Novel Three-Phase 2/3-Modulated Buck-Boost Current Source Inverter System Employing Dual-Gate Monolithic Bidirectional GaN e-FETs

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Energy Solution Development Center
Industrial Solution Company

International Wide-Bandgap Power Electronics Applications Workshop

14th May 2019

- **ETH, Zurich, Switzerland - 7th February 1854**

Facts & Figures

509	Professors
5800	Staff Members
4500	Ph.D. Students
14500	M.Sc. & B.Sc. Students

2	Campuses
16	Departments - **D-ITET**
136	Laboratories - **PES**

► **Main Campus, Zurich City Center**

Power Electronic Systems Laboratory

Organizational Diagram

Industry Relations
R. Coccia / B. Seiler

Johann W. Kolar

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter	AC-AC Converter	DC-DC Converter	**DC-AC Converter**	Multi-Domain Modeling	Measurement Technology	Advanced Mechatronics	Magnetic Levitation
		F. Krismer	D. Bortis	F. Krismer		D. Bortis	D. Bortis
M. Heller D. Menzi D. Neumayr J. Schäfer	J. Azurza P. Czyz	P. Bezerra T. Guillod G. Knabben	M. Antivachis J. Böhler **M. Guacci** M. Haider	P. Papamanolis	P. Niklaus	E. Hubmann	Th. Holenstein P. Püntener S. Miric

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

Introduction

Introduction

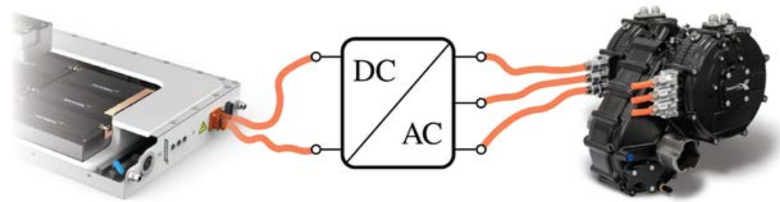
Electric Mobility

Airbus, Siemens, Rolls-Royce: E-FaN X
www.airbus.com

Tesla Motors: Model 3
www.tesla.com

Hybrid Electric Vehicle (**HEV**) 50 kW
Battery Electric Vehicle (**BEV**) 200 kW
Air Taxi 400 kW
More Electric Aircraft (**MEA**) 2 MW
More Electric Engine (**MEE**) 20 MW

On-Board DC/AC Conversion



Energy Storage Electric Machine
Power Electronics

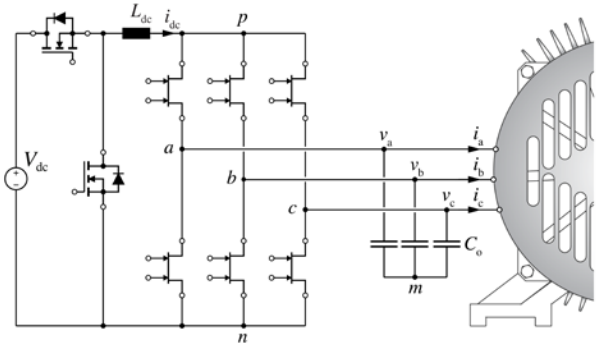
Power Electronics Requirements

Efficiency	> 98 - 99%
Power Density	> 5 - 15 kW/kg

Outline

- Introduction
- Voltage vs. Current DC-Link Inverter
- Monolithic Bidirectional Switch
- 3-ϕ Buck-Boost CSI System
- Hardware & Measurements
- Outlook

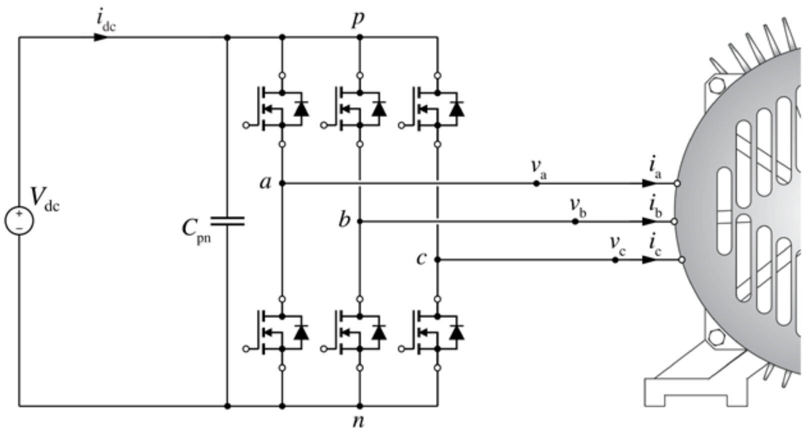
Voltage vs. Current DC-Link Inverter



Continuous Output Voltage
Wide Input Voltage Range
Bidirectional Power Devices

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter

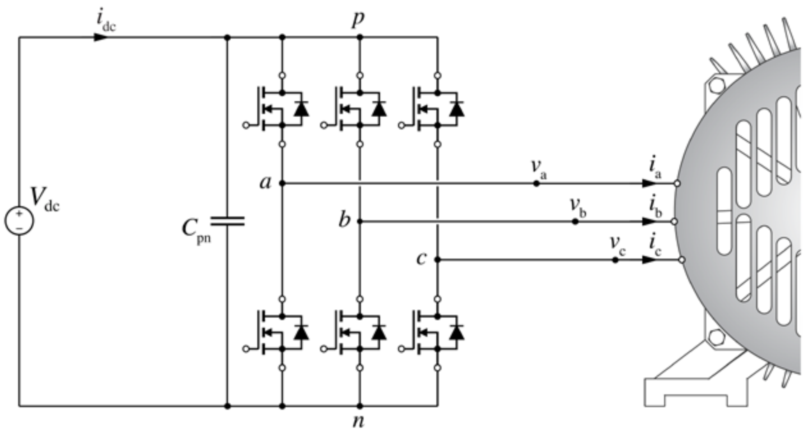


Advantages

Simple Circuit Topology
No Magnetic Components
Only Six Power Semiconductors

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter



Challenges

Switched Output Voltage

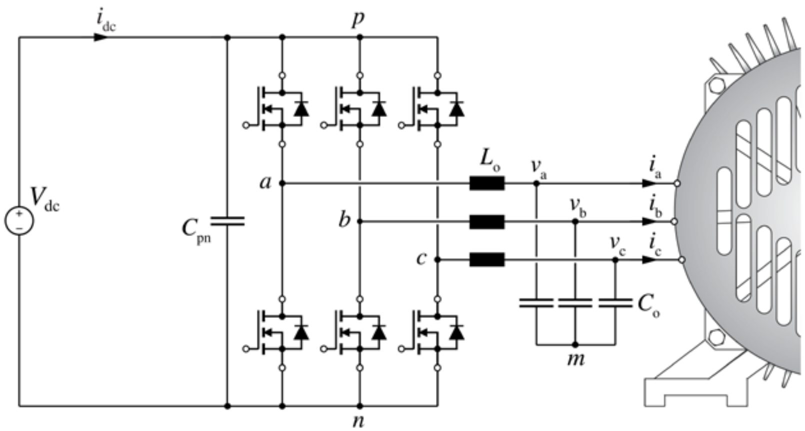
Wave Propagation & Reflection
Partial Discharge (PDIV)
Bearing Currents
Electro-Magnetic (EMI) Emissions

Advantages

Simple Circuit Topology
No Magnetic Components
Only Six Power Semiconductors

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter



Challenges

Switched Output Voltage

Wave Propagation & Reflection
Partial Discharge (PDIV)
Bearing Currents
Electro-Magnetic (EMI) Emissions

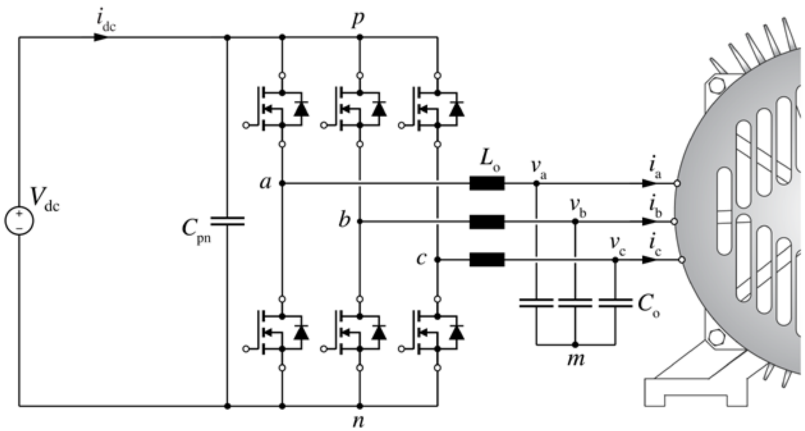
→ External Output Filter
→ Reinforced Insulation
→ Ceramic Bearings
→ Shielded Cables

Advantages

Simple Circuit Topology
No Magnetic Components
Only Six Power Semiconductors

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter



Advantages

Simple Circuit Topology
No Magnetic Components
Only Six Power Semiconductors

Challenges

Switched Output Voltage

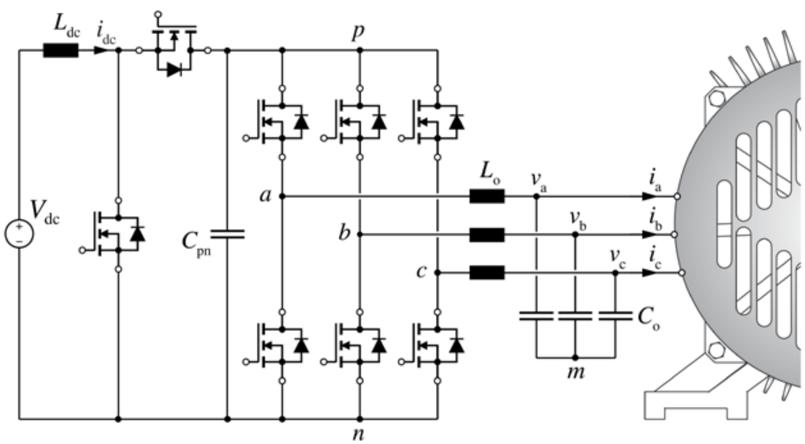
Wave Propagation & Reflection
Partial Discharge (PDIV)
Bearing Currents
Electro-Magnetic (EMI) Emissions
→ External Output Filter

Limited Input Voltage Range

Traction Battery Charge
Fuel-Cell Operating Point

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter



Advantages

Simple Circuit Topology
No Magnetic Components
Only Six Power Semiconductors

Challenges

Switched Output Voltage

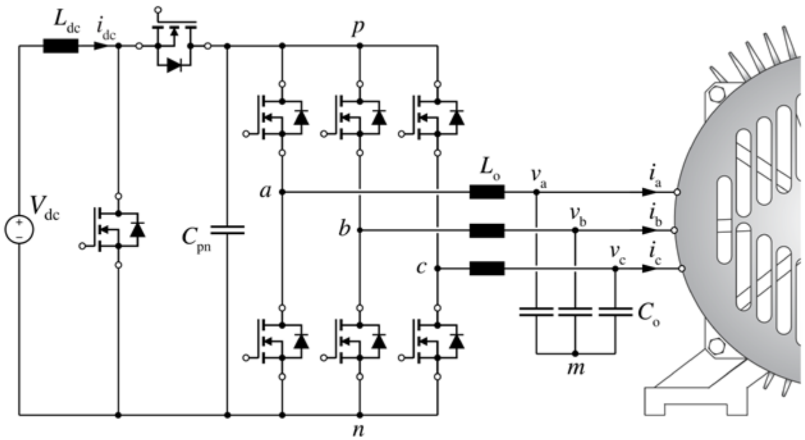
Wave Propagation & Reflection
Partial Discharge (PDIV)
Bearing Currents
Electro-Magnetic (EMI) Emissions
→ External Output Filter

Limited Input Voltage Range

Traction Battery Charge
Fuel-Cell Operating Point
→ Input Boost Stage

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter

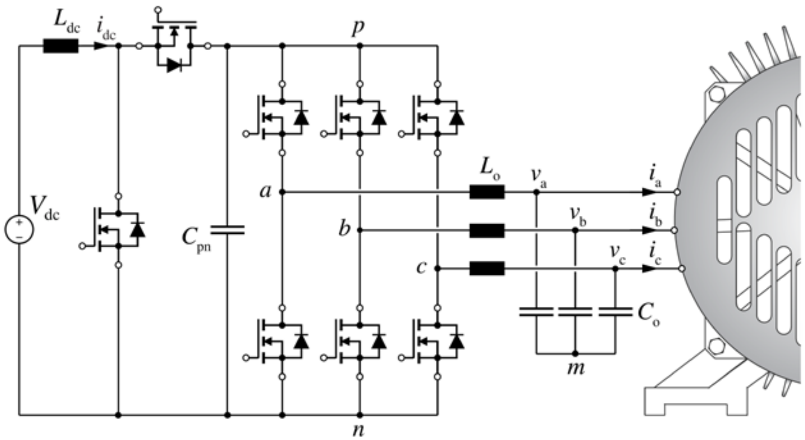


Features

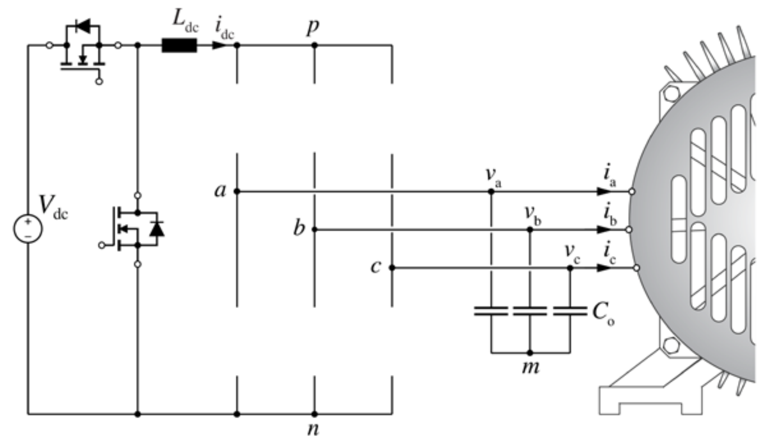
Simple Circuit Topology
Continuous Output Voltage
Wide Input Voltage Range

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter



3-ϕ Current DC-Link Inverter

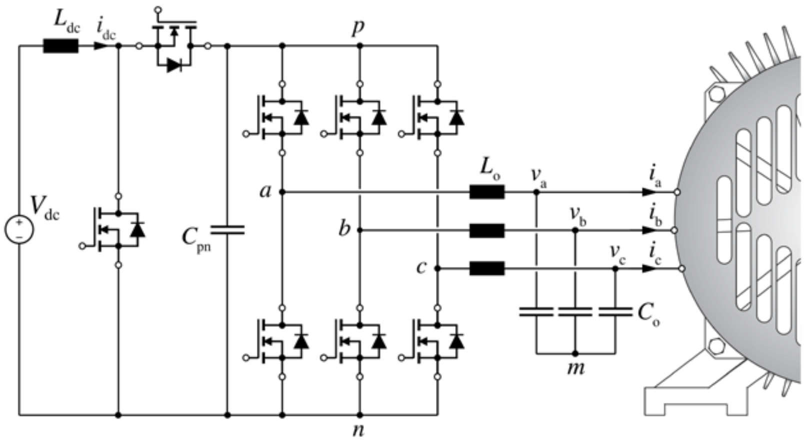


Features

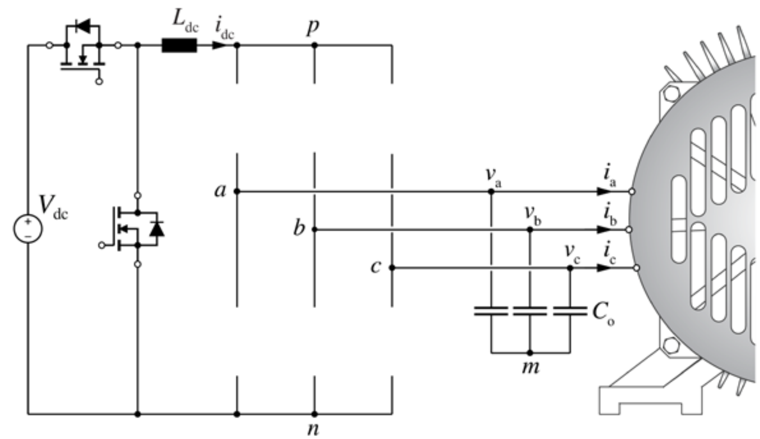
Simple Circuit Topology
Continuous Output Voltage
Wide Input Voltage Range

Voltage vs. Current DC-Link Inverter

3-ϕ Voltage DC-Link Inverter



3-ϕ Current DC-Link Inverter



Features

Simple Circuit Topology
Continuous Output Voltage
Wide Input Voltage Range

Disadvantages

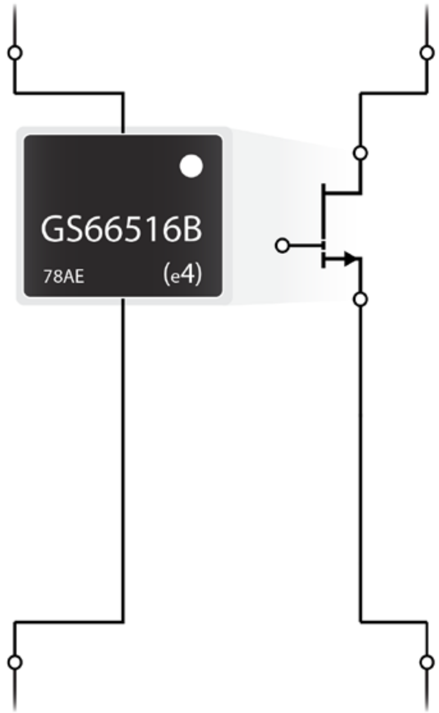
Inductive DC-Link
Bidirectional Power Semiconductors

Monolithic Bidirectional Switch

Specifications
Dual-Gate Structure
Gate Injection Driver

Monolithic Bidirectional Switch

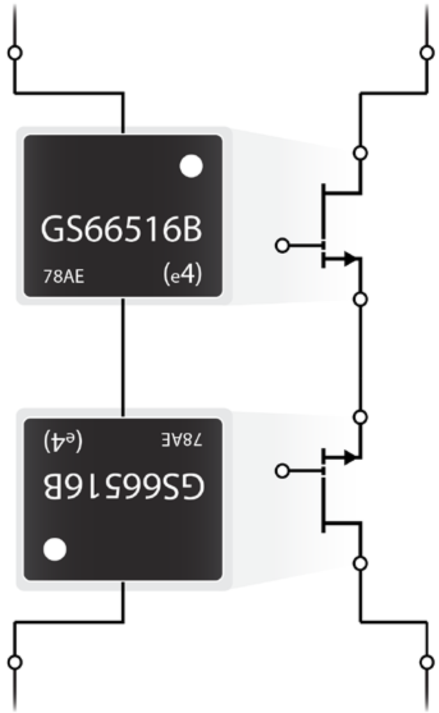
Conventional GaN e-FET (1x)



