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

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**ETH, Zurich, Switzerland - 7<sup>th</sup> February 1854**

**Facts & Figures**

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**Main Campus, Zurich City Center**
Organizational Diagram

Industry Relations
R. Coccia / B. Seiler

Johann W. Kolar

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter
M. Heller
D. Menzi
D. Neumayr
J. Schäfer

AC-AC Converter
J. Azurza
P. Czyz

DC-DC Converter
F. Krismer
P. Bezerra
T. Guillod
G. Knabben

DC-AC Converter
D. Bortis
M. Antivachis
J. Böhler
M. Guacci
M. Haider

Multi-Domain Modeling
F. Krismer
P. Papamanolis

Measurement Technology
P. Niklaus

Advanced Mechatronics
D. Bortis
E. Hubmann

Magnetic Levitation
D. Bortis

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

M. Antivachis
J. Böhler
M. Guacci
M. Haider
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**

  ![Diagram of 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**

![Diagram of 3-φ Voltage DC-Link Inverter](image)

**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
### Voltage vs. Current DC-Link Inverter

#### 3-φ Voltage DC-Link Inverter

![Diagram of 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

- **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

### Advantages

- Simple Circuit Topology
- No Magnetic Components
- Only Six Power Semiconductors
### Voltage vs. Current DC-Link Inverter

#### 3-φ Voltage DC-Link Inverter

![Circuit Diagram](image)

#### 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**

#### Advantages

- Simple Circuit Topology
- No Magnetic Components
- Only Six Power Semiconductors

---

DC-Link: $V$ vs. $I$  
2G MB GaN e-FET  
3-φ bB CSI System  
HW & Measurements
### Voltage vs. Current DC-Link Inverter

**3-φ Voltage DC-Link Inverter**

- 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

![Circuit Diagram for 3-φ Voltage DC-Link Inverter](image)

**Features**
- Simple Circuit Topology
- Continuous Output Voltage
- Wide Input Voltage Range

#### 3-φ Current DC-Link Inverter

![Circuit Diagram for 3-φ Current DC-Link Inverter](image)

**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)

\[ \pm 650V - 50m\Omega \]
Monolithic Bidirectional Switch

Conventional GaN e-FET (4x)

- DC-Link: V vs. I
- 2G MB GaN e-FET
- 3-φ bB CSI System
- HW & Measurements

► ±650V - 25mΩ
Monolithic Bidirectional Switch

Conventional GaN e-FET (4x)

- GS66516B
- 78AEd (4)

DC-Link: V vs. I

- 2G MB GaN e-FET

New Panasonic GaN e-FET (1x)

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

- GS66516B
- 78AEd (4)

DC-Link: V vs. I

- 3-φ bB CSI System

- HW & Measurements

- ±650V - 25mΩ

- ±600V - 26mΩ
Monolithic Bidirectional Switch

Equivalent Circuit

ON  OFF

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

- ON
- OFF

- Bidirectional Voltage Blocking
- Bidirectional Current Flow

Gate Injection Panasonic 2G Driver

Gate Driver Features

- Separate On-Off Paths
- Constant Current Path
- Minimum Component Number

DC-Link: V vs. I
2G MB GaN e-FET
3-φ bB CSI System
HW & Measurements
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

- \([ab]\)
- \([ac]\)
- \([ba]\)
- \([bc]\)
- \([ca]\)
- \([cb]\)

### Zero States

- \([aa]\)
- \([bb]\)
- \([cc]\)

### Equivalent Circuit

- **Space Vector (SV) Diagram**

### Three-State Switches (2x)
### Operating Principle

#### Active States

- **[ab]** \( \vec{i}_{ph} = [+i_{dc}, -i_{dc}, 0] \)
- **[ac]** \( \vec{i}_{ph} = [+i_{dc}, 0, -i_{dc}] \)
- **[ba]** \( \vec{i}_{ph} = [-i_{dc}, +i_{dc}, 0] \)
- **[bc]** \( \vec{i}_{ph} = [0, -i_{dc}, +i_{dc}] \)
- **[ca]** \( \vec{i}_{ph} = [+i_{dc}, 0, -i_{dc}] \)
- **[cb]** \( \vec{i}_{ph} = [0, +i_{dc}, -i_{dc}] \)

