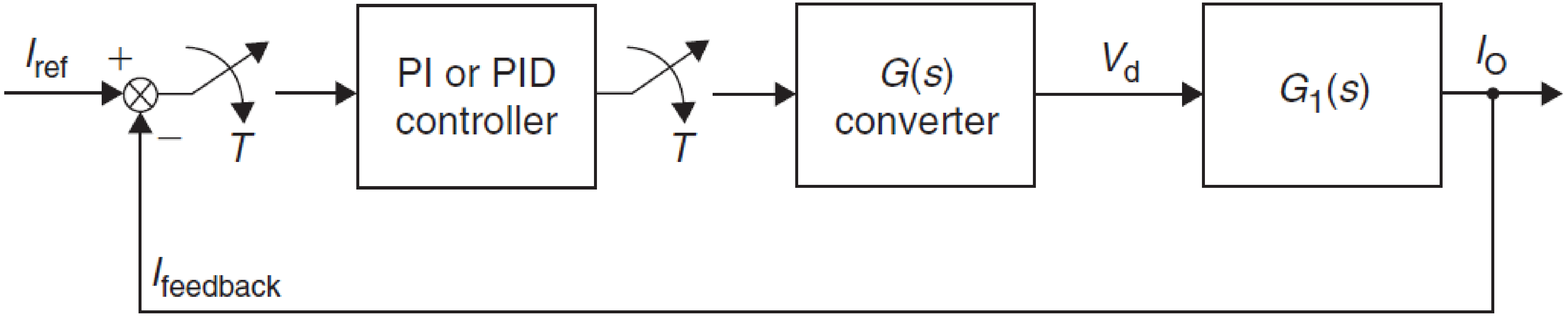
$$G_C(z) = \mathbf{Z}[G_C(s)] = \mathbf{Z}\left[\frac{1 + s\tau_i}{1 + p_C s\tau_i}\right] = \frac{1}{p_C} + \left(1 - \frac{1}{p_C}\right)\frac{z}{z - e^{-T/p_C\tau_i}}$$

- The poles of this system are in the unity-cycle. Therefore, this system is stable.



Analysis of Rectifiers with a First-Order Load

- The closed-loop PI control system of the converter *G*(*s*) with a first-order load is shown in Figure .The converter *G*(*s*) is a ZOH simulating AC/DC rectifiers.



- The closed-loop PI control transfer function of the AC/DC rectifiers with a first-order load in the *s*-domain is:

$$G_C(s) = \frac{G_{pi}(s)G(s)G_1(s)}{1 + G_{pi}(s)G(s)G_1(s)} = \frac{p\frac{1+s\tau_i}{s\tau_i}\frac{1}{1+s\tau_1}}{1 + p\frac{1+s\tau_i}{s\tau_i}\frac{1}{1+s\tau_1}} = \frac{p(1+s\tau_i)}{s\tau_i(1+s\tau_1) + p(1+s\tau_i)}$$

- This is a second-order transfer function with two poles in the left-hand half-plane (LHHP), so that this system is stable. If we carefully select the integral time constant τi $=\tau = L/R$, the items (1+$s\tau$i) in the numerator and the items (1+$s\tau$1) in the denominator can be eliminated each other

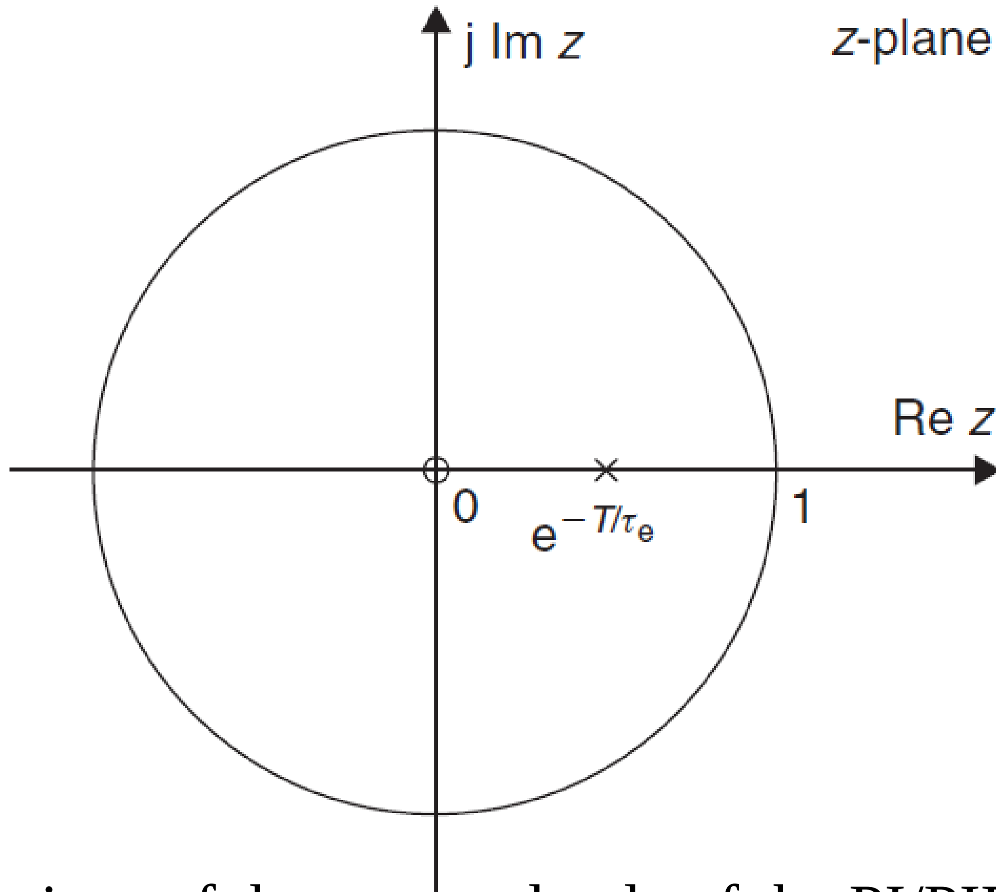
- The closed-loop transfer function can be rewritten as:

$$G_C(s) = \frac{p\frac{1}{s\tau_i}}{1 + p\frac{1}{s\tau_i}} = \frac{p}{s\tau_i + p} = \frac{1}{1 + s\frac{\tau_i}{p}} = \frac{1}{1 + s\tau_e}$$

- The transfer function in the *z*-domain is:

$$G_C(z) = \mathbf{Z}[G_C(s)] = \mathbf{Z}\left[\frac{1}{1 + s\frac{\tau_i}{p}}\right] = \frac{z}{z - e^{-T/\tau_e}}$$

- The system has a pole (e^{-T/τ_e}) located inside the unity-cycle further away from the unity-cycle with comparison to the original pole (e^{-T/τ_i}).



The locations of the zero and pole of the PI/PID controlled closed-loop control system of a converter with a first-order load in the *z*-plane.