- 650V - 25mΩ

Monolithic Bidirectional Switch

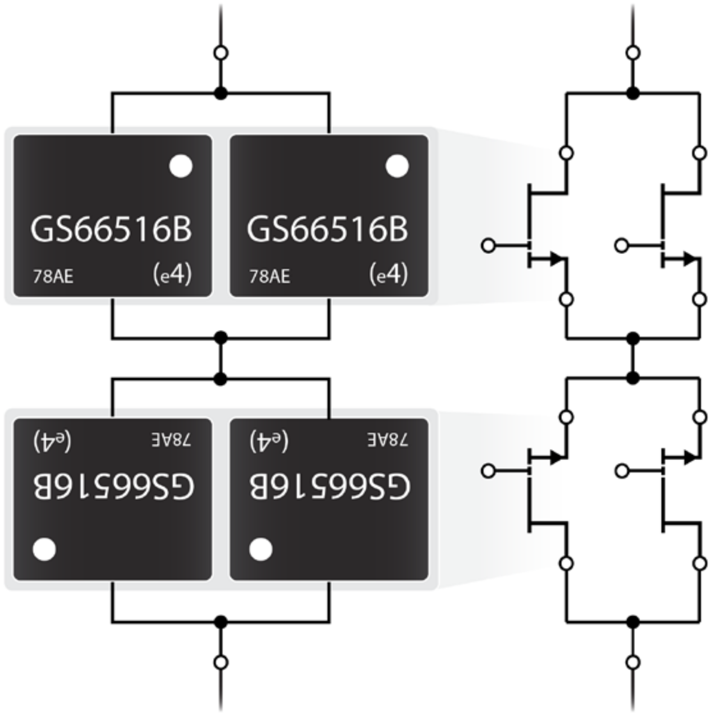
Conventional GaN e-FET (2x)



- ±650V - 50mΩ

Monolithic Bidirectional Switch

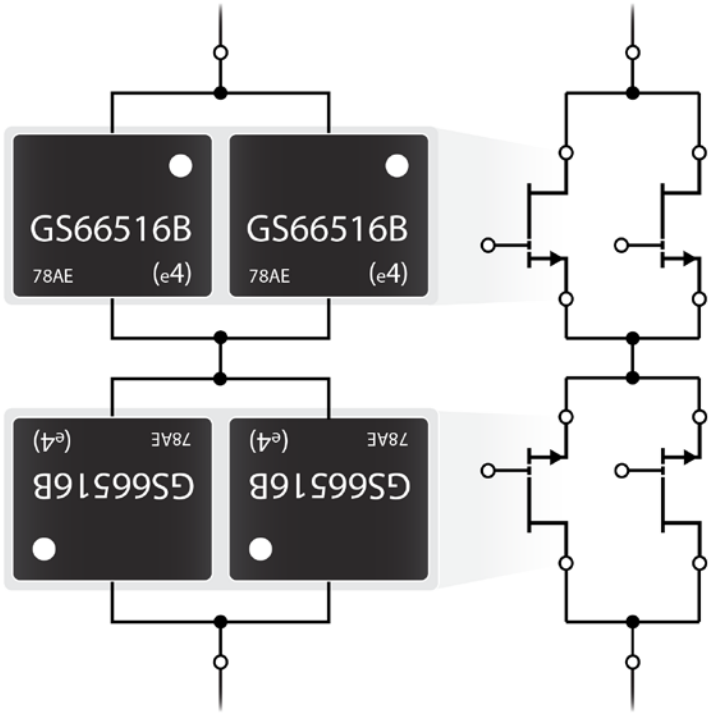
Conventional GaN e-FET (4x)



▶ ±650V - 25mΩ

Monolithic Bidirectional Switch

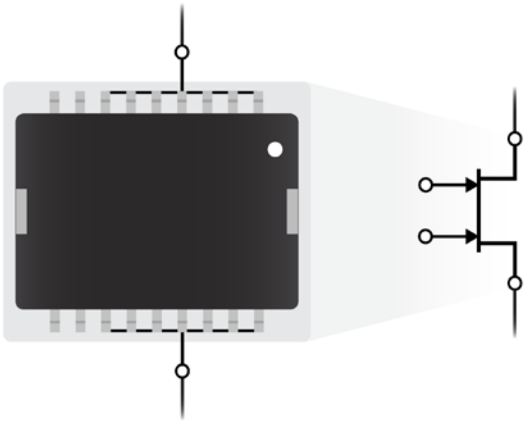
Conventional GaN e-FET (4x)



▶ ±650V - 25mΩ

New Panasonic GaN e-FET (1x)

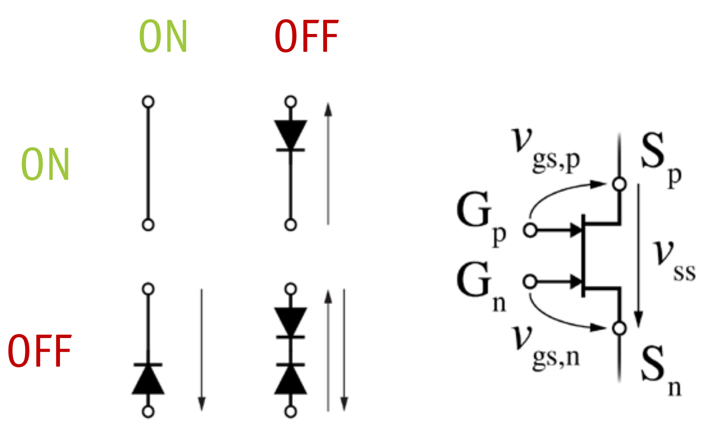
Monolithic Bidirectional Switch (MBS)
Common Drain - Single Drift Layer
Dual-Gate (2G)



▶ ±600V - 26mΩ

Monolithic Bidirectional Switch

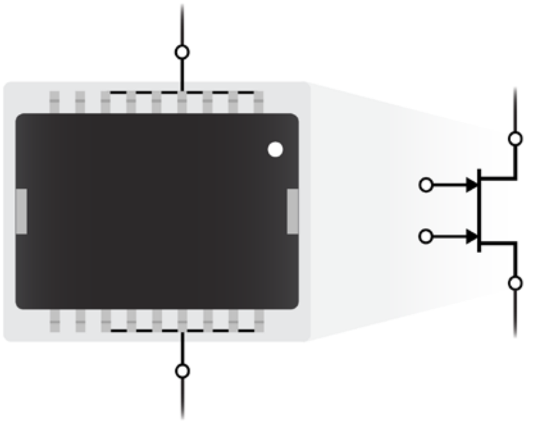
Equivalent Circuit



- ▶ Bidirectional Voltage Blocking
- ▶ Bidirectional Current Flow

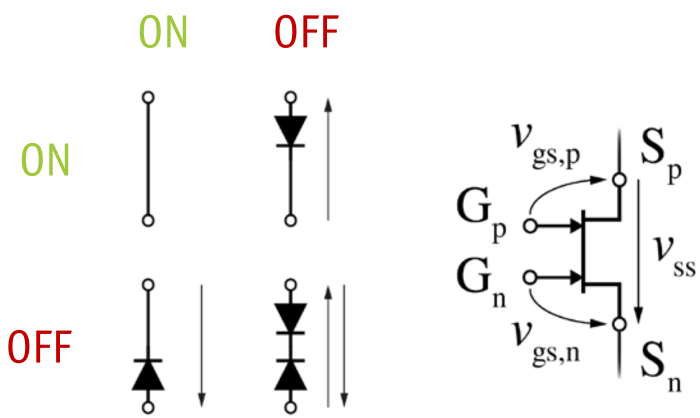
New Panasonic GaN e-FET

Monolithic Bidirectional Switch (MBS)
Common Drain - Single Drift Layer
Dual-Gate (2G)



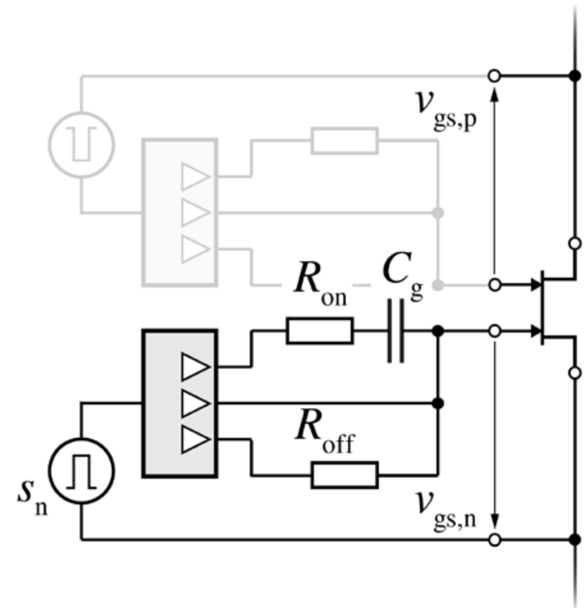
Monolithic Bidirectional Switch

Equivalent Circuit



- ▶ Bidirectional Voltage Blocking
- ▶ Bidirectional Current Flow

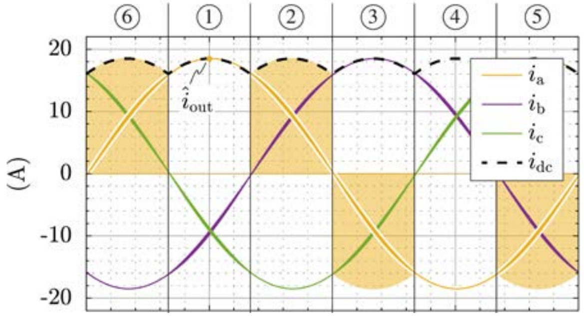
Gate Injection Panasonic 2G Driver



Gate Driver Features

Separate On-Off Paths
Constant Current Path
Minimum Component Number

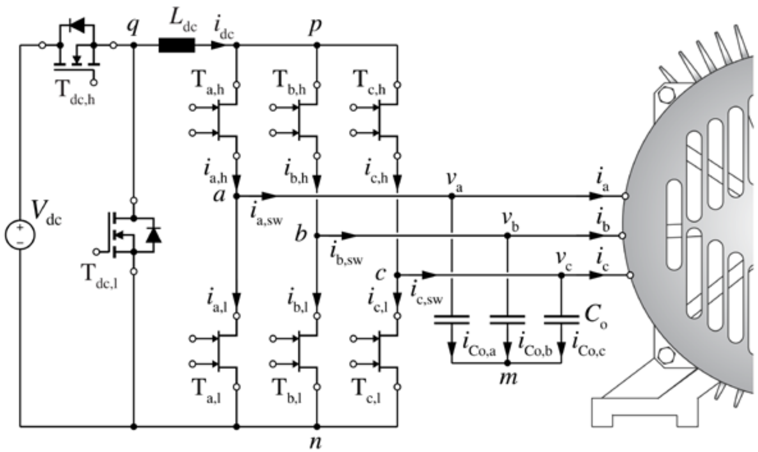
3-ϕ Buck-Boost Current Source Inverter System



Operating Principle
Conventional PWM
Two-Third Modulation (TTM)

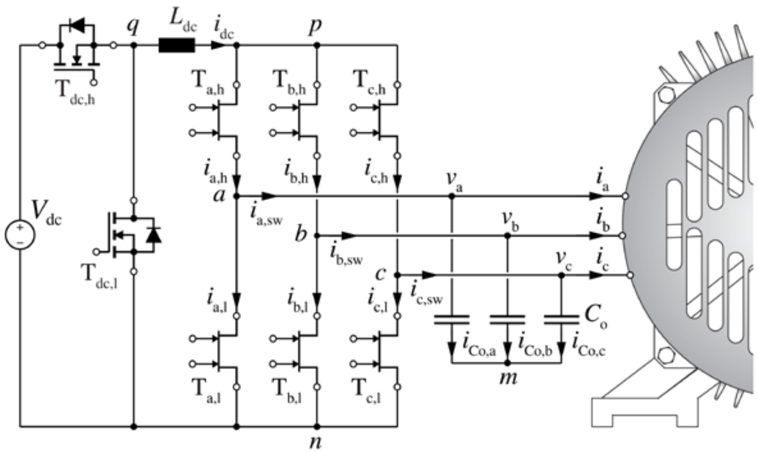
Operating Principle

3-ϕ Buck-Boost Current Source Inverter (CSI) System

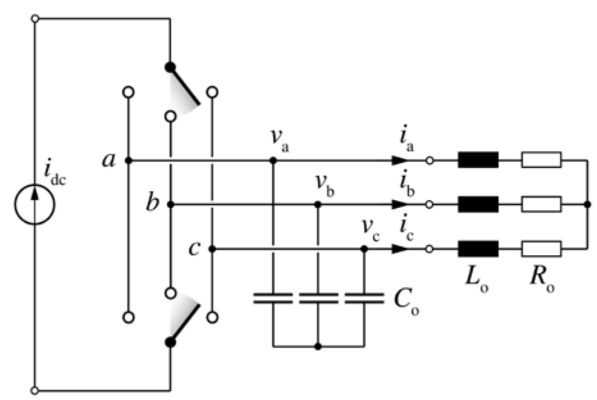


Operating Principle

3-ϕ Buck-Boost CSI System



Equivalent Circuit

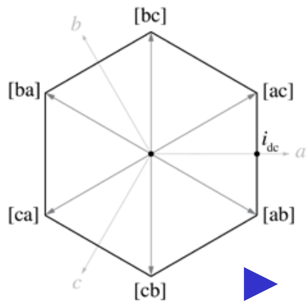


▶ Three-State Switches (2x)

Operating Principle

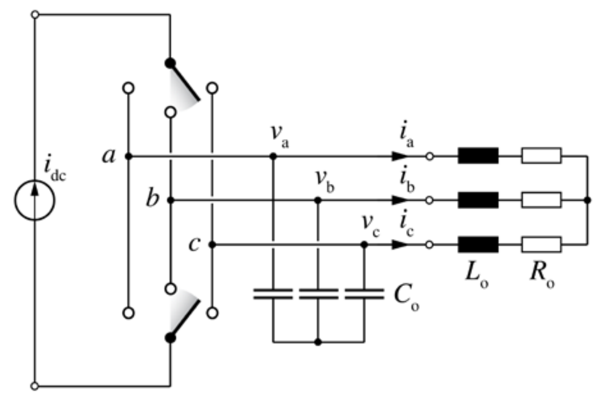
Active States

[ab]
[ac]
[ba]
[bc]
[ca]
[cb]



▶ Space Vector (SV) Diagram

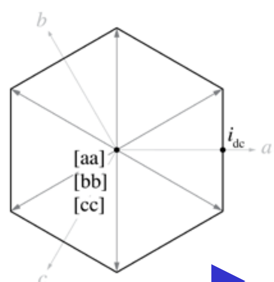
Equivalent Circuit



▶ Three-State Switches (2x)

Zero States

[aa]
[bb]
[cc]



▶ SV Diagram

Operating Principle

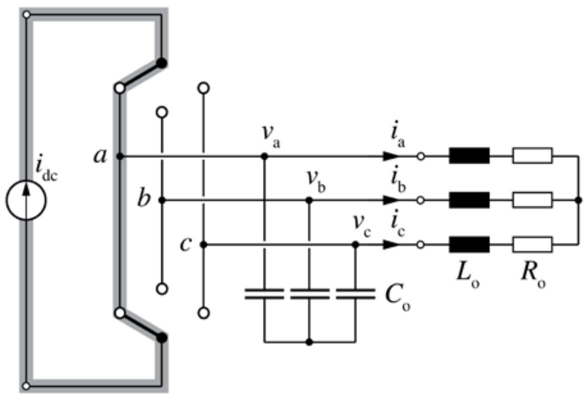
Active States

[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$
[ac] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[ba] $i_{ph} = [-i_{dc}, +i_{dc}, 0]$
[bc] $i_{ph} = [0, -i_{dc}, +i_{dc}]$
[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

Zero States

[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

Equivalent Circuit



▶ [aa]

Input Voltage

▶ Short-Circuit

Operating Principle

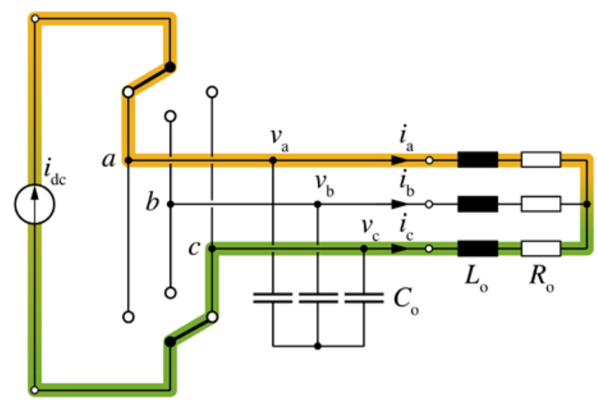
Active States

[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$
[ac] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[ba] $i_{ph} = [-i_{dc}, +i_{dc}, 0]$
[bc] $i_{ph} = [0, -i_{dc}, +i_{dc}]$
[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

Zero States

[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

Equivalent Circuit



▶ [ac]

Input Voltage

▶ Rectified Line-to-Line Voltage

Conventional Pulse-Width Modulation (PWM)