#### Zero States

- **[aa]** \( \vec{i}_{ph} = [0, 0, 0] \)
- **[bb]** \( \vec{i}_{ph} = [0, 0, 0] \)
- **[cc]** \( \vec{i}_{ph} = [0, 0, 0] \)

#### Equivalent Circuit

- **Input Voltage**
  - **[aa]**
  - **Short-Circuit**
### Operating Principle

#### Active States

- **[ab]** \( \dot{i}_{ph} = [+i_{dc}, -i_{dc}, 0] \)
- **[ac]** \( \dot{i}_{ph} = [+i_{dc}, 0, -i_{dc}] \)
- **[ba]** \( \dot{i}_{ph} = [-i_{dc}, +i_{dc}, 0] \)
- **[bc]** \( \dot{i}_{ph} = [0, -i_{dc}, +i_{dc}] \)
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#### Zero States

- **[aa]** \( \dot{i}_{ph} = [0, 0, 0] \)
- **[bb]** \( \dot{i}_{ph} = [0, 0, 0] \)
- **[cc]** \( \dot{i}_{ph} = [0, 0, 0] \)

#### Equivalent Circuit

- **Input Voltage**
  - Rectified Line-to-Line Voltage

- **Rectified Line-to-Line Voltage**

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DC-Link: V vs. I  
2G MB GaN e-FET  
3-Φ bB CSI System  
HW & Measurements
Conventional Pulse-Width Modulation (PWM)

Active States

\[
\begin{align*}
\text{[ab]} & \quad i_{ph} = [+i_{dc}, -i_{dc}, 0] \\
\text{[ac]} & \quad i_{ph} = [+i_{dc}, 0, -i_{dc}] \\
\text{[ba]} & \quad i_{ph} = [-i_{dc}, +i_{dc}, 0] \\
\text{[bc]} & \quad i_{ph} = [0, -i_{dc}, +i_{dc}] \\
\text{[ca]} & \quad i_{ph} = [+i_{dc}, 0, -i_{dc}] \\
\text{[cb]} & \quad i_{ph} = [0, +i_{dc}, -i_{dc}]
\end{align*}
\]

Zero States

\[
\begin{align*}
\text{[aa]} & \quad i_{ph} = [0, 0, 0] \\
\text{[bb]} & \quad i_{ph} = [0, 0, 0] \\
\text{[cc]} & \quad i_{ph} = [0, 0, 0]
\end{align*}
\]
Conventional Pulse-Width Modulation (PWM)

### Active States

- **[ab]** \(i_{ph} = [+i_d, -i_d, 0]\)
- **[ac]** \(i_{ph} = [+i_d, 0, -i_d]\)
- **[ba]** \(i_{ph} = [-i_d, +i_d, 0]\)
- **[bc]** \(i_{ph} = [0, -i_d, +i_d]\)
- **[ca]** \(i_{ph} = [+i_d, 0, -i_d]\)
- **[cb]** \(i_{ph} = [0, +i_d, -i_d]\)

### 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

![Load Current Waveforms Diagram](image)
Conventional Pulse-Width Modulation (PWM)

Active States

\[
\begin{align*}
\text{[ab]} & : i_{ph} = [+i_{dc}, -i_{dc}, 0] \\
\text{[ac]} & : i_{ph} = [+i_{dc}, 0, -i_{dc}] \\
\text{[ba]} & : i_{ph} = [-i_{dc}, +i_{dc}, 0] \\
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Zero States

\[
\begin{align*}
\text{[aa]} & : i_{ph} = [0, 0, 0] \\
\text{[bb]} & : i_{ph} = [0, 0, 0] \\
\text{[cc]} & : i_{ph} = [0, 0, 0]
\end{align*}
\]
### Conventional Pulse-Width Modulation (PWM)