Unity-Step Responses

- The output signal of the closed loop system in the *s*-domain is:

$$V_{\mathrm{O}}(s) = G_{\mathrm{C}}(s)V_{\mathrm{in}}(s) = \frac{1}{s}\frac{G_{\mathrm{pi}}(s)G(s)}{1+G_{\mathrm{pi}}(s)G(s)} = \frac{1}{s}\frac{1+s\tau_{\mathrm{i}}}{1+p_{\mathrm{C}}s\tau_{\mathrm{i}}}$$

- The unit-step response in the time domain is:

$$v_{\mathrm{O}}(t) = \frac{1}{p_{\mathrm{C}}} + \left(1 - \frac{1}{p_{\mathrm{C}}}\right)(1 - \mathrm{e}^{-t/p_{\mathrm{C}}\tau_{\mathrm{i}}})$$

- The output signal of the closed-loop system is a constant plus an exponential function, so that it is stable.

- The output signal of the closed-loop system in the *z*-domain is:

$$G_{\mathrm{C}}(z) = \mathbf{Z}\left[\frac{1}{s}G_{\mathrm{C}}(s)\right] = \mathbf{Z}\left[\frac{1}{s}\frac{1+s\tau_{\mathrm{i}}}{1+p_{\mathrm{C}}s\tau_{\mathrm{i}}}\right] = \frac{z}{z-1}\left[\frac{1}{p_{\mathrm{C}}} + \left(1-\frac{1}{p_{\mathrm{C}}}\right)\frac{1-\mathrm{e}^{-T/p_{\mathrm{C}}\tau_{\mathrm{i}}}}{z-\mathrm{e}^{-T/p_{\mathrm{C}}\tau_{\mathrm{i}}}}\right]$$

- The poles of this system are in the unity-cycle. Therefore, this system is stable

Analysis of Rectifiers with a First-Order Load

- The closed-loop PI control system of the converter $G(s)$ with a first-order load is shown in Figure
- The converter $G(s)$ is a ZOH simulating AC/DC rectifiers. The input signal is a unit-step function $I_{in}(s)=1/s$
- The unit-step response of the closed-loop PI control transfer function of the AC/DC rectifiers with a first-order load in the *s*-domain is:

$$I_O(s) = G_C(s)I_{in}(s) = \frac{1}{s}\frac{G_{pi}(s)G(s)G_1(s)}{1+G_{pi}(s)G(s)G_1(s)} = \frac{1}{s}\frac{1/(1+s\tau_e)}{1+1/(1+s\tau_e)} = \frac{1}{s}\frac{0.5}{1+0.5s\tau_e}$$

- This is a second-order transfer function, and it is stable.
- Therefore, the unit-step response of the closed-loop control system in the time domain is:

$$i_O(t) = 0.5(1 - e^{-2t/\tau_e})$$

- It means that the unit-step response of the closed-loop control system is an exponential function, so that it is stable. The unit-step response will have quicker settling process since it has a smaller time constant.
- The transfer function in the *z*-domain is:

$$I_O(z) = \mathbf{Z}\left[\frac{1}{s}\frac{0.5}{1 + 0.5s\tau_e}\right] = \frac{0.5z(1 - e^{-2T/\tau_e})}{(z - 1)(z - e^{-2T/\tau_e})}$$

PI CONTROL FOR DC/AC INVERTERS AND AC/AC (AC/DC/AC) CONVERTERS

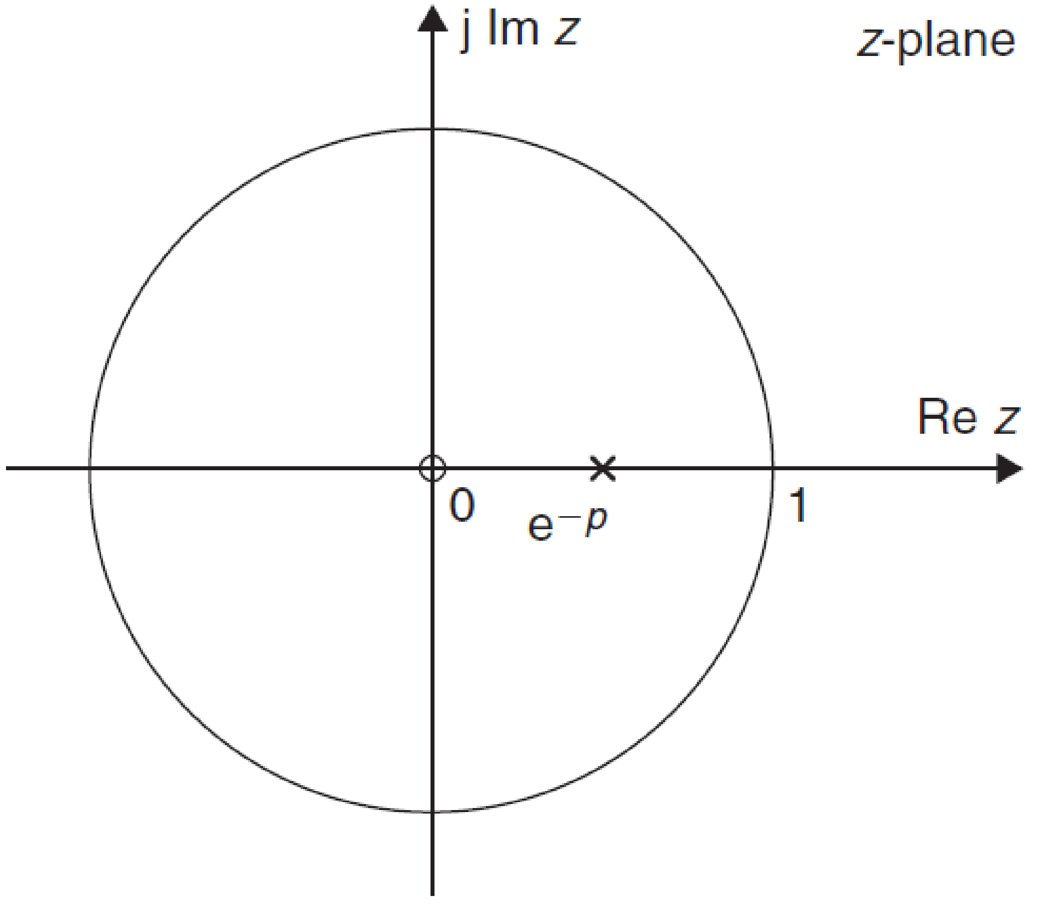
- **Stability Analysis**
- The converter $G(s)$ is a first-order hold (FOH) with the sampling interval T to simulate the DC/AC inverters and AC/AC (AC/DC/AC) converters.
- The feedback network is assumed as a unity element. We still select the PI controller's integral time constant $\tau_i = T$. The system closed-loop transfer function in the s-domain is:

$$G_C(s) = \frac{G_{pi}(s)G(s)}{1 + G_{pi}(s)G(s)} = \frac{p\frac{1+s\tau_i}{s\tau_i}\frac{1}{1+sT}}{1 + p\frac{1+s\tau_i}{s\tau_i}\frac{1}{1+sT}} = \frac{1}{1 + s\frac{T}{p}}$$

- The closed-loop transfer function is stable.
- The system closed-loop transfer function in the *z*-domain is:

$$G_C(z) = \mathbf{Z}[G_C(s)] = \mathbf{Z}\left[\frac{1}{1 + s\frac{T}{p}}\right] = \frac{z}{z - e^{-p}}$$

- The pole of this system is inside the unity-cycle. Therefore, this system is stable.