Active States

[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$

[ac] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$

[ba] $i_{ph} = [-i_{dc}, +i_{dc}, 0]$

[bc] $i_{ph} = [0, -i_{dc}, +i_{dc}]$

[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$

[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

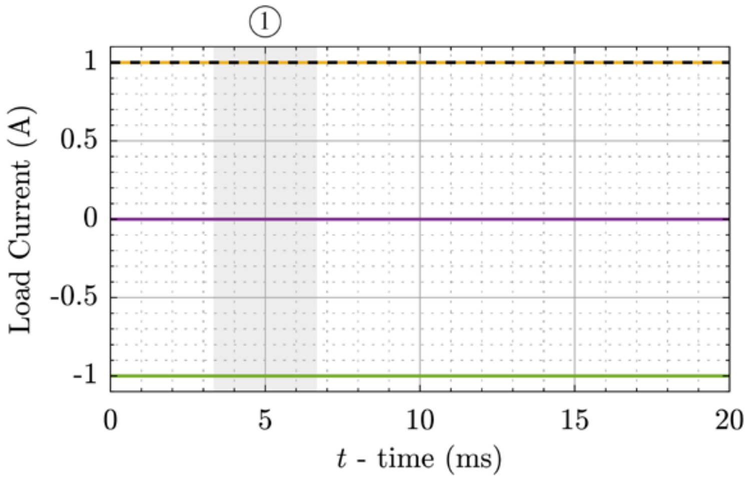
Zero States

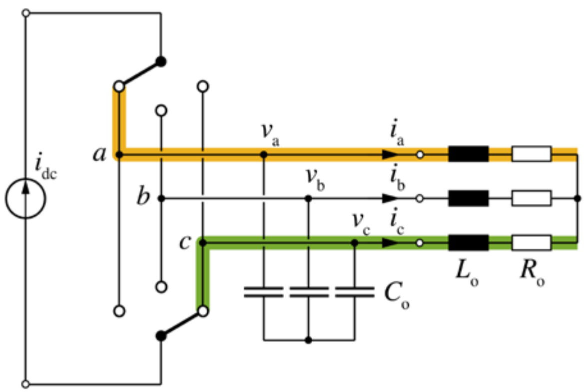
[aa] $i_{ph} = [0, 0, 0]$

[bb] $i_{ph} = [0, 0, 0]$

[cc] $i_{ph} = [0, 0, 0]$

3-ϕ Load Current Waveforms





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Zero States

[aa] $i_{ph} = [0, 0, 0]$
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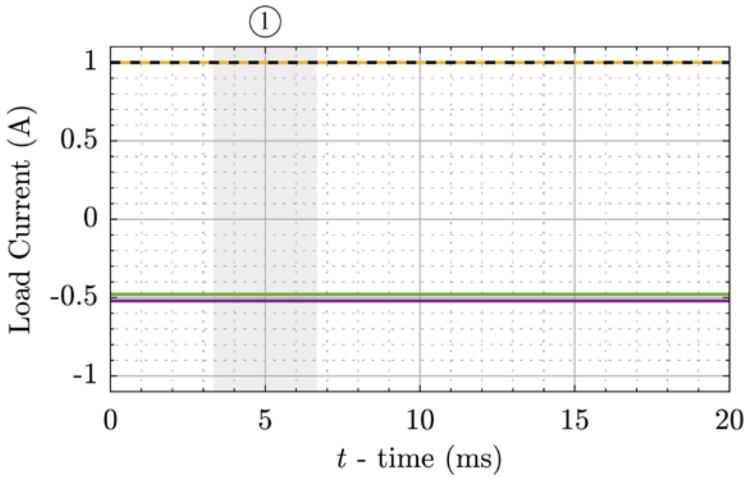
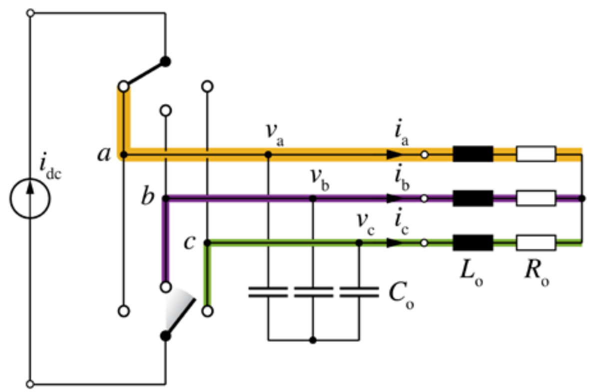
3-ϕ Load Current Waveforms





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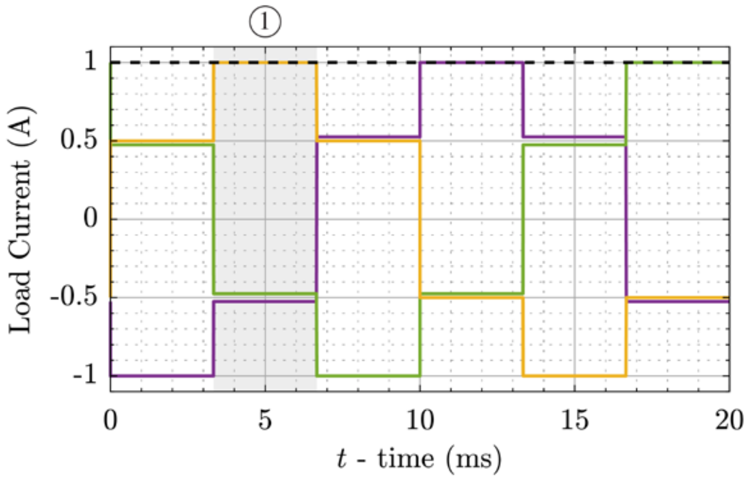
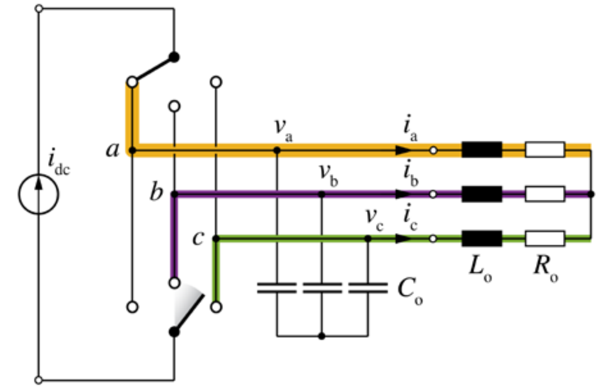
[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

Zero States

[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

3-ϕ Load Current Waveforms





Conventional Pulse-Width Modulation (PWM)

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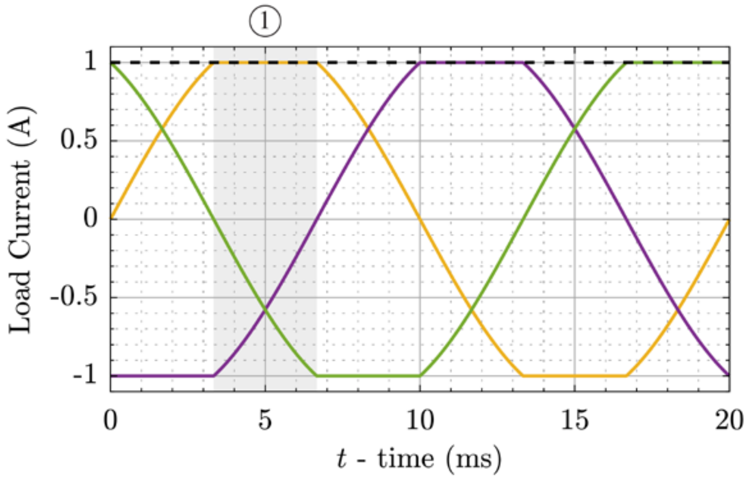
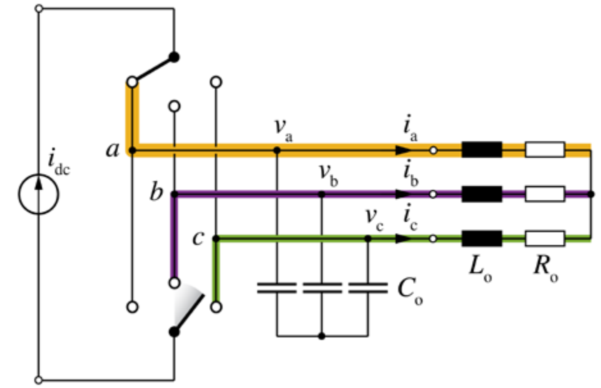
Zero States

[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

3-ϕ Load Current Waveforms





Conventional Pulse-Width Modulation (PWM)

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[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$

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[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$

[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

Zero States

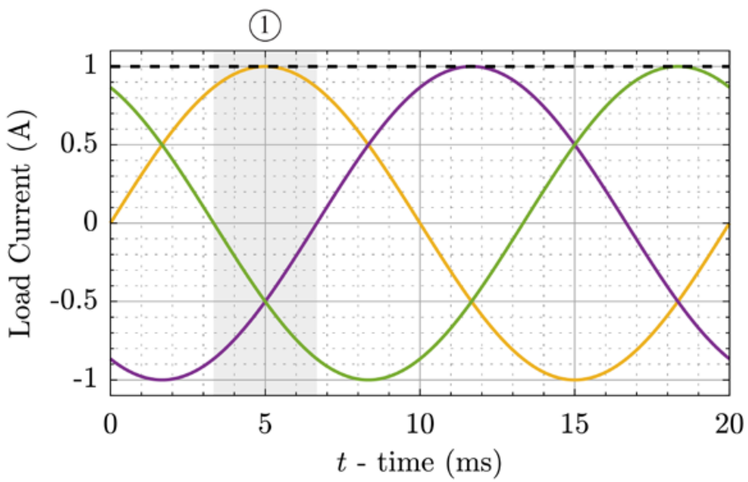
[aa] $i_{ph} = [0, 0, 0]$

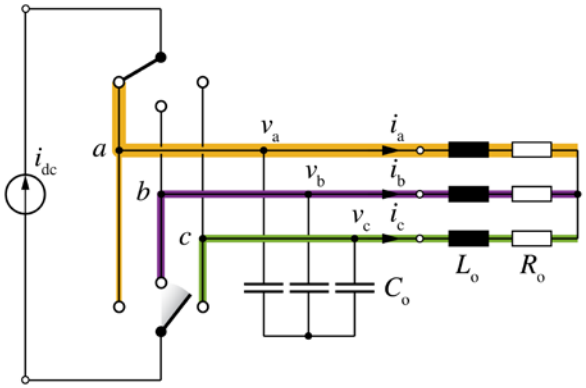
[bb] $i_{ph} = [0, 0, 0]$

[cc] $i_{ph} = [0, 0, 0]$

► Two Active States + One Zero State

3-ϕ Load Current Waveforms





Two-Third Modulation (TTM)

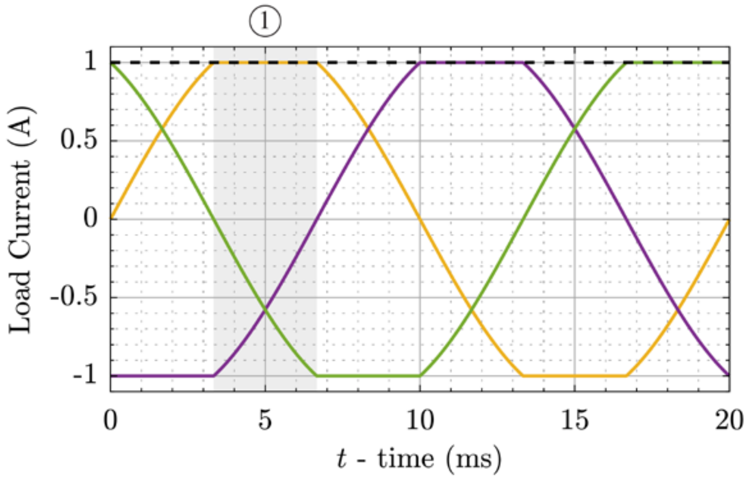
Active States

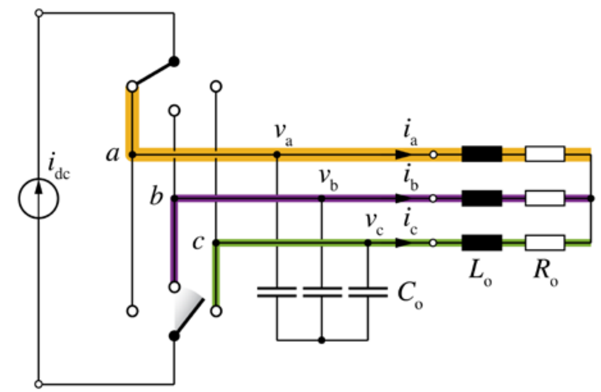
[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$
[ac] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[ba] $i_{ph} = [-i_{dc}, +i_{dc}, 0]$
[bc] $i_{ph} = [0, -i_{dc}, +i_{dc}]$
[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

Zero States

[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

3-ϕ Load Current Waveforms





Two-Third Modulation (TTM)

Active States

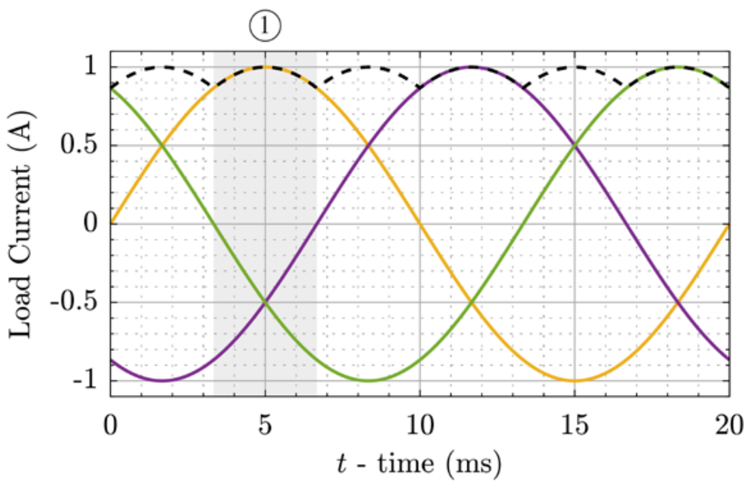
[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$
[ac] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[ba] $i_{ph} = [-i_{dc}, +i_{dc}, 0]$
[bc] $i_{ph} = [0, -i_{dc}, +i_{dc}]$
[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