The locations of the zero and pole of the PI control closed-loop control system (FOH) in the *z*-plane.

Analysis of Rectifiers with a First-Order Load

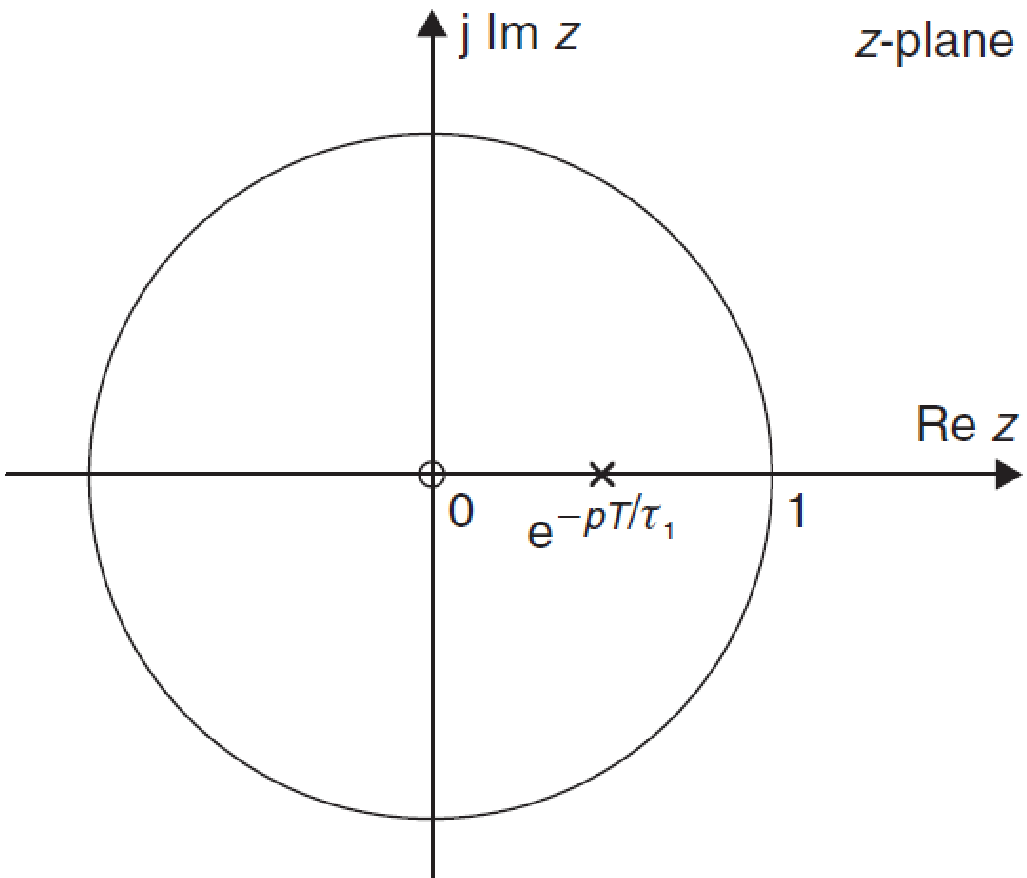
- The converter $G(s)$ is an FOH simulating DC/AC inverters and AC/AC (AC/DC/AC) converters. The feedback network is assumed as a unity element. We still select the PI controller's integral time constant $\tau_i = \tau_1$.
- The system closed-loop transfer function in the *s*-domain is:

$$G_C(s) = \frac{G_{pi}(s)G(s)G_1(s)}{1 + G_{pi}(s)G(s)G_1(s)} = \frac{p\frac{1+s\tau_i}{s\tau_i}\frac{1}{1+s\tau_1}\frac{1}{1+sT}}{1 + p\frac{1}{s\tau_i}\frac{1}{1+s\tau_1}\frac{1}{1+sT}} = \frac{p}{s\tau_1(1 + sT) + p}$$

- This is a second-order transfer function with two poles in the LHHP, so that this system is stable.

- The transfer function in the z-domain is:

$$G_C(z) = \mathbf{Z}[G_C(s)] = \mathbf{Z}\left[\frac{1}{1 + s\frac{\tau_1}{p}}\right] = \frac{z}{z - e^{-pT/\tau_1}}$$



Unit-Step Response for PI Controlled DC/AC Inverters and AC/AC (AC/DC/AC) Converters

- The converter $G(s)$ is an FOH simulating DC/AC inverters and AC/AC (AC/DC/AC) converters. The feedback network is assumed as a unity element.
- The output signal of the closed-loop system in the *s*-domain:

$$V_O(s) = G_C(s)V_{in}(s) = \frac{1}{s}\frac{G_{pi}(s)G(s)}{1+G_{pi}(s)G(s)} = \frac{1}{s}\frac{1}{1+s\frac{T}{p}}$$

- The unit-step response of the closed-loop transfer function is stable.

- The unit-step response in the time domain is:

$$v_O(t) = 1 - e^{-pt/T}$$

- The output signal of the closed-loop system is an exponential function, so that it is stable.
- The unit-step response of the closed-loop system in the *z*-domain is:

$$G_C(z) = \mathbf{Z}\left[\frac{1}{s}G_C(s)\right] = \mathbf{Z}\left[\frac{1}{s}\frac{1}{1+s\frac{T}{p}}\right] = \frac{z}{z-1}\frac{1-e^{-p}}{z-e^{-p}}$$

- The pole of this system is in the unity-cycle. Therefore, this system is stable.

Unit-V

Energy Factor Application in AC and DC Motor Drives

- AC and DC motors are an important equipment to convert the electrical energy to mechanical energy
- The main parts of the stored energy in a DC motor are kinetic energy since the armature inductance is comparably small

ENERGY STORAGE IN MOTORS

- If a motor is supplied by a converter or other switching circuit the energy transfer from the source to the motor is by the quantization manner.
- The energy is pumped to the motor by energy quantum in each sampling interval, although the sampling interval *T* is small.

Energy Storage in AC Motor

- Energy storage in AC motor has two parts: mechanical stored energy (*MSE*) and electrical stored energy (*ESE*).
- Total stored energy (*SE*) is defined as:

$$SE = MSE + ESE$$

Mechanical Stored Energy

- Usually the mechanical stored energy of an AC motor includes few parts:
- The mechanical stored energy in the rotor.
- The mechanical stored energy in the joint and gear-box.
- The mechanical stored energy in the further equipment.

- All the mechanical stored energy as kinetic energy which is measured by:

$$MSE = \frac{1}{2} J_{\mathrm{e}} \omega^2$$

- where J_e is the equivalent inertia including motor rotor, joint and gear-box, and the further mechanical equipment. It is measured in kgm^2, ω is the motor running speed and measured in rad/s.

- To simplify the investigation we may ignore the other energy losses/storage in the motor such as hit, frictional and windage energy losses, which will affect the transient process.

Electrical Stored Energy

- The electrical stored energy in an AC motor is considered in the stator circuit.
- Back electromagnetic force (EMF) is corresponding to the motor running speed.
- Assume the stator inductance is *L* and the stator current is *I*s, the electrical stored energy is measured by:

$$ESE = \frac{1}{2} L I_s^2$$

- where L_s is the stator inductance including the cable's inductance in H, I_s is the AC motor stator current in A.

Energy Storage in DC Motor

- Energy storage in a DC motor has two parts: mechanical stored energy (*MSE*) and electrical stored energy (*ESE*).
- Total stored energy is defined as:

$$SE = MSE + ESE$$

Mechanical Energy Storage

- Usually the mechanical stored energy of a DC motor includes few parts:
- The mechanical stored energy in the rotor.
- The mechanical stored energy in the joint and gear-box.
- The mechanical stored energy in the further equipment.

- consider all the mechanical stored energy is kinetic energy measured by:

$$MSE = \frac{1}{2} J_e \omega^2$$

- where J_e is the equivalent inertia including motor rotor, jointer and gear-box, and the further mechanical equipment. It is measured in kgm^2, ω is the DC motor running speed and measured in rad/s.

Electrical Energy Storage

- The electrical stored energy in a DC motor is considered in the armature circuit and the back EMF.
- Assume the armature inductance is L_a and the armature current is I_a,
- The field inductance is L_f and the field current is I_f The electrical stored energy is measured by

$$ESE = \frac{1}{2}(L_a I_a^2 + L_f I_f^2) + EI_a$$

- where E is the DC motor back EMF,

- A PM DC motor has no field winding, so the equation can be simplified as:

$$ESE = \frac{1}{2} L_{\mathrm{a}} I_{\mathrm{a}}^2 + E I_{\mathrm{a}}$$

A DC/AC VOLTAGE SOURCE

- We introduce an application of DC/AC PWM inverter in this section.
- It is called zero-phase odd-harmonic repetitive controller for a single-phase PWM inverter

Zero-Phase Odd-Harmonic Repetitive Control

- Zero-phase odd-harmonic repetitive control is a novel approach of digital control methods.
- Assume that all harmonics are in odd orders.

Odd-Harmonic Periodic Signal Generator

- In the discrete time domain, a conventional periodic signal generator can be written as:

$$G_r(z) = \frac{z^{-N}}{1 - z^{-N}} = \frac{1}{z^N - 1}$$

- where $N = Ts/T$, Ts and T being the signal period and the sampling time, respectively
- The generator in Equation can eliminate the harmonics that are belowthe Nyquist frequency, ω ($=\pi/T$), by introducing infinite gain at both even and odd-harmonic frequencies

- For systems such as the CVCF PWM inverters, the references and disturbances mainly contain odd-harmonic frequencies.
- When a conventional repetitive controller is used, it updates the control output every N sampling intervals with at least N memory cells.
- In the following, we investigate a new odd-harmonic periodic signal generator, which occupies $N/2$ data memory cells and updates control output every $N/2$ sampling intervals.

- A discrete-time signal $x(n)$ with period $N \times T$ can be written as:

$$x(n+N) = x(n), \quad \forall\, n \in \mathrm{Z}$$

Its Fourier series is as follows:

$$\begin{cases} x(n) = \sum_{k=0}^{N-1} c_k \mathrm{e}^{\mathrm{j}2\pi kn/(NT)} \\ c_k = \frac{1}{N} \sum_{n=0}^{N-1} x(n) \mathrm{e}^{-\mathrm{j}2\pi kn/(NT)} \end{cases}$$

- In Equation (previous slide), if the coefficients c_k are zero for even index (k mod 2=0) (including k =0), then the signal is an odd-harmonic periodic signal.
- If the period N is even, the discrete-time signal, $x(n)$, is an odd-harmonic signal if and only if $x(n+(N/2))=x(n)$.
- A discrete time odd-harmonic periodic signal generator has the following transfer function:

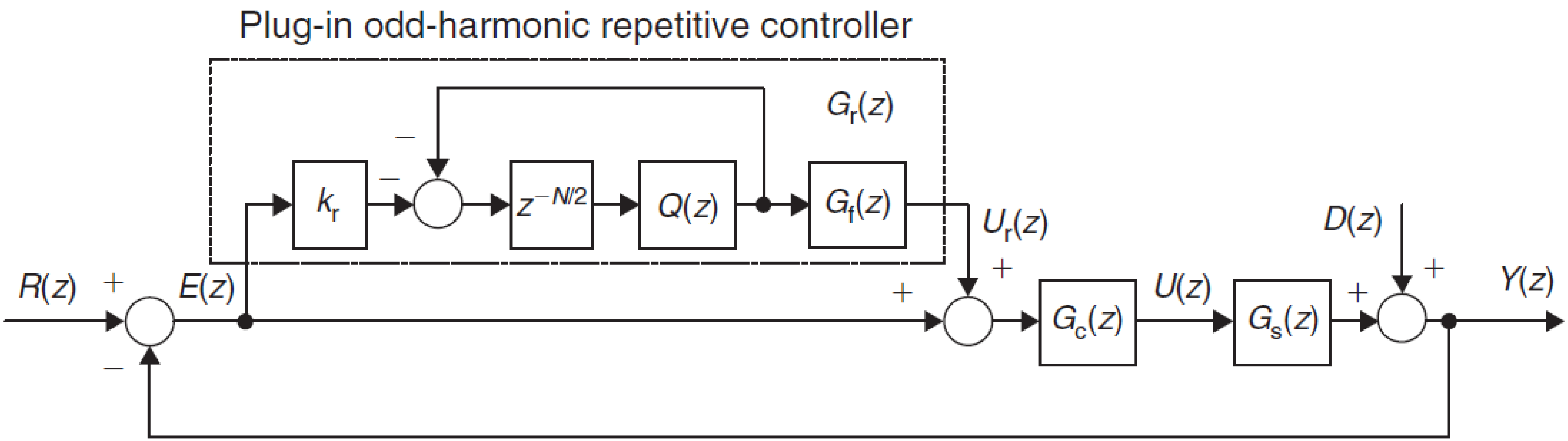
$$G_r(z) = -\frac{1}{z^{N/2}+1}$$

- The generator has its poles at:

$$z = \mathrm{e}^{\mathrm{j}(2k+1)\frac{2\pi}{NT}} \quad k = 0, 1, \ldots, \frac{N}{2} - 1$$

- if the odd-harmonic signal generator as in Equation (previous slide) is incorporated in a system, it will achieve perfect asymptotic tracking or disturbance rejection for this class of periodic signals.