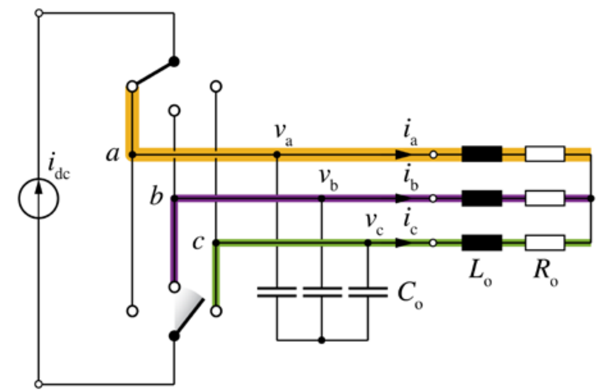
Zero States

[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

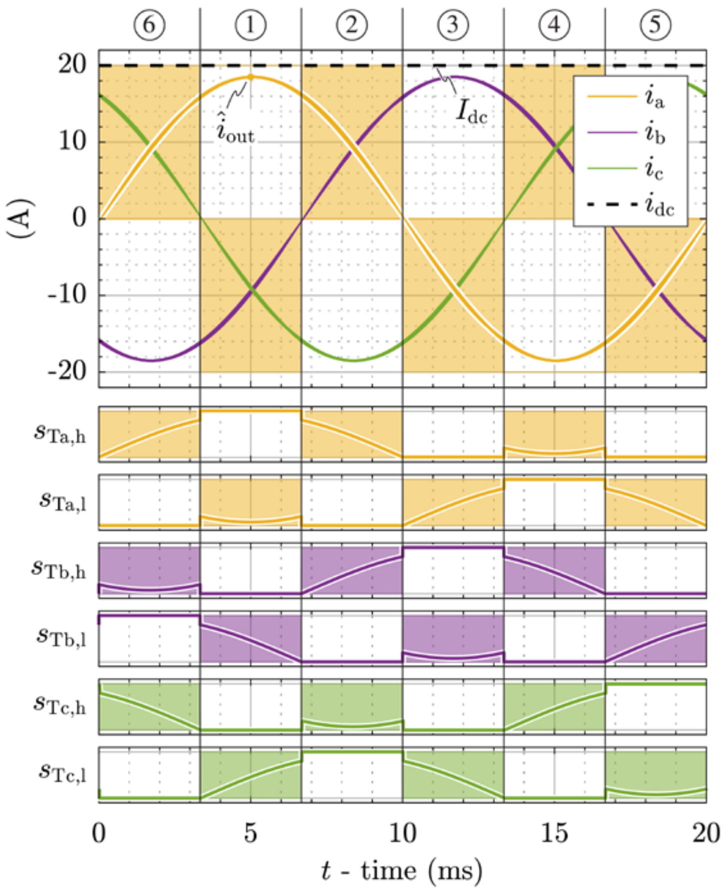
► Two Active States

3-ϕ Load Current Waveforms

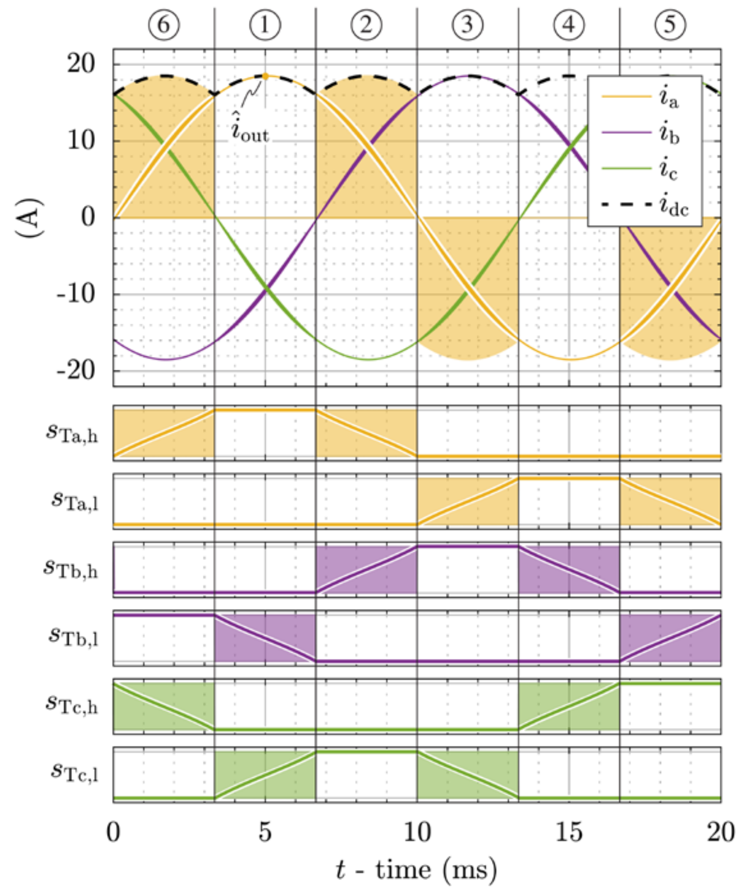




Conventional PWM vs. TTM



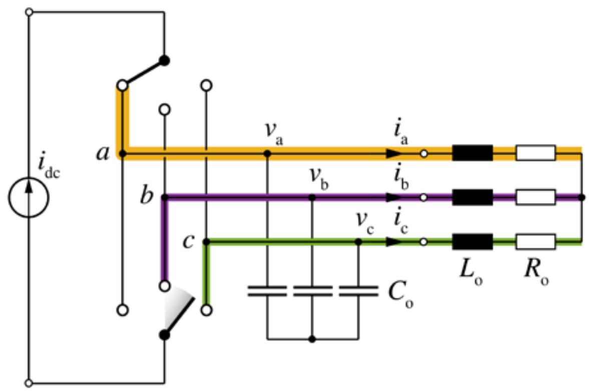
► Conventional PWM



► TTM

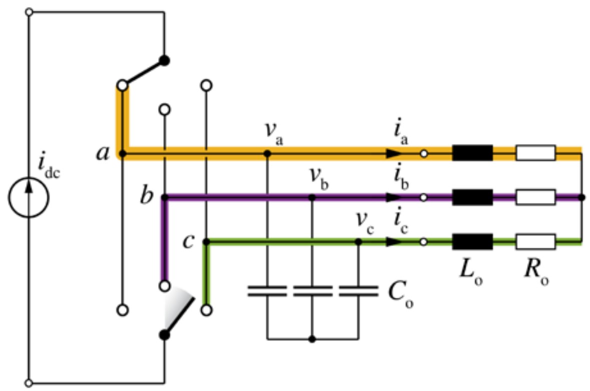
Conventional PWM vs. TTM

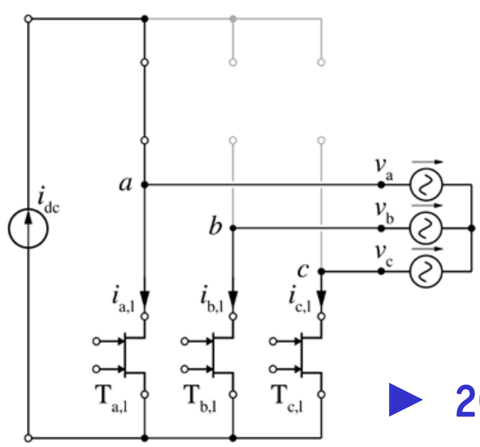
Equivalent Circuit



Conventional PWM vs. TTM

Equivalent Circuit

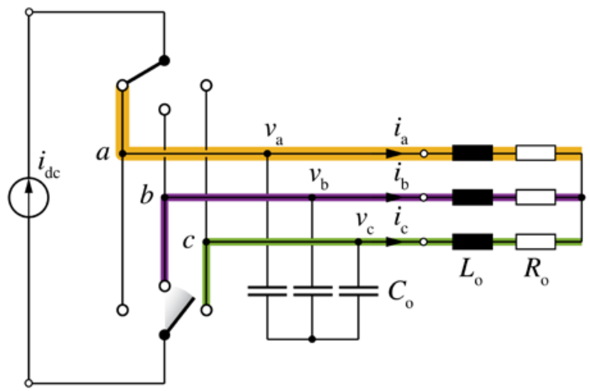


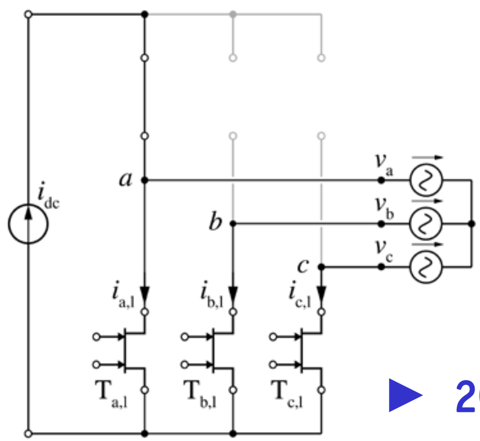


▶ 2G MB GaN e-FETs

Conventional PWM vs. TTM

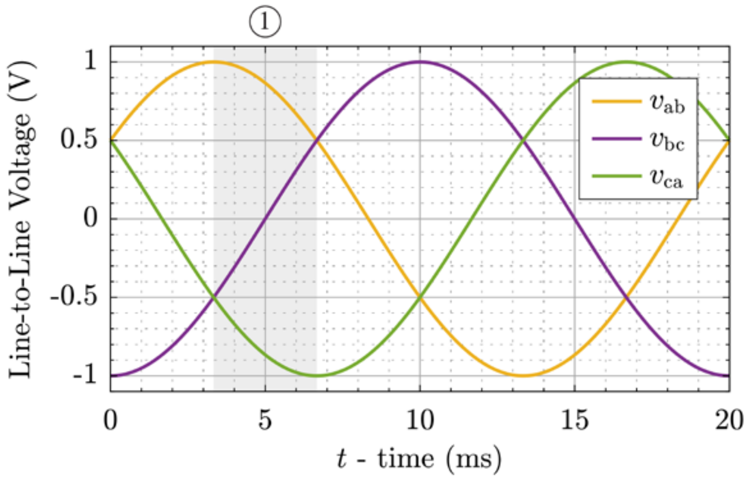
Equivalent Circuit





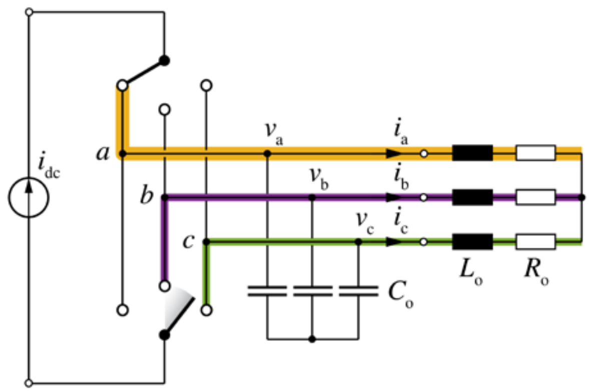
▶ 2G MB GaN e-FETs

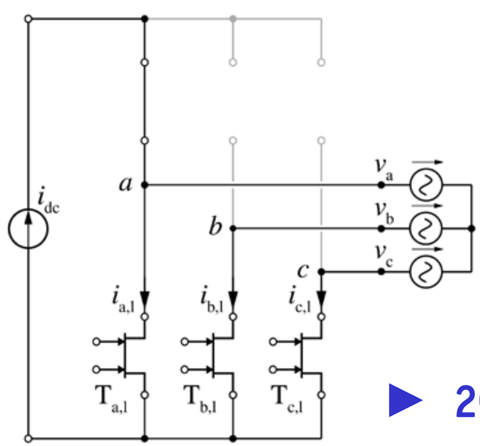
3-ϕ Line-to-Line Voltage Waveforms



Conventional PWM vs. TTM

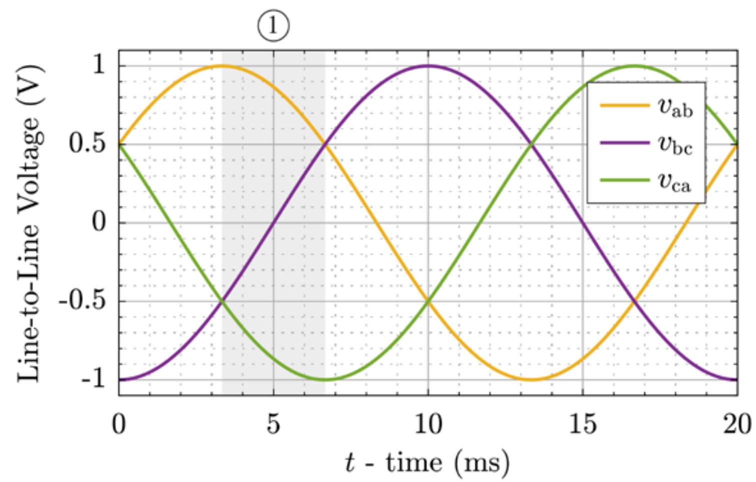
Equivalent Circuit

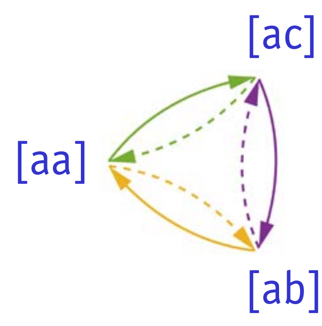




▶ 2G MB GaN e-FETs

3-ϕ Line-to-Line Voltage Waveforms

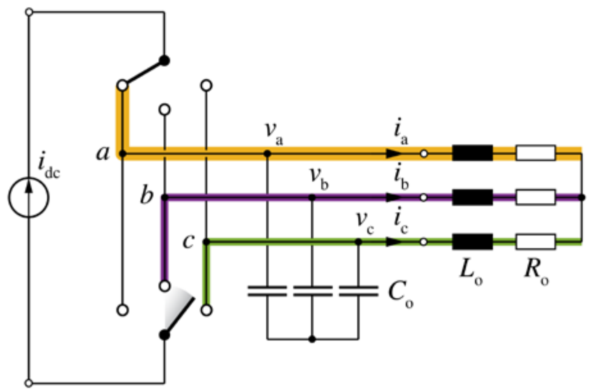


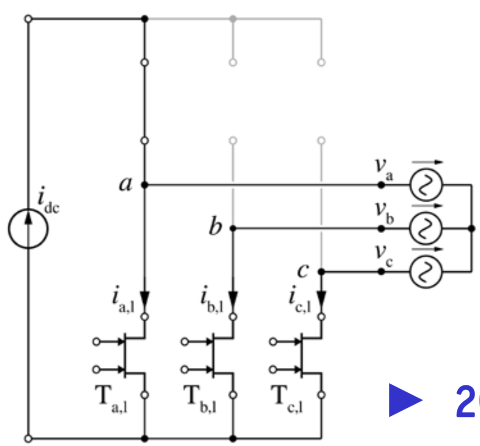


▶ State Sequence

Conventional PWM vs. TTM

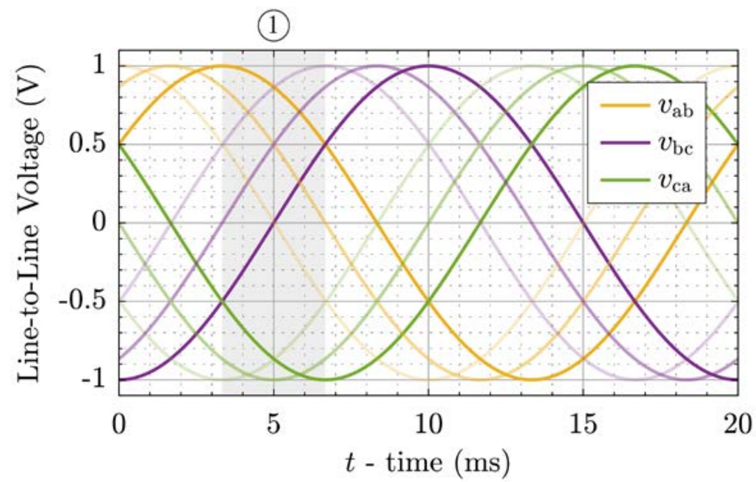
Equivalent Circuit

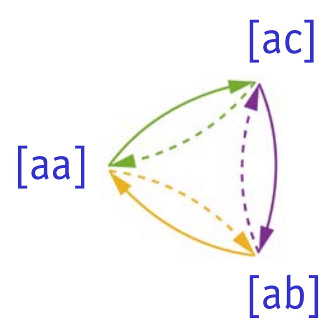




► 2G MB GaN e-FETs

3-ϕ Line-to-Line Voltage Waveforms

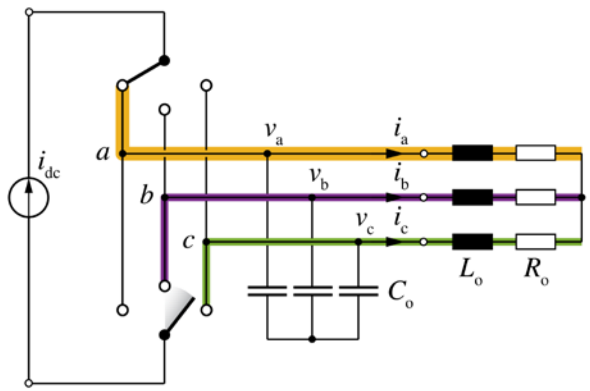


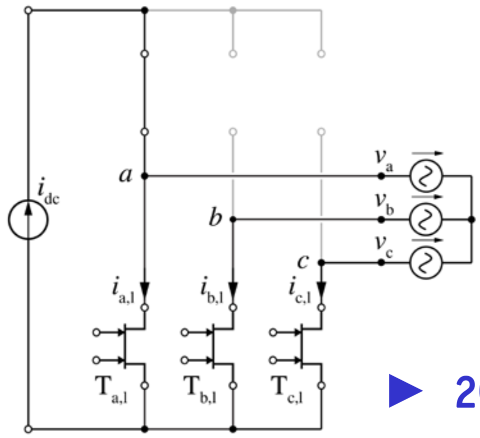


► State Sequence

Conventional PWM vs. TTM

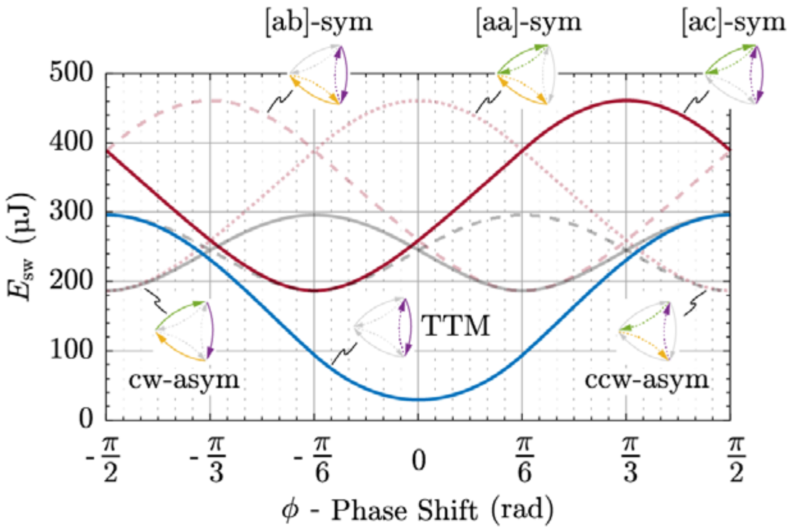
Equivalent Circuit

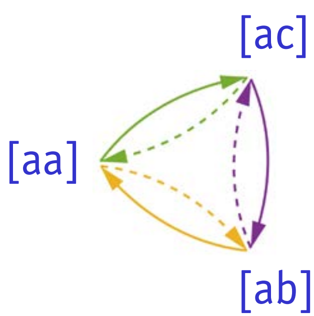




▶ 2G MB GaN e-FETs