Odd-Harmonic Repetitive Control



- *R*(*z*) is the reference input, *Y* (*z*) is the output, *E*(*z*)=*R*(*z*)−*Y* (*z*) is the tracking error, *D*(*z*) is the disturbance, *G*c(*z*) is the conventional controller, $G_s(z)$ is the plant, $G_r(z)$ is a feedforward plug-in odd-harmonic repetitive controller,
- *k*r is the *repetitive control gain*, *U*r(*z*) is the output of the repetitive controller,

- $G_f(z)$ is a filter to obtain a stable overall closed-loop system, and $Q(z)$ is a low-pass filter to enhance the robustness of the overall system.
- The proposed plug-in odd-harmonic repetitive control law can be expressed as:

$$U_r(z) = -Q(z)(z^{-N/2}U_r(z) + k_r z^{-N/2}G_f(z)E(z))$$

- The transfer functions from $R(z)$ and $D(z)$ to $Y(z)$ in the overall closed-loop control system can be derived as:

$$\frac{Y(z)}{R(z)} = \frac{(1+G_r(z))G_c(z)G_s(z)}{1+(1+G_r(z))G_c(z)G_s(z)} = \frac{(1+z^{-N/2}Q(z)(1-k_r G_f(z)))H(z)}{1+z^{-N/2}Q(z)(1-k_r G_f(z)H(z))}$$

$$\frac{Y(z)}{D(z)} = \frac{1+z^{-N/2}}{1+G_c(z)G_s(z)} \frac{1}{1+z^{-N/2}Q(z)(1-k_r G_f(z)H(z))}$$

where

$$H(z) = \frac{G_c(z)G_s(z)}{1+G_c(z)G_s(z)}$$

- The overall closed-loop system is stable if the following conditions hold:

1. the roots of $1+G_c(z)G_s(z)=0$ are located inside the unit circle;
2. $\|Q(z)(1-k_r G_f(z)H(z))\| < 1 \quad \forall z = e^{j\omega}, \quad 0 < \omega < \frac{\pi}{T}$

- The error transfer function of the overall system is:

$$G_e(z) = \frac{E(z)}{R(z) - D(z)} = \frac{1 + z^{-N/2}}{1 + G_c(z)G_s(z)} \frac{1}{1 + z^{-N/2}Q(z)(1 - k_r G_f(z)H(z))}$$

Thus, if the overall closed-loop system is asymptotically stable and the angular frequency, ω, of the reference input $R(t)$ and disturbance $D(t)$ approaches to $\omega_m = (2m+1)2\pi/(NT)$, $m = 0, 1, 2, \ldots, (N/2) - 1$, then $z^{-N/2} \to 1$, thus:

$$\lim_{\omega \to \omega_m} \|e(j\omega)\| = 0$$

- According to Equation, if the frequencies of odd-harmonic references and/or disturbances are less than half of the sampling frequency (Nyquist frequency), steady state zero-tracking error can be ensured by using the odd-harmonic repetitive controller $G\mathrm{r}(z)$.
- Theoretically, for CVCF PWM inverters, the odd-harmonic repetitive controller Equation is a zero-tracking error control law, if there are no even-harmonics disturbances.

AN AC/DC CURRENT SOURCE

- an application of AC/DC silicon controlled rectifier (SCR) rectifying current source
- It is called "digitally controlled AC/DC SCR rectifying current source".

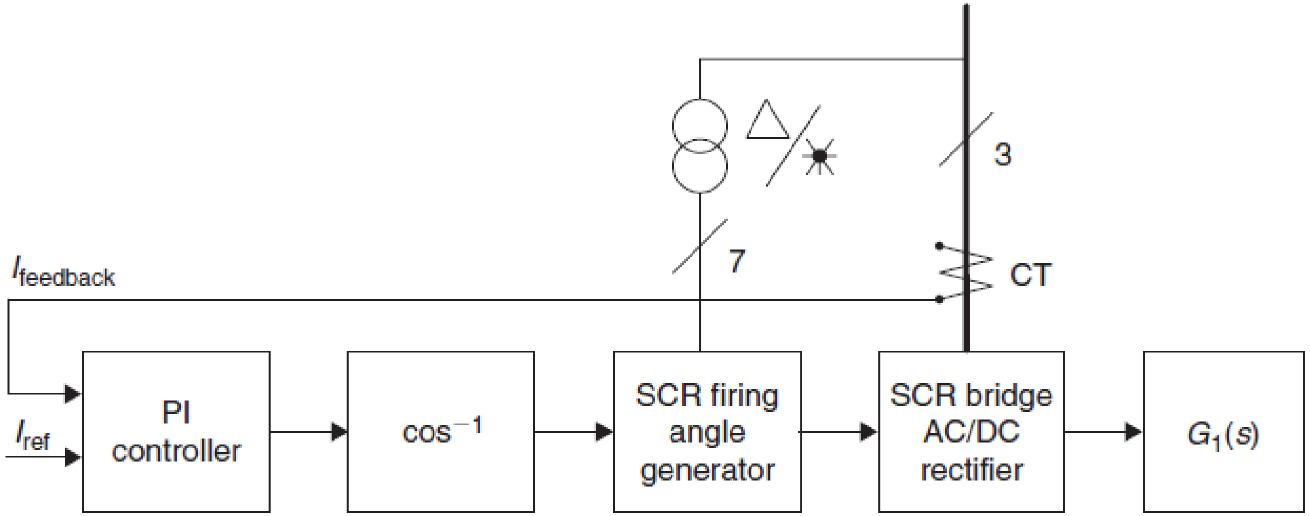


Figure 11.18 Digitally controlled AC/DC SCR rectifying current source.

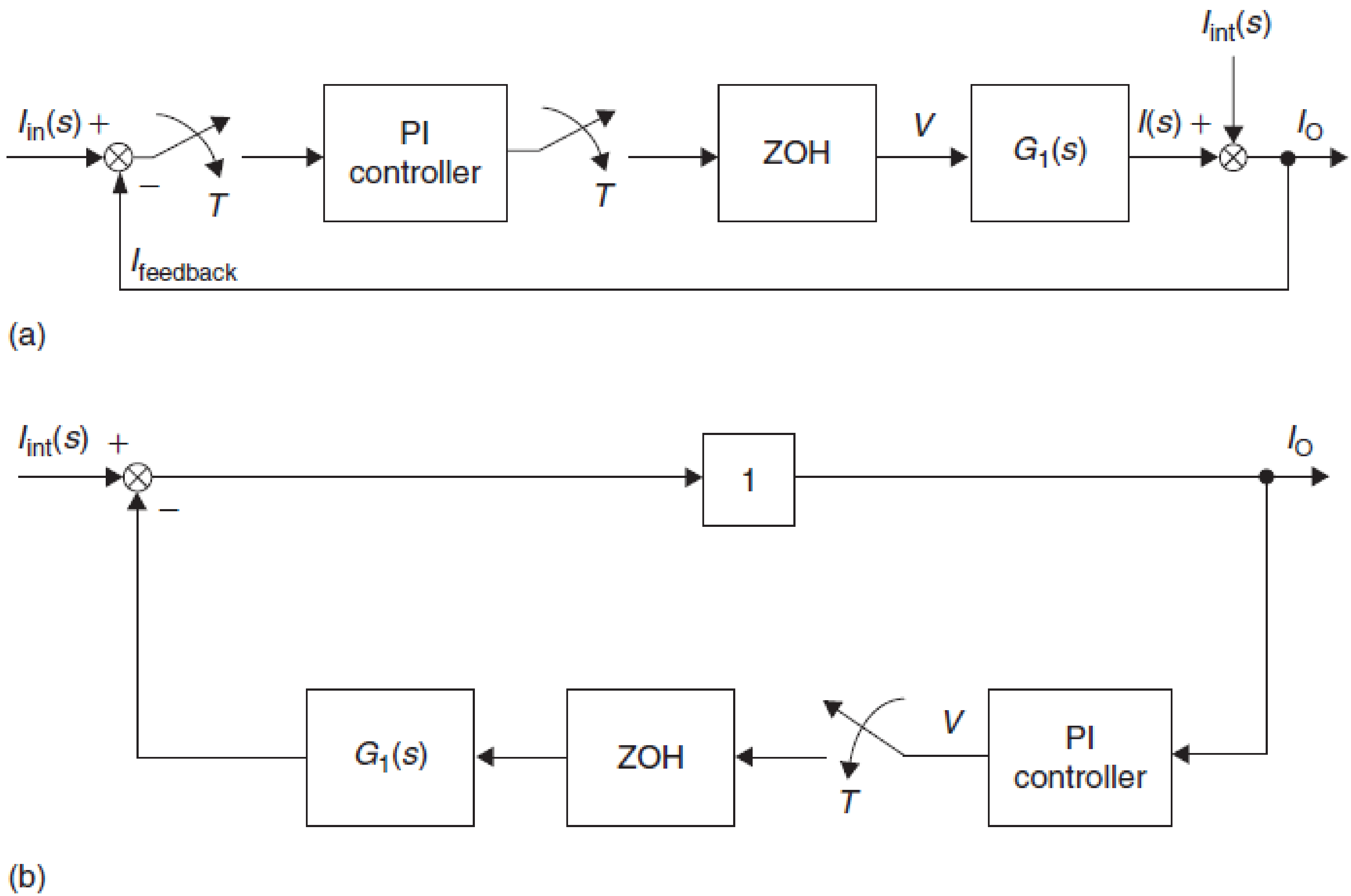


Figure 11.19 System block diagram of an AC/DC SCR rectifying current source. (a) System block diagram for stability and unit-step response. (b) Equivalent block diagram for disturbance analysis.

- The block diagram of the SCR current source with PI-controller is shown in Figure 11.19.
- The input signal is $I_{in}(s)$, the output current is $I_O(s)$ and the interference signal is $I_{int}(s)$ in Figure 11.19(a).
- Usually, when we analyze the disturbance response, the input signal is assumed no change
- The equivalent block diagram for disturbance analysis is shown in Figure 11.19(b).
- The PI-controller is effective to keep the current source to have satisfied system stability, unit-step response and interference impulse response.

System Arrangement

There are three important elements in this system:

- PI-controller
- ZOH
- the first-order load

PI-Controller

- The PI-controller is designed in digital form,
- Transfer function in the *s*-domain is:

$$G_{\mathrm{pi}}(s) = K_{\mathrm{p}} + \frac{K_{\mathrm{i}}}{s}$$

- The transfer function of the PI-controller in the *z*-domain is:

$$G_{\mathrm{pi}}(z) = K_{\mathrm{p}} + \frac{z}{z-1}K_{\mathrm{i}}$$

- Where *K*p is the proportional gain, and *K*i is the integral gain.
- The PI-control algorithm has been implemented by a digital signal processor (DSP).
- The input of the PI-controller is the error between the input current reference and the current feedback signals.

ZOH to Simulate the SCR

- The AC/DC SCR is a three-phase thyristor bridge with six devices. The output DC voltage of the AC/DC SCR is determined by the firing angle α.

$$V_{\mathrm{d}} = V_{\mathrm{dO}} \cos \alpha$$

- where V_{dO} is the maximum DC output voltage corresponding to the firing angle α=0.
- Since the thyristor is out of control once it starts conducting in a period until the current through it reduces to zero

- The AC/DC thyristor bridge rectifier is inherently a sample and hold element in the control system.
- The system may, therefore, be implemented by a latch so the thyristor bridge rectifier is considered a ZOH in the algorithm.
- Its transfer function in the *s*-domain is:

$$G(s) = \frac{1 - \mathrm{e}^{-Ts}}{s}$$

- where T is the sampling interval, $T = 1/6f$. In a power supply network with the frequency of 50 Hz, the frequency is f =50 Hz. So that T =1/300 s=3.33 ms.

- The ZOH's transfer function in the *z*-domain is:

$$G(z) = \frac{z}{z-1}$$

- The output value of the ZOH will keep a constant in a sampling interval *T*.

The First-Order Load

- Transfer function in the *s*-domain is:

$$G_1(s) = \frac{1}{1 + s\tau_1}$$

- Its transfer function in the *z*-domain is:

$$G_1(z) = \frac{z}{z - \mathrm{e}^{-T/\tau_1}}$$

Disturbance Signal

- The interference signal is a unit-delta function. It means that the signal disappears in a short time.
- If the interference is kept such as the load resistance *R* changed.
- The disturbance signal $I_{int}(s)$ is assumed as a unit-step function.
- Transfer function in the *s*-domain is:

$$I_{\text{int}}(s) = \frac{1}{s}$$

- The corresponding transfer function in the *z*-domain is:

$$I_{\mathrm{int}}(z) = \frac{z}{z-1}$$

System Stability Analysis

- The system closed-loop transfer function as:

$$G_C(s) = \frac{G_{pi}(s)G(s)G_1(s)}{1 + G_{pi}(s)G(s)G_1(s)} = \frac{\left(K_p + \frac{K_i}{s}\right)\frac{1 - e^{-Ts}}{s}\frac{1}{1 + s\tau_1}}{1 + \left(K_p + \frac{K_i}{s}\right)\frac{1 - e^{-Ts}}{s}\frac{1}{1 + s\tau_1}}$$

- This is stable system if we carefully select the proportional gain *K*p and the integral gain *K*i to keep all poles are in the LHHP in the *s*-plane.

- The closed-loop transfer function in the *z*-domain is:

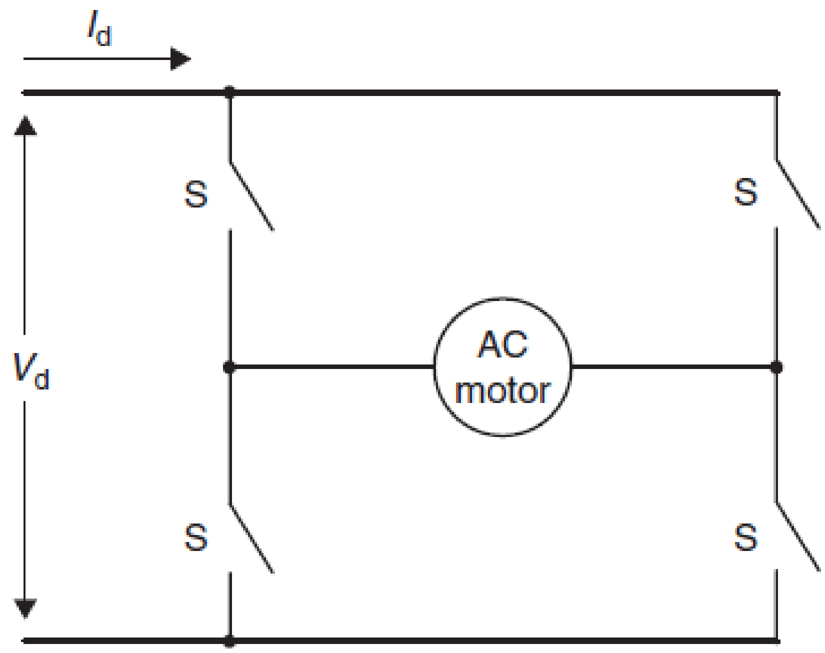
$$G_C(z) = \frac{G_{pi}(z)G(z)G_1(z)}{1 + G_{pi}(z)G(z)G_1(z)} = \frac{\left(K_p + \frac{z}{z-1}K_i\right)\frac{z}{z-1}\frac{z}{z-e^{-T/\tau 1}}}{1 + \left(K_p + \frac{z}{z-1}K_i\right)\frac{z}{z-1}\frac{z}{z-e^{-T/\tau 1}}}$$

- This is a stable system if we carefully select the proportional gain *K*p and the integral gain *K*i to keep all poles inside the unit-cycle in the *z*-plane.