Switching Losses

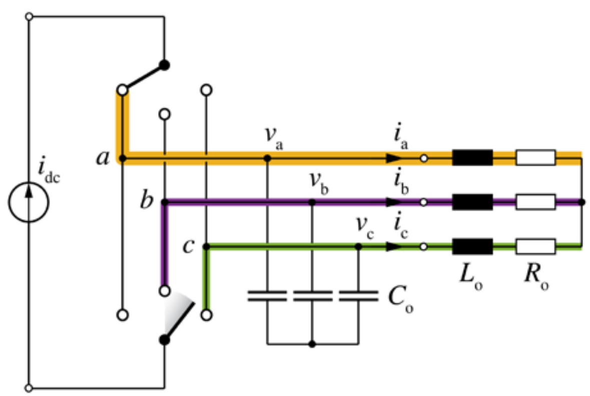


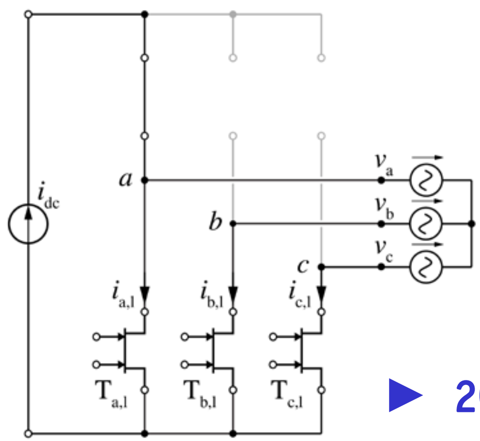


▶ State Sequence

Conventional PWM vs. TTM

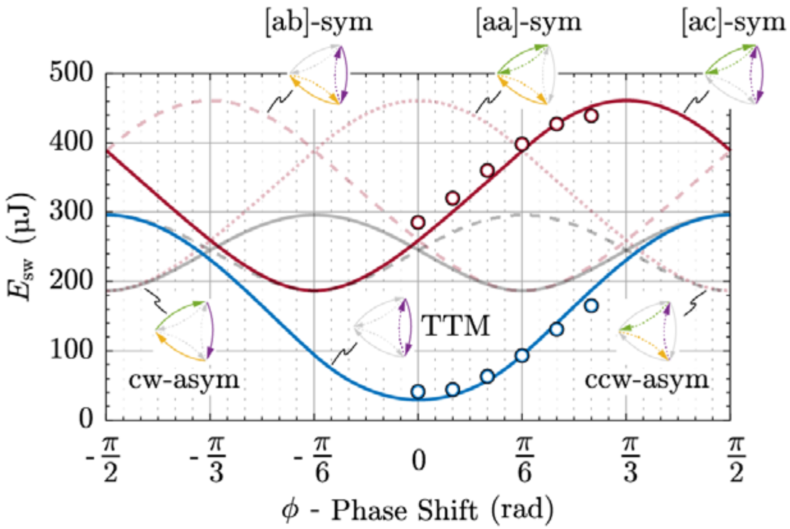
Equivalent Circuit

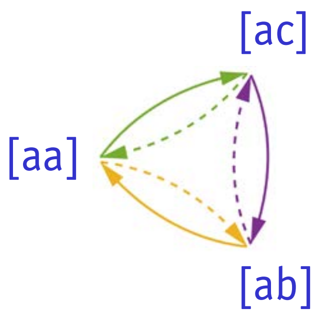




▶ 2G MB GaN e-FETs

Switching Losses

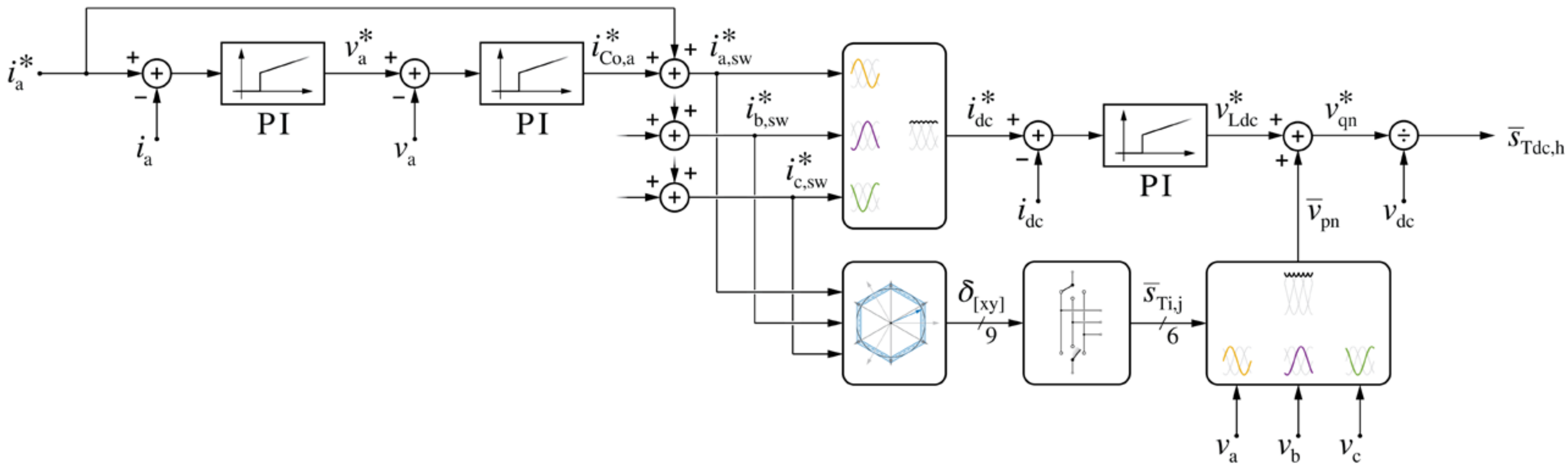




▶ State Sequence

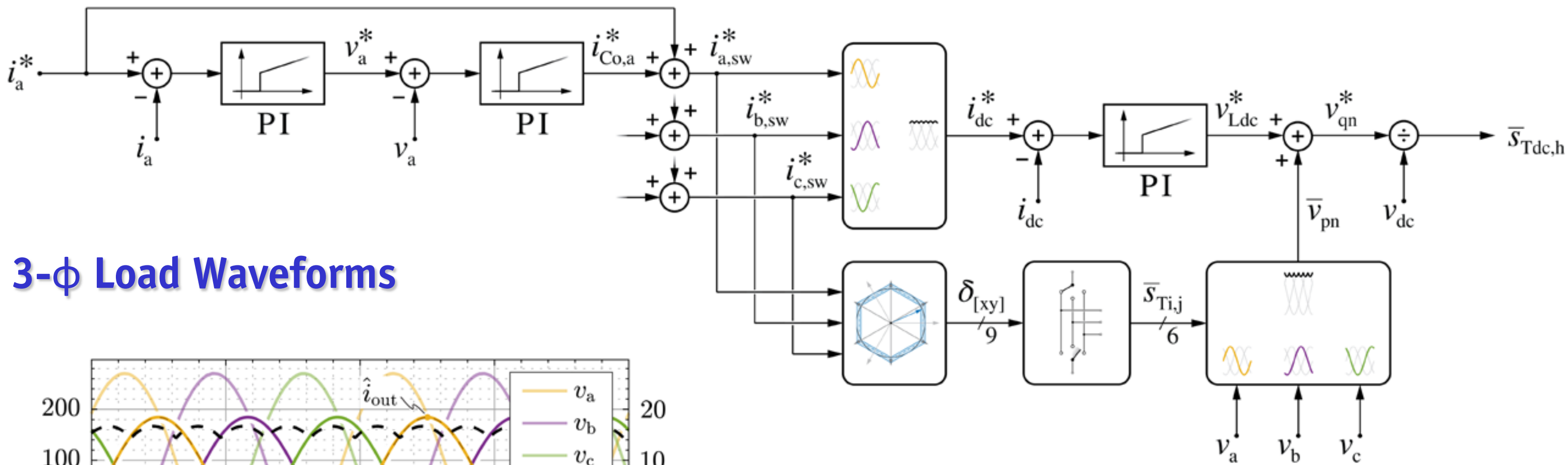
▪ Synergetic Control

Control Structure

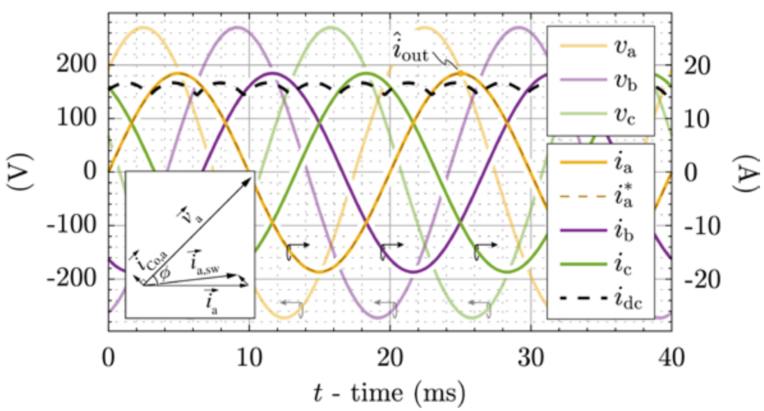


Synergetic Control

Control Structure

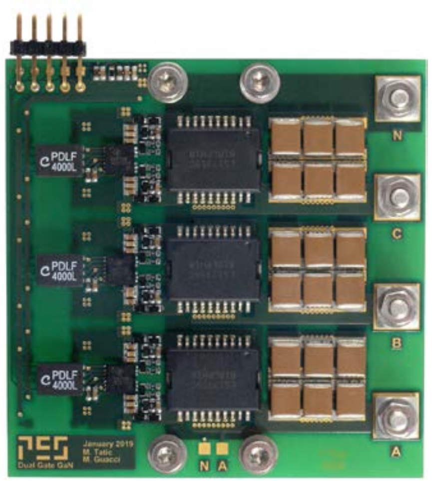


3-ϕ Load Waveforms



► Simulated Waveforms

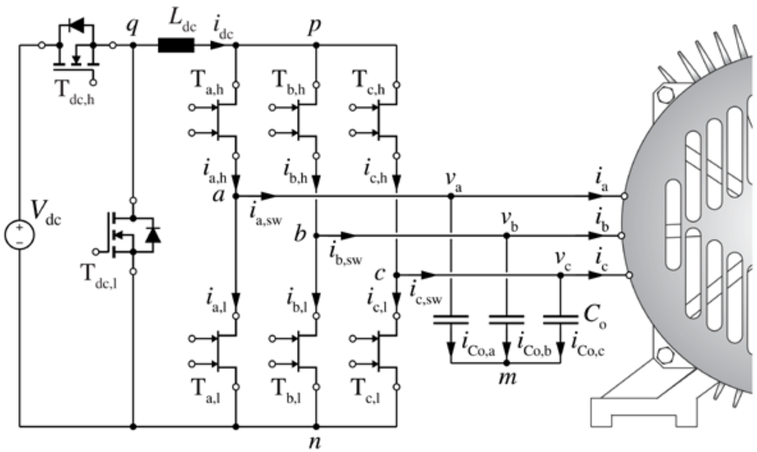
Hardware & Measurements



Hardware Design
Multi-Step Commutation Strategy
Measured Waveforms

Hardware Design

3-ϕ Buck-Boost CSI System

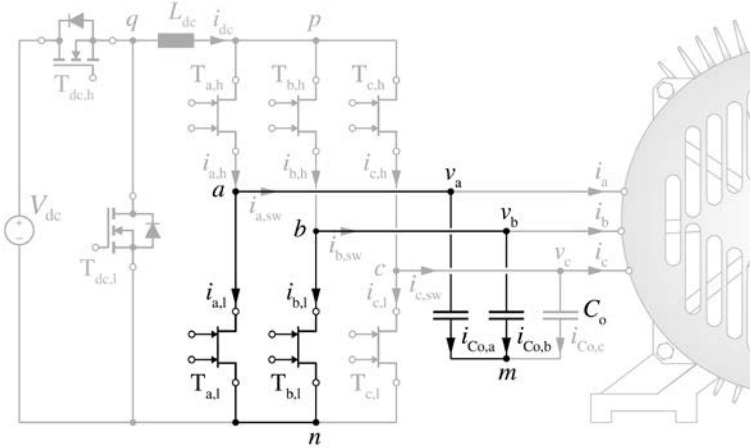


DC/AC Operating Point

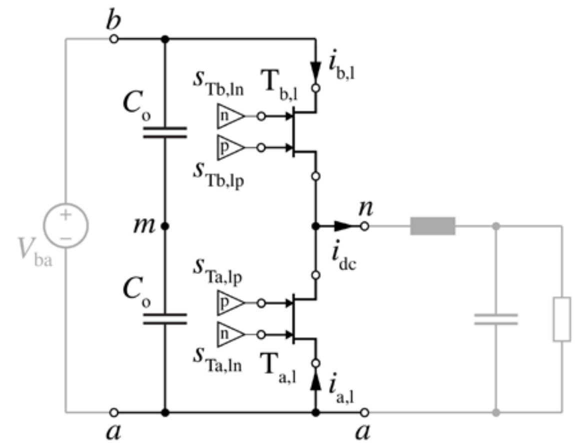
Input Current	i_{dc}	20A
Output Power	P_{out}	7.5kW

Hardware Design

3-ϕ Buck-Boost CSI System



1-ϕ Half-Bridge



DC/AC Operating Point

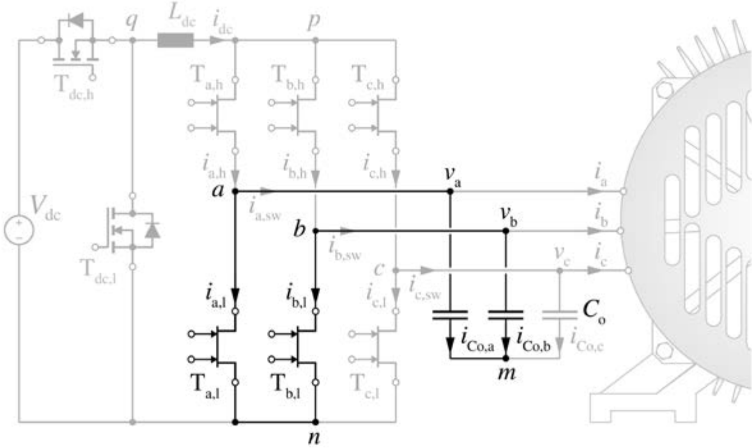
Input Current	i_{dc}	20A
Output Power	P_{out}	7.5kW

DC/DC Operating Point

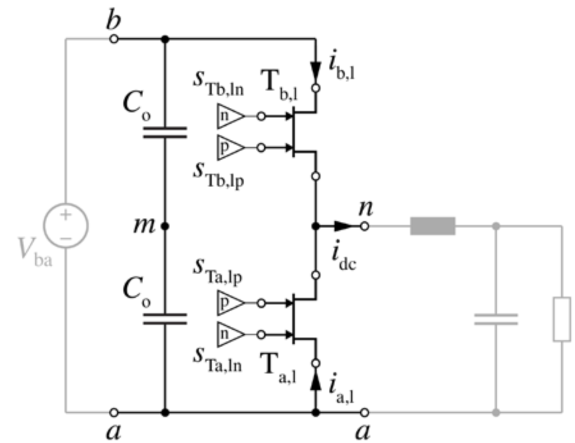
Output Current	i_{dc}	20A

Hardware Design

3-ϕ Buck-Boost CSI System



1-ϕ Half-Bridge



DC/AC Operating Point

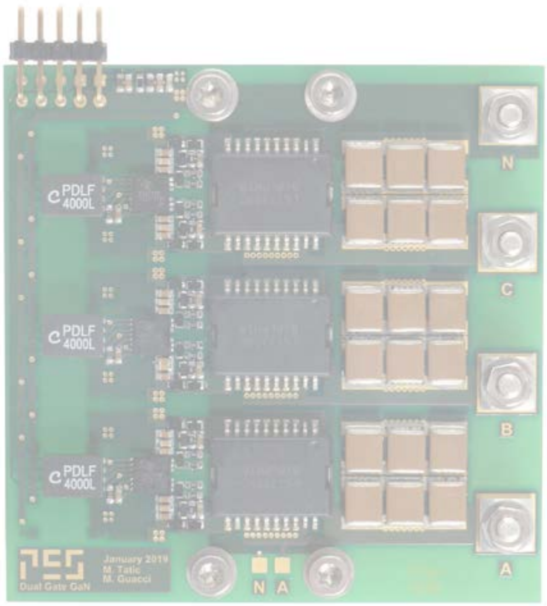
Input Current	i_{dc}	20A
Output Power	P_{out}	7.5kW
Output Voltage	$V_{out,pk}$	250V
	$V_{out,ll,pk}$	433V

DC/DC Operating Point

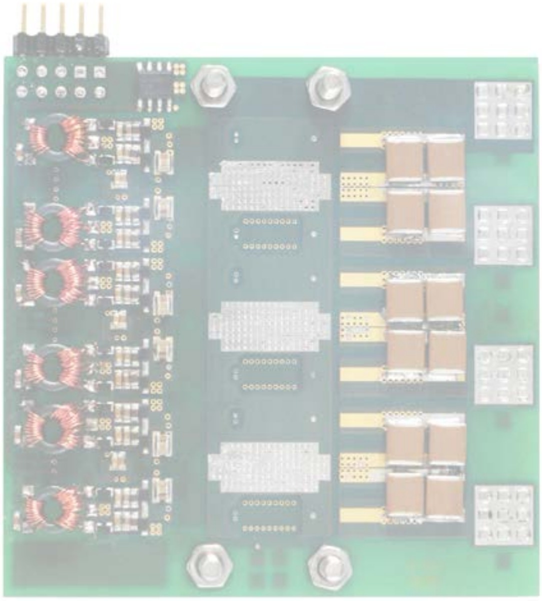
Output Current	i_{dc}	20A
Input Voltage	V_{ba}	400V

▪ Hardware Design

3-ϕ Buck-Boost CSI System → One-Side Module



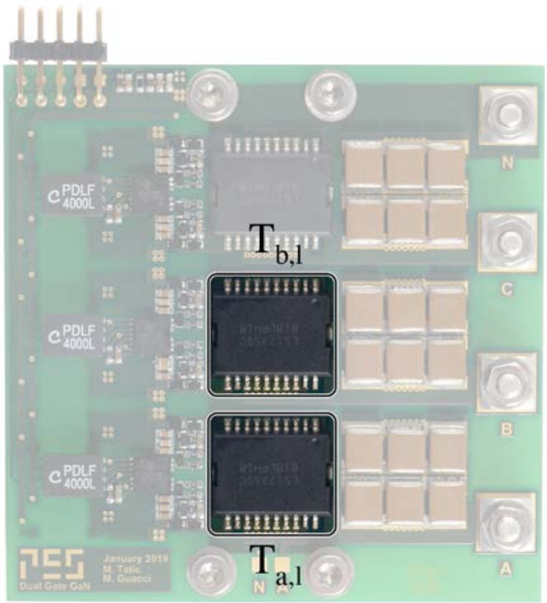
▶ Top-View



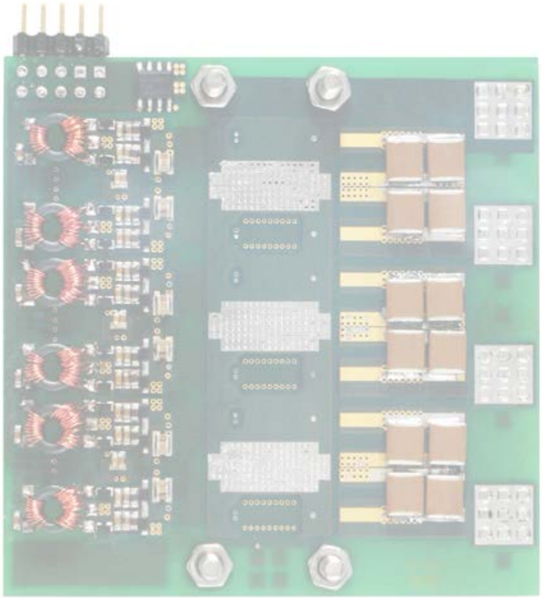
▶ Bottom-View

Hardware Design

3-ϕ Buck-Boost CSI System → One-Side Module



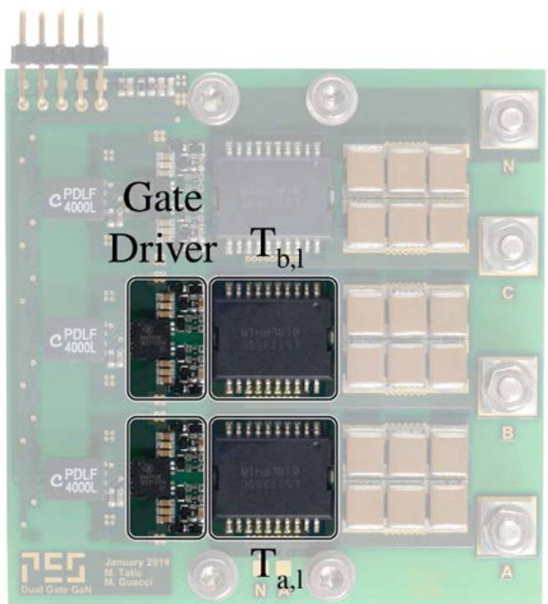
▶ Top-View



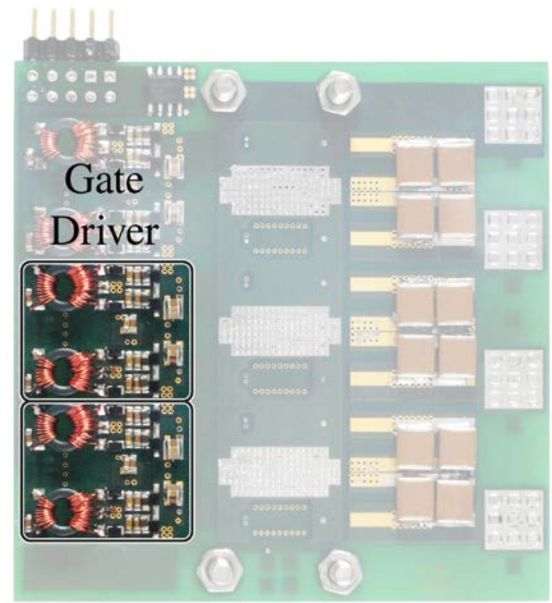
▶ Bottom-View

Hardware Design

3-ϕ Buck-Boost CSI System → One-Side Module



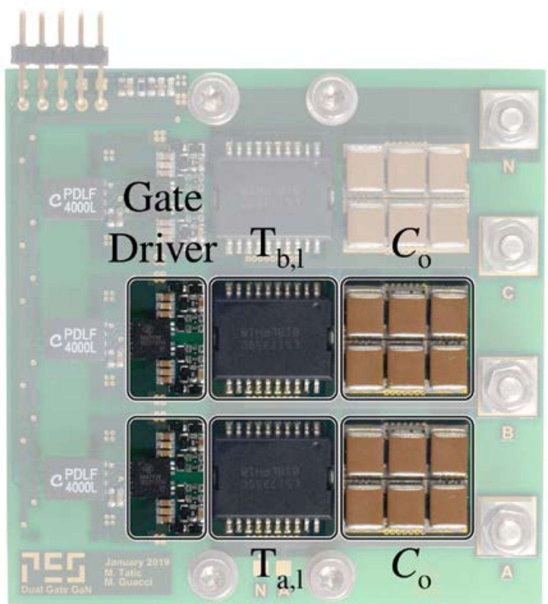
▶ Top-View



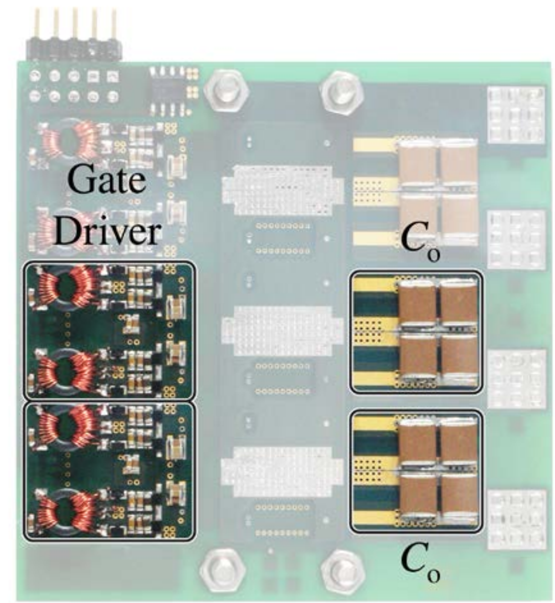
▶ Bottom-View

Hardware Design

3-ϕ Buck-Boost CSI System → One-Side Module



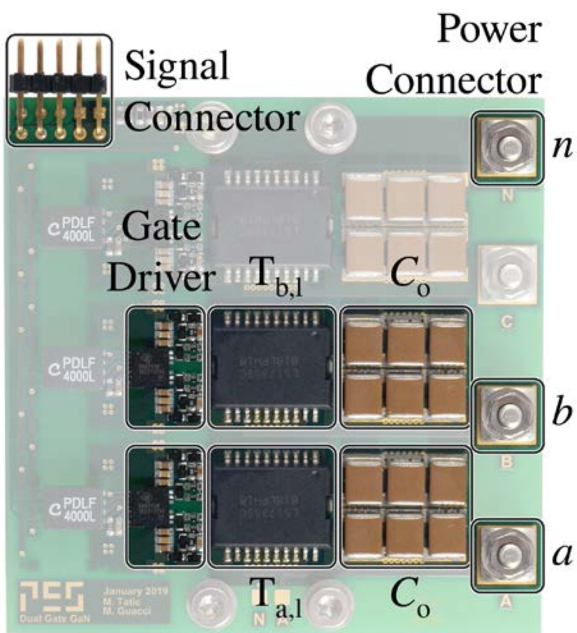
▶ Top-View



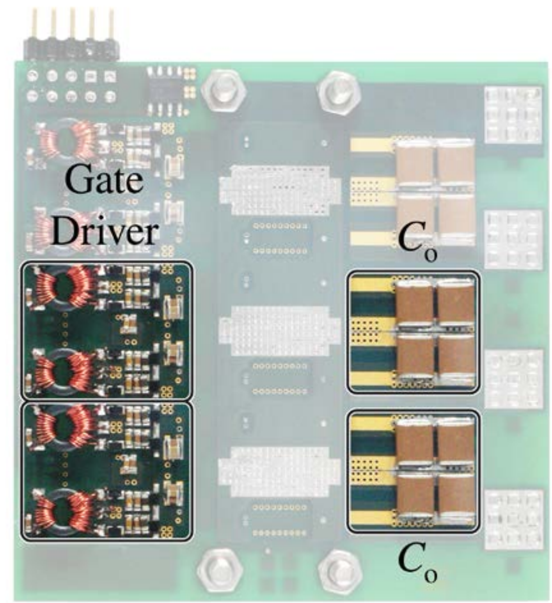
▶ Bottom-View

▪ Hardware Design

3-ϕ Buck-Boost CSI System → One-Side Module



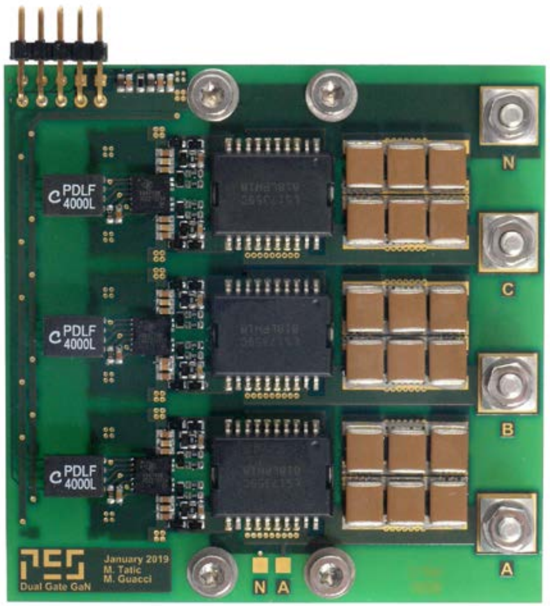
► Top-View



► Bottom-View

Hardware Design

3-ϕ Buck-Boost CSI System → One-Side Module

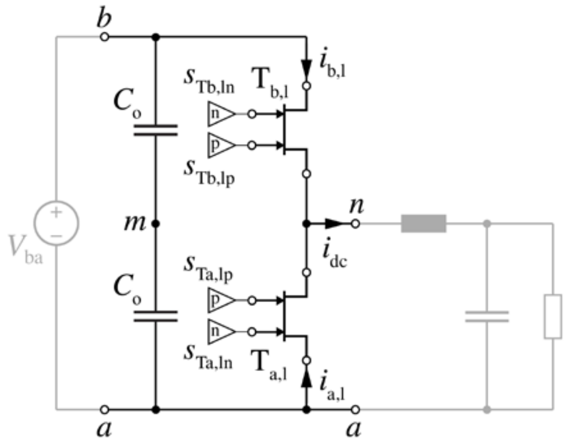


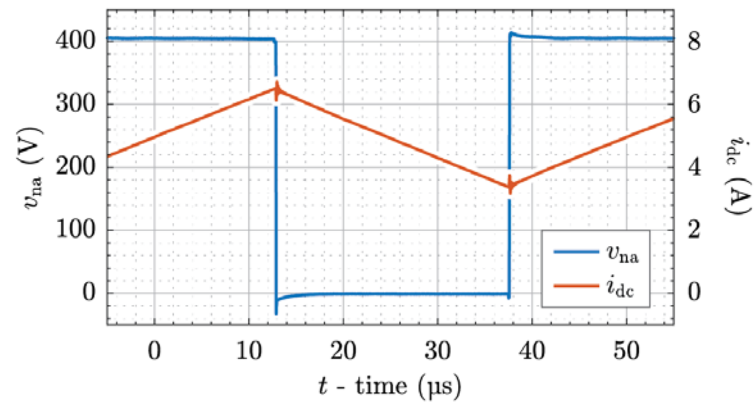
► Top-View

► 3.5″ Floppy Disk

Measurements

1-ϕ Half-Bridge





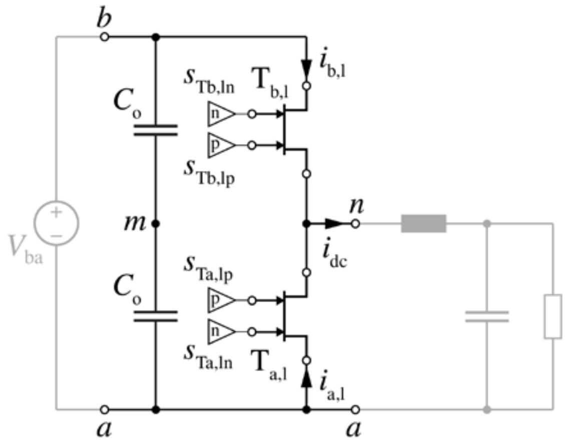
DC/DC Operating Point

Input Voltage	V_{ba}	400V
Output Current	i_{dc}	5A

Measured Waveforms ▶

Measurements

1-ϕ Half-Bridge



DC/DC Operating Point

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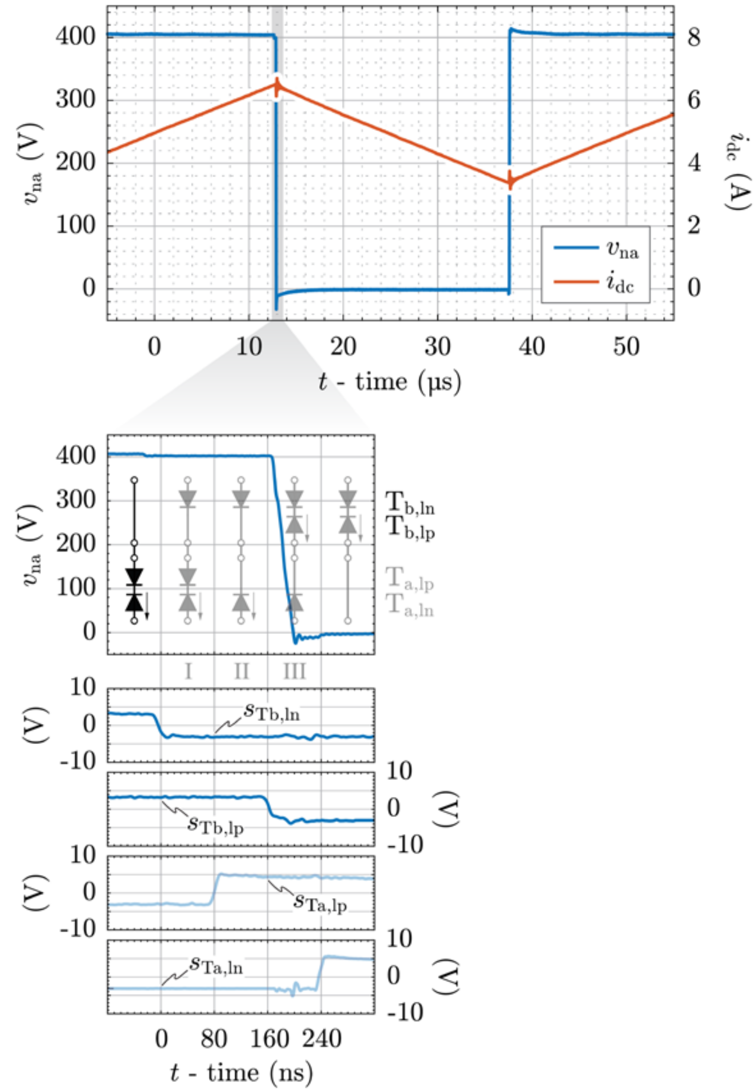
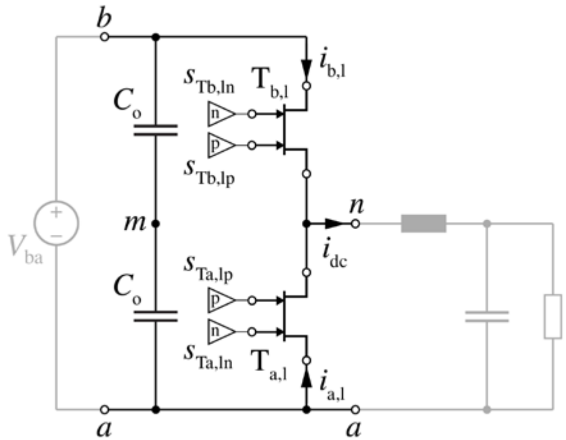
Measured Waveforms ▶



Measurements

1-ϕ Half-Bridge



DC/DC Operating Point

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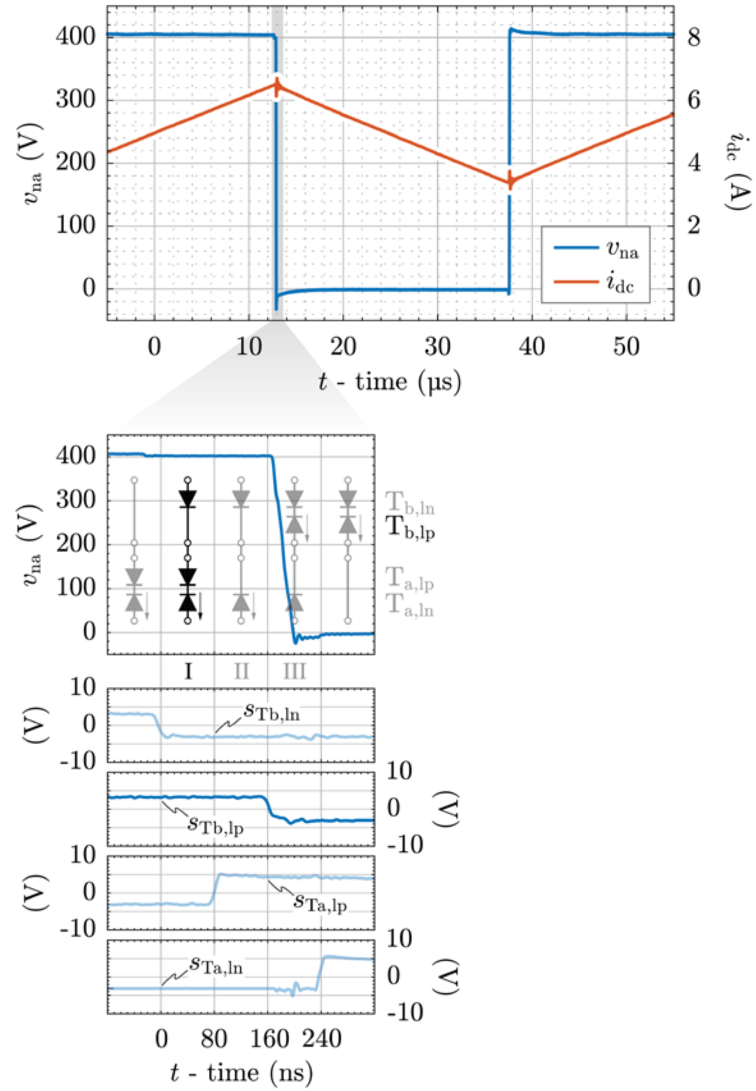
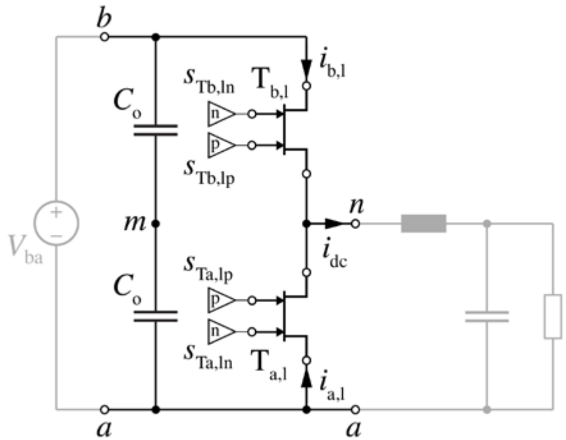
Measured Waveforms ▶



Measurements

1-ϕ Half-Bridge



DC/DC Operating Point

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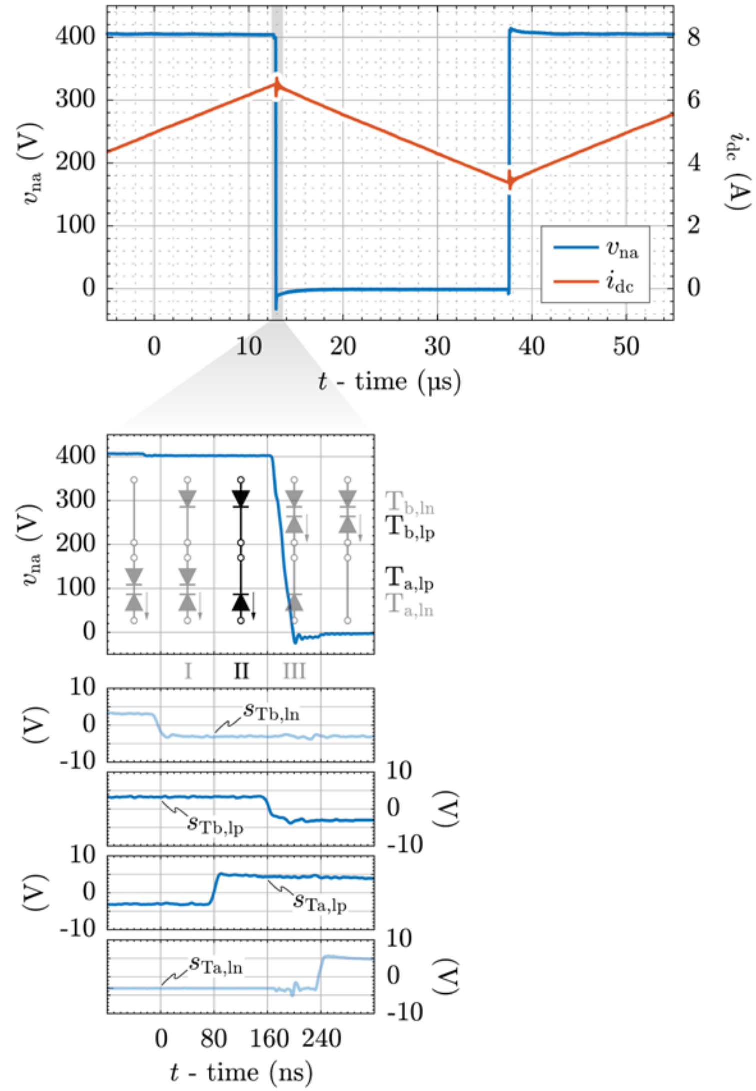
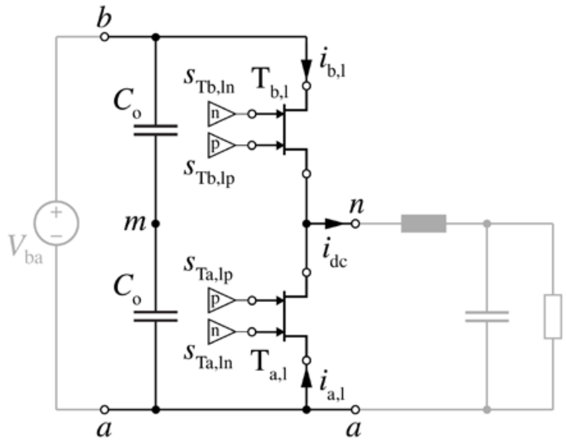
Measured Waveforms ▶