AC MOTOR DRIVES

- AC motor drive is the one main method to transfer AC electrical energy to mechanical energy.

AC Motor Supplied by a Chopper



A single-phase AC motor supplied by a chopper.

- The pumping energy (*PE*) is:

$$PE = V_{\mathrm{d}} I_{\mathrm{d}} T$$

- where *V*d is the DC link source voltage, *I*d is the DC source current, *T* is the chopping period (*T* =1/*f* , where *f* is the switching frequency).

$$EF = \frac{SE}{PE} = \frac{MSE + ESE}{PE}$$

$$t_{\mathrm{settling}} = EF \times T = \frac{MSE + ESE}{V_{\mathrm{d}} I_{\mathrm{d}}}$$

- The settling time from one running speed to another speed is approximately estimated as:

$$\Delta t_{\text{settling}} = \Delta EF \times T = \frac{\Delta MSE + \Delta ESE}{V_{\text{d}} I_{\text{d}}}$$

- t_{settling} is the transient settling time from one running speed to another,
- ΔEF is the EF variation between the two running states,
- $\Delta\, MSE$ is the mechanical stored energy variation between the two running states and
- $\Delta\, ESE$ is the electrical stored energy variation between the two running states.

Variable-Speed AC Motor Drive System Supplied by a FOH

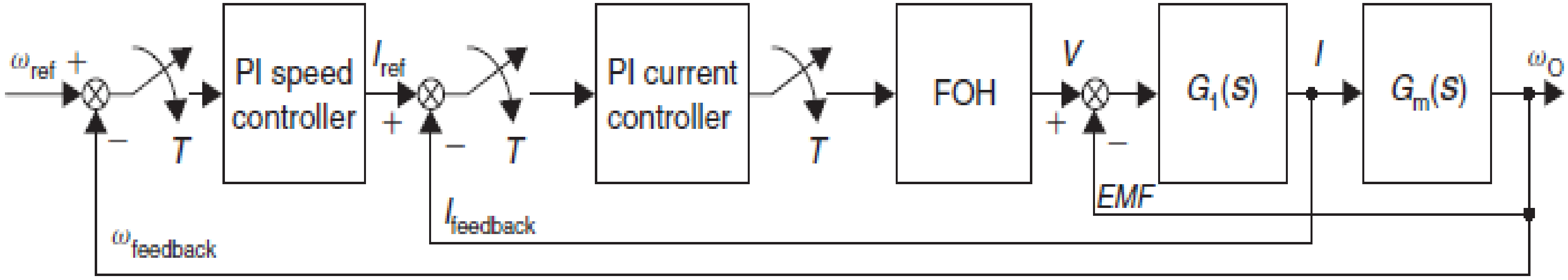


Figure 11.23 The system block diagram of the AC motor supplied by a FOH.

- The inner current closed-loop control transfer function is:

$$G_{C-i}(s) = \frac{G_{pi2}(s)G(s)G_1(s)}{1 + G_{pi2}(s)G(s)G_1(s)} = \frac{p_2 \frac{1+s\tau_{i2}}{s\tau_{i2}} \frac{1}{1+sT} \frac{1}{1+s\tau_1}}{1 + p_2 \frac{1+s\tau_{i2}}{s\tau_{i2}} \frac{1}{1+sT} \frac{1}{1+s\tau_1}}$$

- We select the PI-control integral time constant $\tau i2$ to be equal to the time constant $\tau 1$ of the first-order circuit. Considering that the sampling interval T is very small, we obtain the closed-loop transfer function in the *s*-domain of the inner current loop as:

$$G_{C-i}(s) = \frac{p_2 \frac{1}{s\tau_1} \frac{1}{1+sT}}{1 + p_2 \frac{1}{s\tau_1} \frac{1}{1+sT}} \approx \frac{1}{1 + s\frac{\tau_1}{p_2}}$$

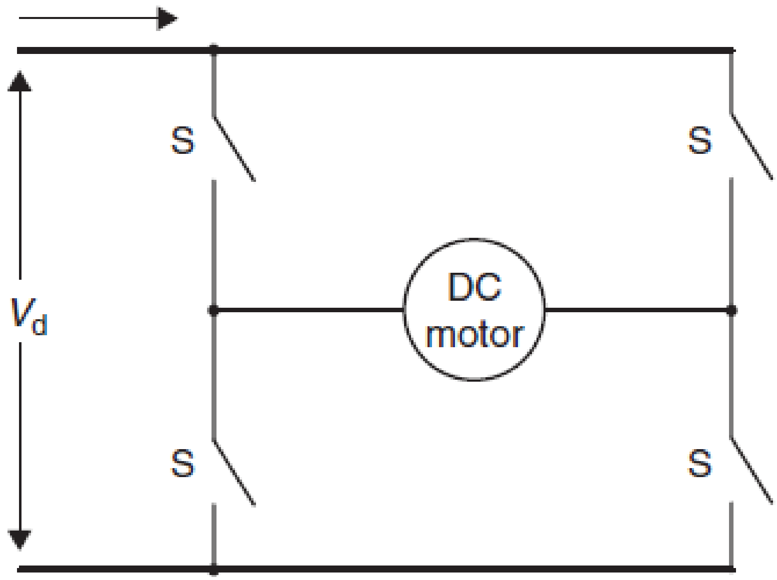
- Transfer function in the *z*-domain is:

$$G_{C-i}(z) = \frac{z}{z - e^{-p_2 T/\tau_1}}$$

DC MOTOR DRIVES

- DC motor drive is the one main method to transfer DC electrical energy to mechanical energy.

DC Motor Supplied by a Chopper



A PM DC motor supplied by a chopper.

- DCmotor supplied by a chopper (assuming the field is a permanent magnet).
- The power supply is a DC voltage source with DC link voltage V_d and the copping frequency is f , and the sampling period is $T = 1/f$.
- The pumping energy (PE) is

$$PE = V_d I_d T$$

$$EF = \frac{SE}{PE} = \frac{MSE + ESE}{PE}$$

$$t_{settling} = EF \times T = \frac{MSE + ESE}{V_d I_d}$$

- The settling time from one running speed to another speed is approximately estimated as:

$$\Delta t_{\text{settling}} = \Delta EF \times T = \frac{\Delta MSE + \Delta ESE}{V_{\text{d}} I_{\text{d}}}$$

- where t_{settling} is the transient settling time from one running speed to another,
- ΔEF is the energy factor variation between the two running states,
- Δ *MSE* is the energy mechanical stored energy variation between the two running states
- Δ *ESE* is the electrical stored energy variation between the two running states.