Measurements

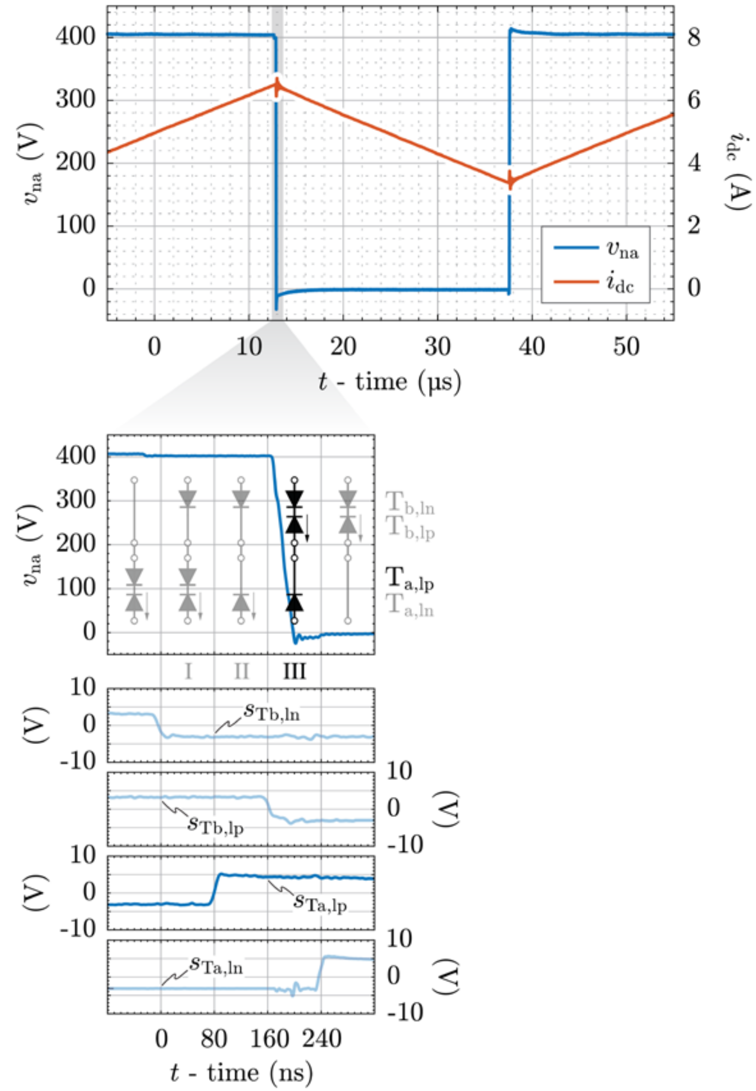
1-ϕ Half-Bridge



DC/DC Operating Point

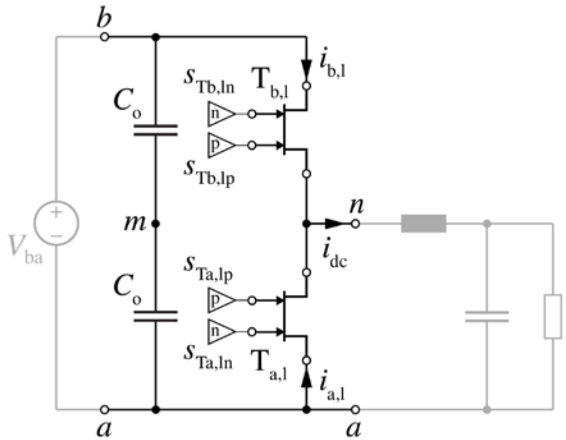
Input Voltage	V_{ba}	400V
Output Current	i_{dc}	5A

Measured Waveforms ▶



▪ Measurements

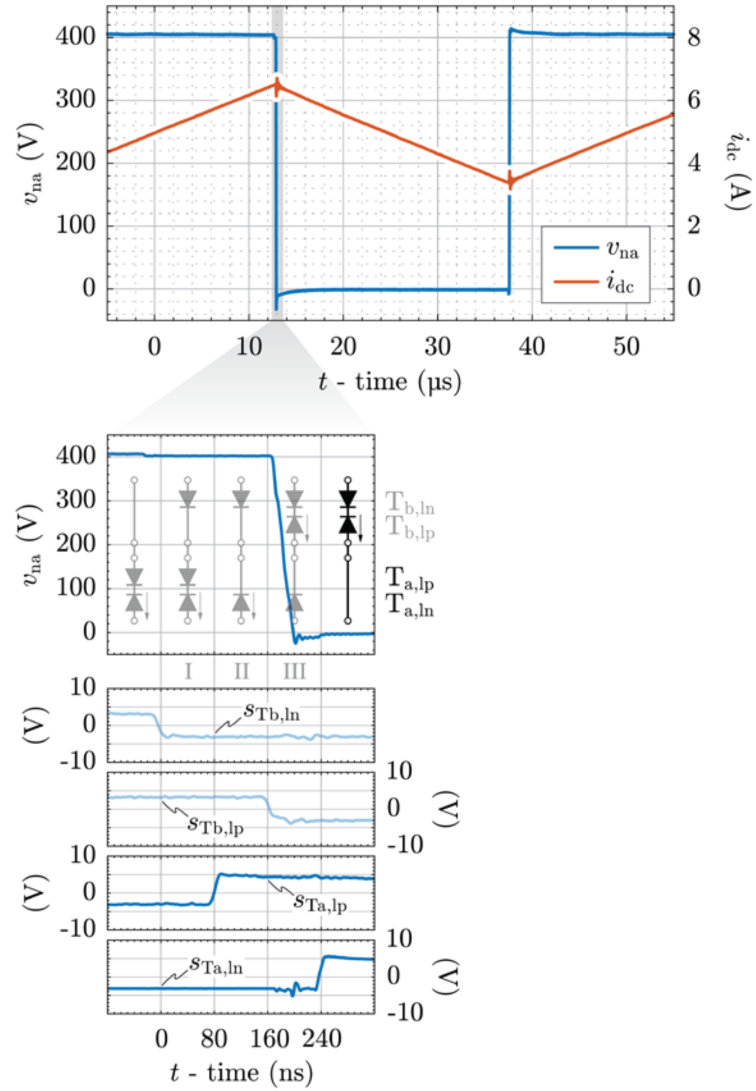
1-ϕ Half-Bridge



DC/DC Operating Point

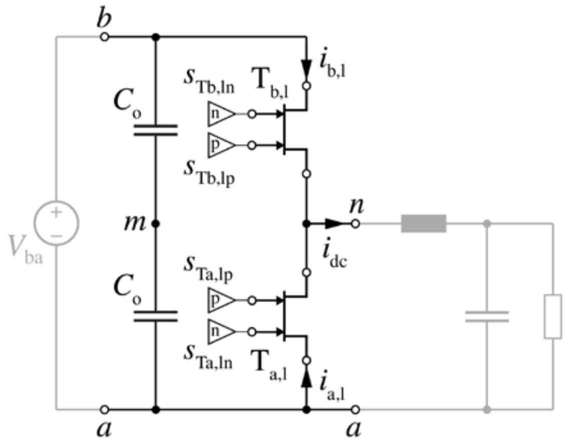
Input Voltage	V_{ba}	400V
Output Current	i_{dc}	5 A

Measured Waveforms ▶



Measurements

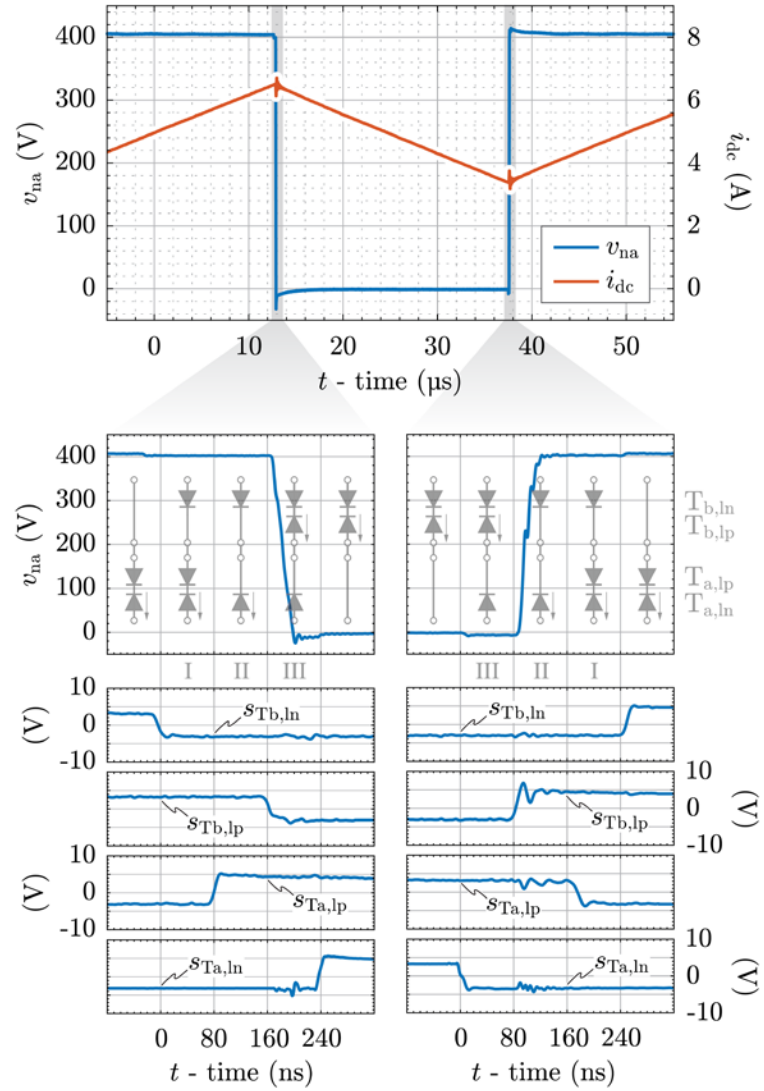
1-ϕ Half-Bridge



DC/DC Operating Point

Input Voltage	V_{ba}	400V
Output Current	i_{dc}	5A

Measured Waveforms ▶



Outlook

Conclusion

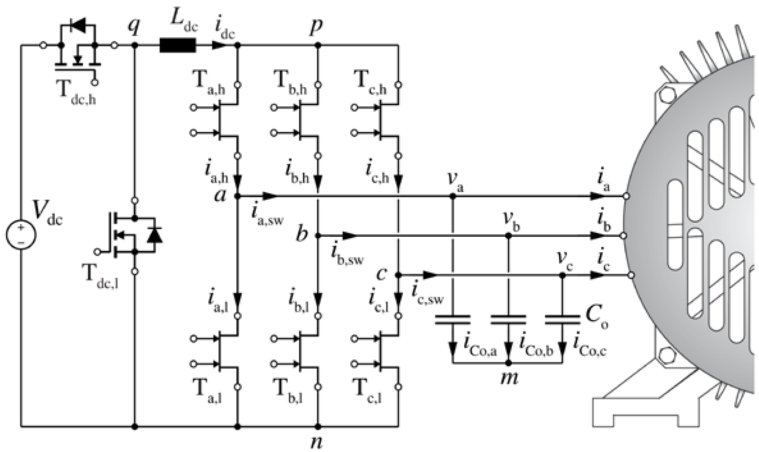
Future Work

Outlook

Conclusion

Inverter:

Continuous Output Voltage
Wide Input Voltage Range



► 3-ϕ Buck-Boost CSI System

Outlook

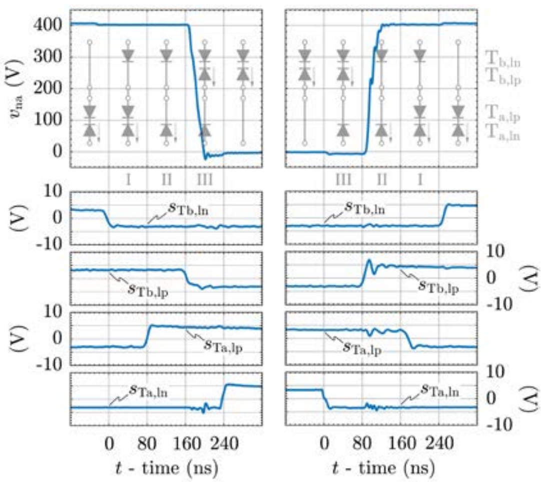
Conclusion

Inverter:

Continuous Output Voltage
Wide Input Voltage Range

Panasonic 2G MB GaN e-FET:

Dual-Gate - Gate Injection
Monolithic Bidirectional
Switching Performance



▶ Multi-Step Commutation Strategy

Outlook

Conclusion

Inverter:

Continuous Output Voltage
Wide Input Voltage Range

Panasonic 2G MB GaN e-FET:

Dual-Gate - Gate Injection
Monolithic Bidirectional
Switching Performance

Two-Third Modulation (TTM):

Operating Principle
Synergetic Control
-8% Conduction Losses
-86% Switching Losses

Outlook

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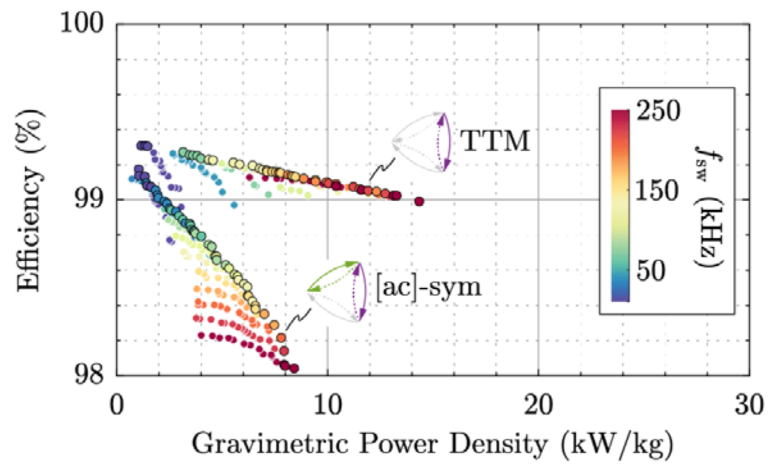
Future Research

3-ϕ Buck-Boost CSI System:
- Optimization



Outlook

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- Continuous Output Voltage
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Future Research

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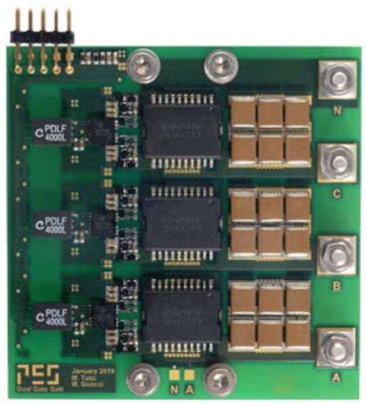
- Optimization
- Complete Design



Outlook

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- Continuous Output Voltage
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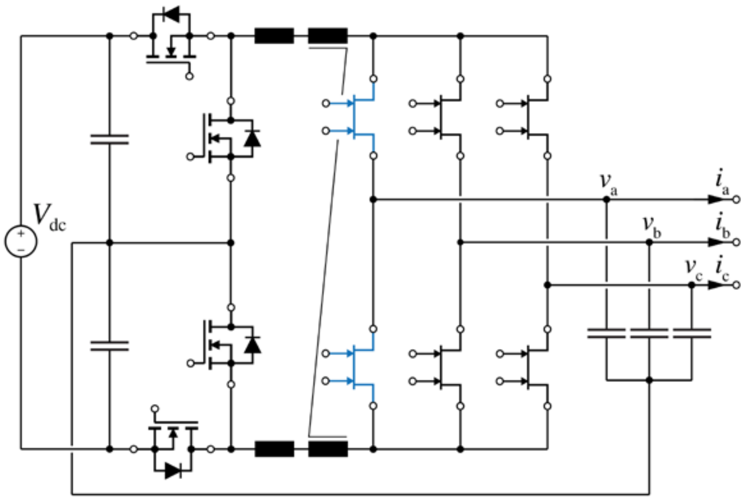
Future Research

3-ϕ Buck-Boost CSI System:
- Optimization
- Complete Design

Investigate Different Concepts



► Normally-On

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Energy Solution Development Center
Industrial Solution Company

Thank You !

Tack så mycket !

RI. SE

SiC PC

YOLE Développement

Swedish Energy Agency

Back-Up Slides

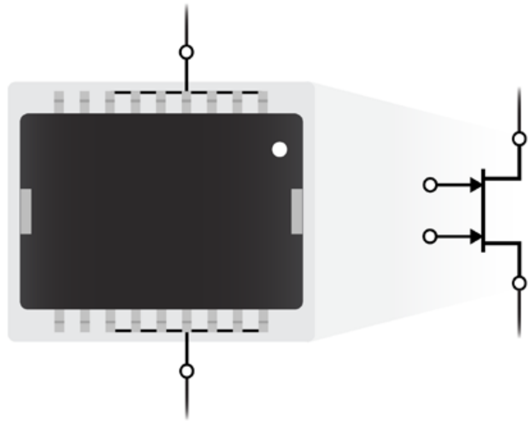
Monolithic Bidirectional Switch

Advantages

Cost
Parasitic Output Capacitance C_{oss}
On-State Resistance $R_{ss,on}$
Figure of Merit (FoM)
Thermal Performance
Package Size - PCB Area
Switching Performance

New Panasonic GaN e-FET

Monolithic Bidirectional Switch (MBS)
Common Drain - Single Drift Layer
Dual-Gate (2G)

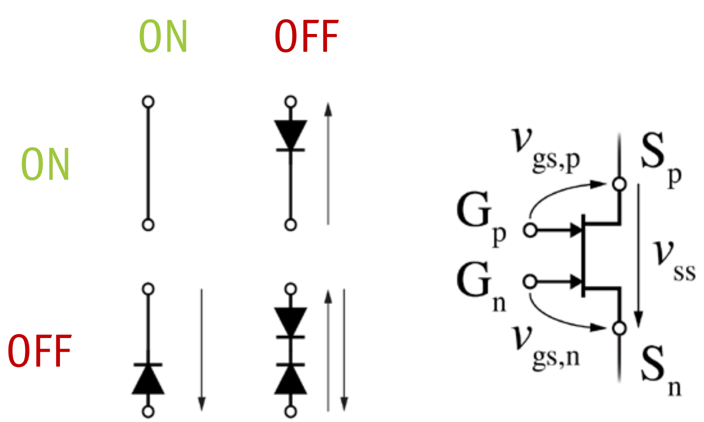


Datasheet Parameters

Power Semiconductor			$V_{ss,MAX}$	$I_{ss,MAX}$ @ 25 °C	$R_{ss,on}$ @ 25 – 150 °C	$C_{oss,Q}$ @ 400 V	$C_{rss,Q}$	FoM = $(R_{ss,on}Q_{oss})^{-1}$ @ 25 °C – 400 V	Package Size
Panasonic Co.	EDLS06SMD		±600 V	92 A	26 – 43 mΩ	190 pF	40 pF	506 MHz/V	2.3 cm^2
GaN Systems Inc.	GS66516	(1x)	650 V	60 A	25 – 65 mΩ	281 pF	8 pF	355 MHz/V	1.0 cm^2
		(4x)	±650 V	120 A		562 pF	16 pF	178 MHz/V	4.0 cm^2