Variable-Speed DC PM Motor Drive System Supplied by a SOH

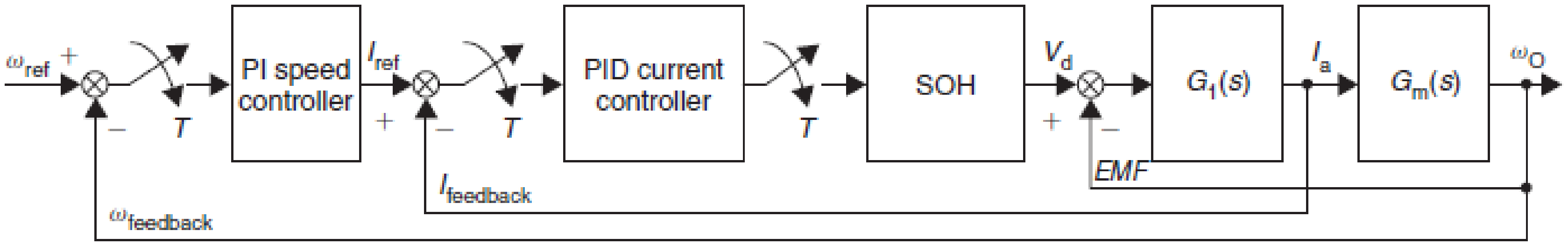


Figure 11.28 The system block diagram of a PM DC motor supplied by a SOH.

- The inner current closed-loop control transfer function is:

$$G_{C-i}(s) = \frac{G_{pid2}(s)G(s)G_1(s)}{1 + G_{pid2}(s)G(s)G_1(s)} = \frac{p_2 \frac{1 + s\tau_{i2} + s^2\tau_{i2}\tau_{d2}}{s\tau_{i2}} \frac{1}{1 + s\tau + s^2\tau\tau_d} \frac{1}{1 + s\tau_1}}{1 + p_2 \frac{1 + s\tau_{i2} + s^2\tau_{i2}\tau_{d2}}{s\tau_{i2}} \frac{1}{1 + s\tau + s^2\tau\tau_d} \frac{1}{1 + s\tau_1}}$$

- We select the PID current-control integral time constant τ_{i2} and the differential time constant τ_{d2} to be equal to the time constant τ and damping time constant τ_d of the DC/DC converter, respectively.
- We obtain the closed-loop transfer function in the *s*-domain of the inner current loop as:

$$G_{C-i}(s) = \frac{p_2 \frac{1}{s\tau} \frac{1}{1+s\tau_1}}{1 + p_2 \frac{1}{s\tau} \frac{1}{1+s\tau_1}} = \frac{1}{1 + s\frac{\tau}{p_2} + s^2 \frac{\tau}{p_2} \tau_1}$$

- Usually the equivalent damping time constant $\tau 1$ is smaller than the time constant $\tau/p2$. So that this inner closed-loop transfer function can be rewritten as:

$$G_{C-i}(s) = \frac{1}{1 + s\frac{\tau}{p_2}}$$

- The corresponding transfer function in the *z*-domain is:

$$G_{C-i}(z) = \frac{z}{z - e^{-p_2 T/\tau}}$$

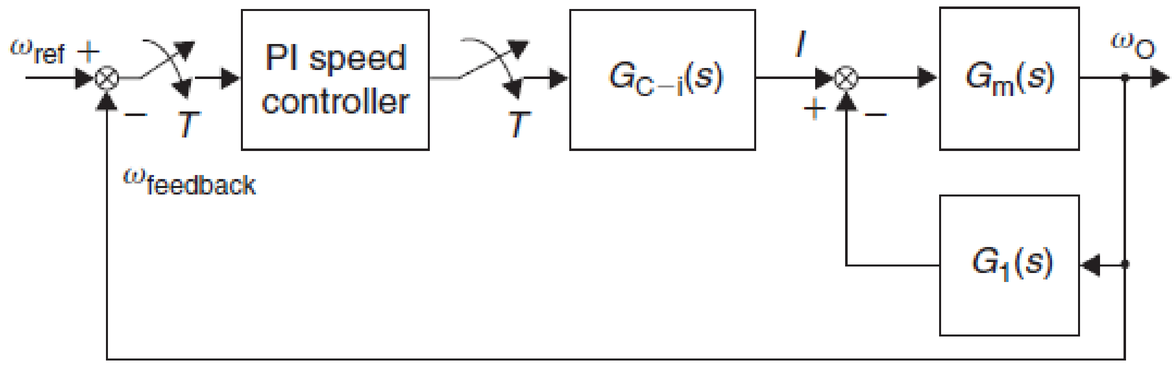


Figure 11.29 The outer system block diagram of the PM DC motor supplied by a SOH.

- The transfer function of the outer closed-loop transfer function in the *s*-domain is:

$$G_{C-s}(s) = \frac{G_{pi}(s)G_{C-i}(s)\frac{G_m(s)}{1+G_1(s)G_m(s)}}{1 + G_{pi}(s)G_{C-i}(s)\frac{G_m(s)}{1+G_1(s)G_m(s)}} = \frac{p_1\frac{1+s\tau_{i1}}{s\tau_{i1}}\frac{1}{1+s\tau/p_2}\frac{1/s\tau_m}{1+\frac{1/s\tau_m}{1+s\tau_1}}}{1 + p_1\frac{1+s\tau_{i1}}{s\tau_{i1}}\frac{1}{1+s\tau/p_2}\frac{1/s\tau_m}{1+\frac{1/s\tau_m}{1+s\tau_1}}}$$

- The integral element has very large time constant τm, which is much greater than the time constant of the first-order circuit, i.e. τm>>τ1.
- We select the PI speed control integral time constant τi1 to be equal to the time constant τm of the integral element.
- We obtain the closed-loop transfer function in the *s*-domain of the outer speed loop as:

$$G_{C-s}(s) \approx \frac{p_1 \frac{1+s\tau_{i1}}{s\tau_{i1}} \frac{1}{1+s\tau/p_2} \frac{1}{1+s\tau_m}}{1 + p_1 \frac{1+s\tau_{i1}}{s\tau_{i1}} \frac{1}{1+s\tau/p_2} \frac{1}{1+s\tau_m}} = \frac{p_1 \frac{1}{s\tau_m} \frac{1}{1+s\tau/p_2}}{1 + p_1 \frac{1}{s\tau_m} \frac{1}{1+s\tau/p_2}} \approx \frac{1}{1 + \frac{s\tau_m}{p_1}}$$

- Transfer function in the *z*-domain is:

$$G_{\mathrm{C-s}}(z) = \frac{z}{z - \mathrm{e}^{-p_1 T/\tau_{\mathrm{m}}}}$$