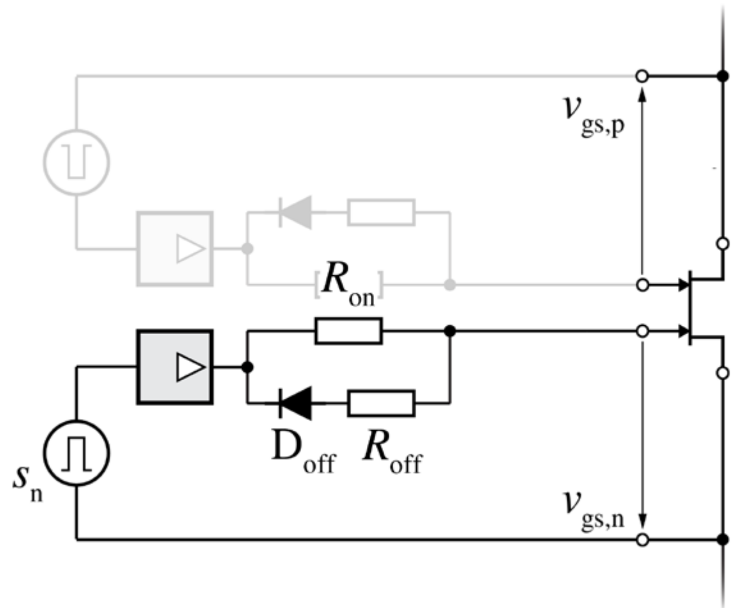
Monolithic Bidirectional Switch

Equivalent Circuit



- ▶ Bidirectional Voltage Blocking
- ▶ Bidirectional Current Flow

Conventional 2G Driver

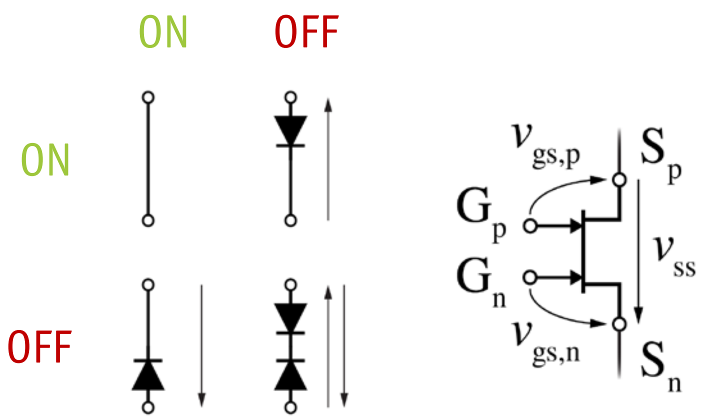


Gate Driver Features

Separate On-Off Paths

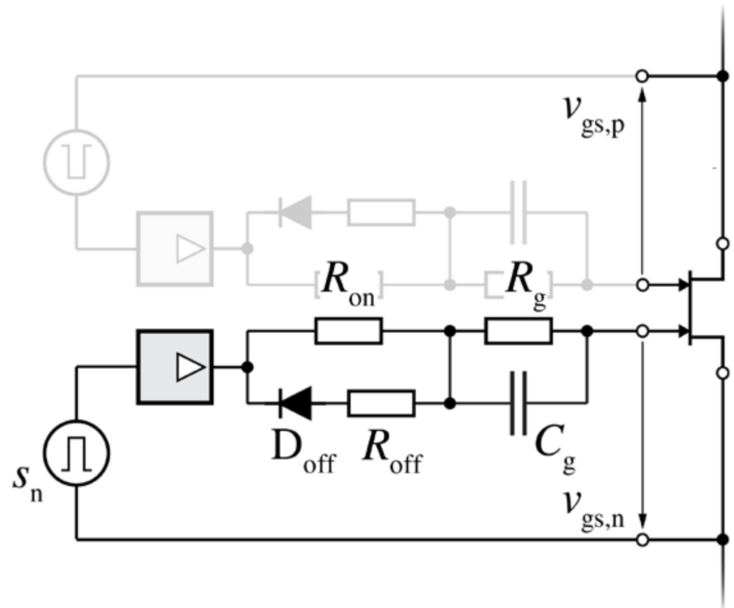
Monolithic Bidirectional Switch

Equivalent Circuit



- Bidirectional Voltage Blocking
- Bidirectional Current Flow

Gate-Injection 2G Driver



Gate Driver Features

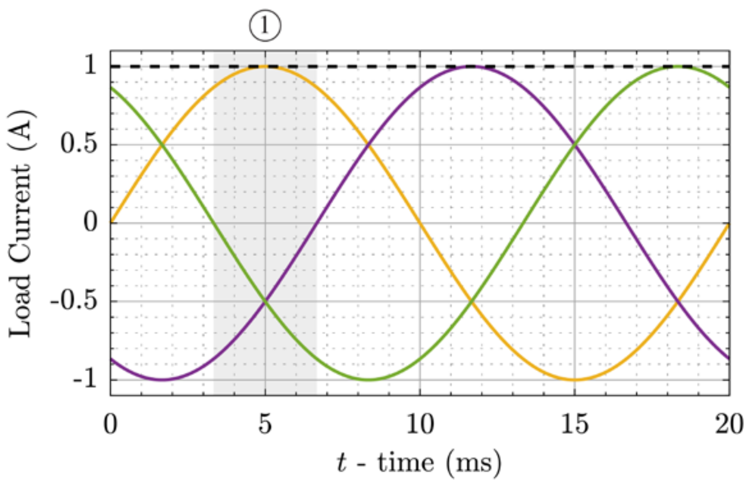
Separate On-Off Paths
Constant Current Path

Conventional Pulse-Width Modulation (PWM)

Active States

[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$
[ac] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[ba] $i_{ph} = [-i_{dc}, +i_{dc}, 0]$
[bc] $i_{ph} = [0, -i_{dc}, +i_{dc}]$
[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

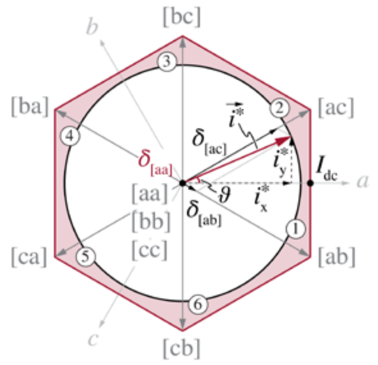
3-ϕ Load Current Waveforms

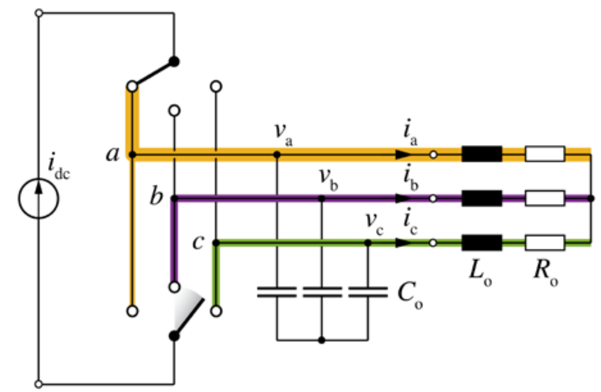


Zero States

[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

▶ SV Diagram





Two-Third Modulation (TTM)

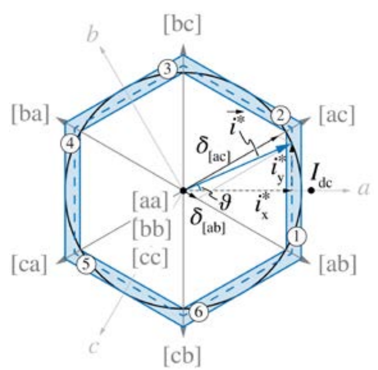
Active States

[ab] $i_{ph} = [+i_{dc}, -i_{dc}, 0]$
[ac] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[ba] $i_{ph} = [-i_{dc}, +i_{dc}, 0]$
[bc] $i_{ph} = [0, -i_{dc}, +i_{dc}]$
[ca] $i_{ph} = [+i_{dc}, 0, -i_{dc}]$
[cb] $i_{ph} = [0, +i_{dc}, -i_{dc}]$

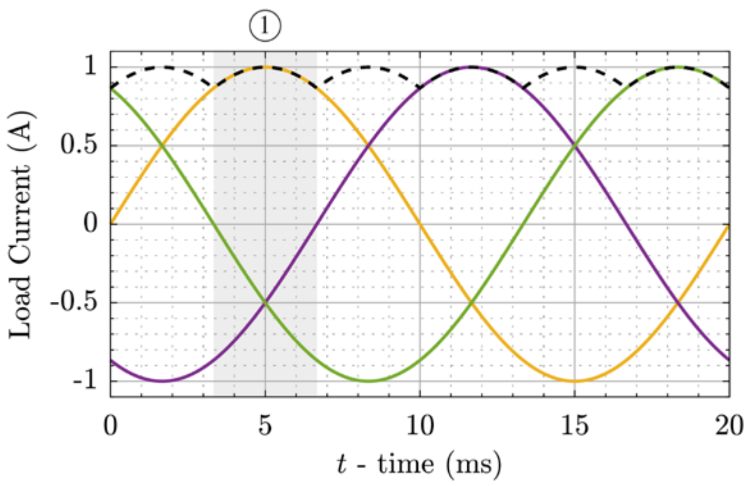
Zero States

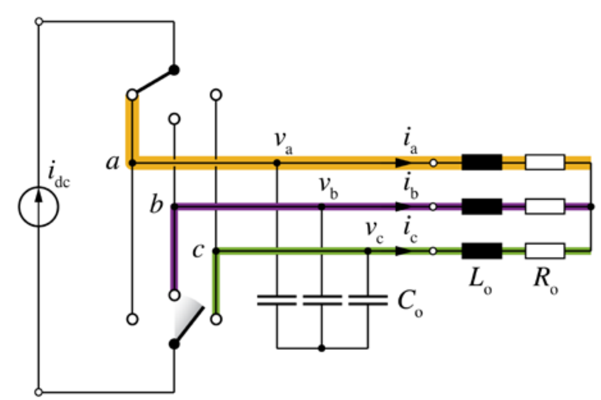
[aa] $i_{ph} = [0, 0, 0]$
[bb] $i_{ph} = [0, 0, 0]$
[cc] $i_{ph} = [0, 0, 0]$

▶ SV Diagram

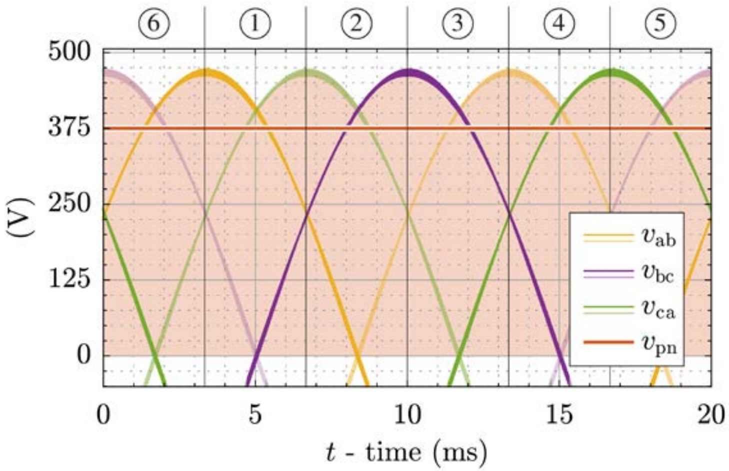


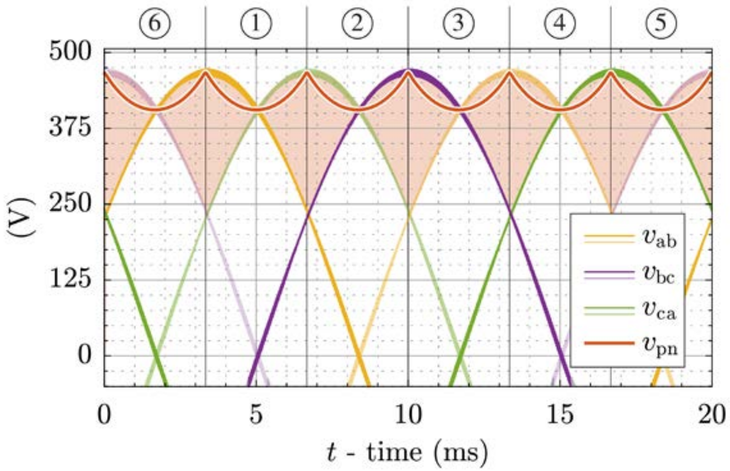
3-ϕ Load Current Waveforms





▪ Conventional PWM vs. TTM (2)

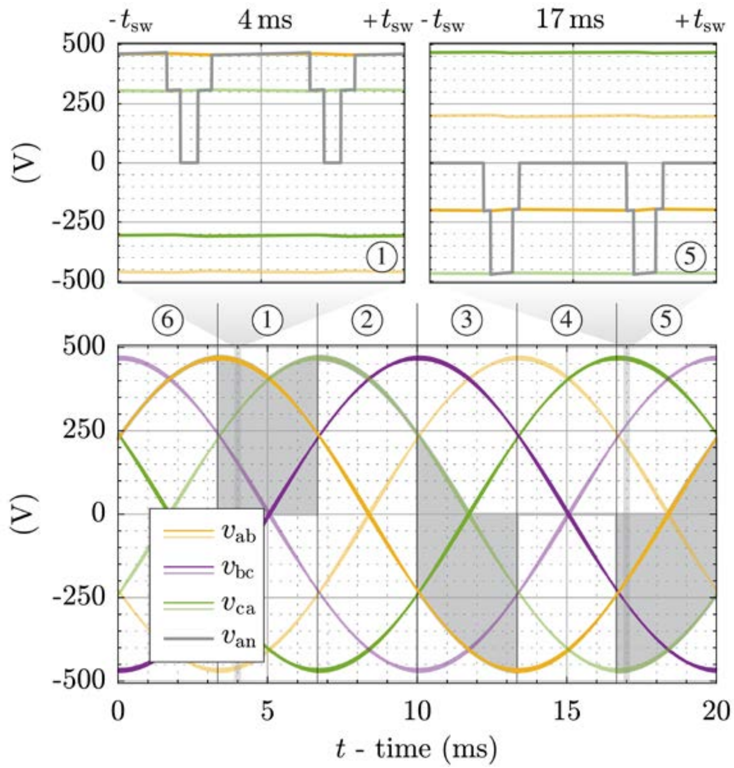




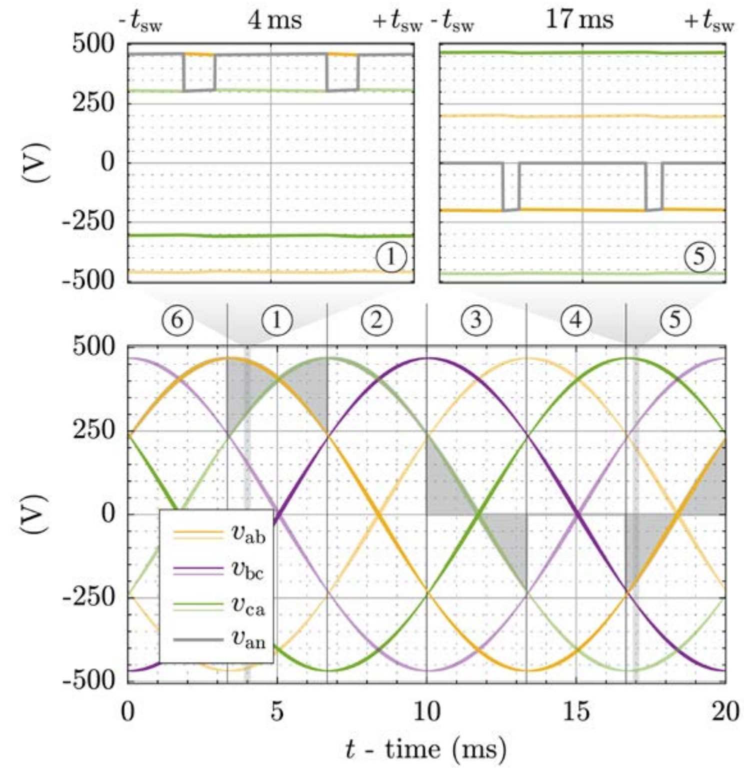
► Conventional PWM

► TTM

Conventional PWM vs. TTM (3)



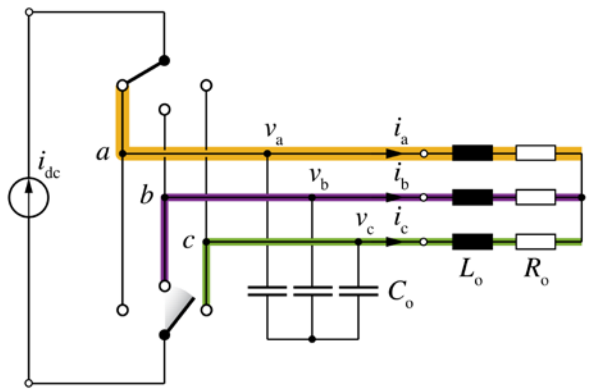
▶ Conventional PWM

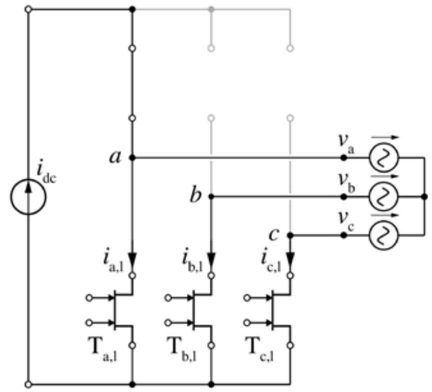


▶ TTM

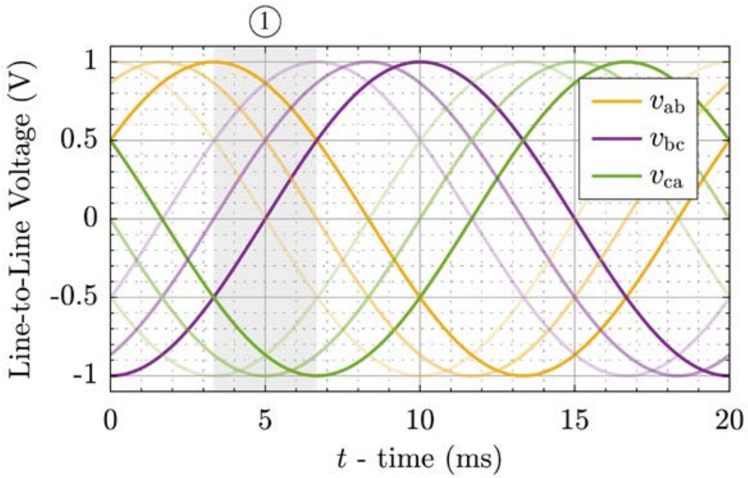
▪ Conventional PWM vs. TTM

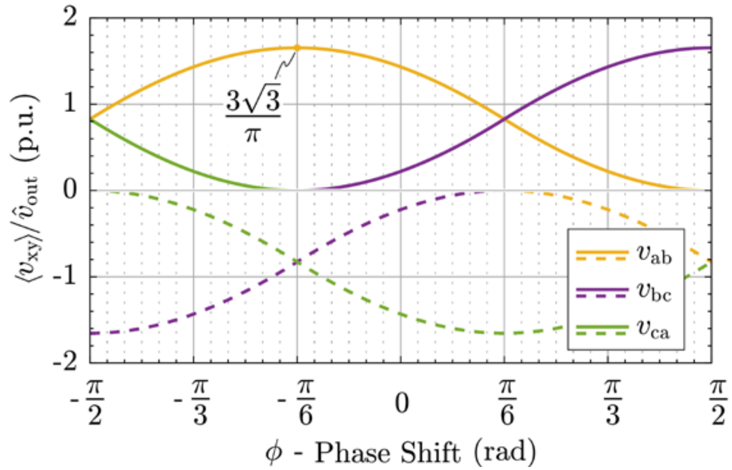
Equivalent Circuit





3-ϕ Line-to-Line Voltage Waveforms





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Thank You !

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