#### Active States

- **[ab]** \( i_{ph} = [+i_{dc}, -i_{dc}, 0] \)
- **[ac]** \( i_{ph} = [+i_{dc}, 0, -i_{dc}] \)
- **[ba]** \( i_{ph} = [-i_{dc}, +i_{dc}, 0] \)
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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]** \( i_{ph} = [0, 0, 0] \)

---

**3-Φ Load Current Waveforms**

![Load Current Waveform Graph]
### 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]** \( i_{ph} = [0, 0, 0] \)

- **Two Active States + One Zero State**
Two-Third Modulation (TTM)

Active States

- \([ab]\) \(i_{\text{ph}} = [+i_{\text{dc}}, -i_{\text{dc}}, 0]\)
- \([ac]\) \(i_{\text{ph}} = [+i_{\text{dc}}, 0, -i_{\text{dc}}]\)
- \([ba]\) \(i_{\text{ph}} = [-i_{\text{dc}}, +i_{\text{dc}}, 0]\)
- \([bc]\) \(i_{\text{ph}} = [0, -i_{\text{dc}}, +i_{\text{dc}}]\)
- \([ca]\) \(i_{\text{ph}} = [+i_{\text{dc}}, 0, -i_{\text{dc}}]\)
- \([cb]\) \(i_{\text{ph}} = [0, +i_{\text{dc}}, -i_{\text{dc}}]\)

Zero States

- \([aa]\) \(i_{\text{ph}} = [0, 0, 0]\)
- \([bb]\) \(i_{\text{ph}} = [0, 0, 0]\)
- \([cc]\) \(i_{\text{ph}} = [0, 0, 0]\)
### Two-Third Modulation (TTM)

#### Active States

- **[ab]** \( i_{ph} = [+i_{dc}, -i_{dc}, 0] \)
- **[ac]** \( i_{ph} = [+i_{dc}, 0, -i_{dc}] \)
- **[ba]** \( i_{ph} = [-i_{dc}, +i_{dc}, 0] \)
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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**
### Conventional PWM vs. TTM

**Conventional PWM**

**TTM**
• Conventional PWM vs. TTM

Equivalent Circuit

[Diagram showing an equivalent circuit with labels for different components and variables.]
**Conventional PWM vs. TTM**

Equivalent Circuit

- 2G MB GaN e-FETs
### Conventional PWM vs. TTM

#### Equivalent Circuit

- **Diagram:**
  - DC Link: \( i_{dc} \)
  - Line-to-Line Voltages: \( v_a, v_b, v_c \)
  - Currents: \( i_a, i_b, i_c \)
  - Capacitor: \( C_o \)
  - Inductor: \( L_o \)
  - Resistor: \( R_o \)

#### 3-φ Line-to-Line Voltage Waveforms

- **Graph:**
  - Voltages: \( v_{ab}, v_{bc}, v_{ca} \)
  - Time: \( t \)

#### 2G MB GaN e-FETs

- **Note:**
  - 2G MB GaN e-FETs used in the system.
Conventional PWM vs. TTM

Equivalent Circuit

3-φ Line-to-Line Voltage Waveforms

► State Sequence

2G MB GaN e-FETs
Conventional PWM vs. TTM

Equivalent Circuit

3-ϕ Line-to-Line Voltage Waveforms

► State Sequence

▶ 2G MB GaN e-FETs
- **Conventional PWM vs. TTM**

**Equivalent Circuit**

- **Switching Losses**

- **State Sequence**

- **2G MB GaN e-FETs**

---

**DC-Link: V vs. I**

**2G MB GaN e-FET**

**3-ϕ bB CSI System**

**HW & Measurements**
Conventional PWM vs. TTM

Equivalent Circuit

Switching Losses

- Conventional PWM vs. TTM

- Equivalent Circuit

- 2G MB GaN e-FETs

- Switching Losses

- State Sequence
**Synergetic Control**

**Control Structure**

![Control Structure Diagram]

- $i_a^*$
- $v_a^*$
- $i_{C_o,a}^*$
- $i_{a,sw}^*$
- $i_{dc}^*$
- $v_{Ldc}^*$
- $v_{qn}^*$
- $v_{dc}$
- $v_{pa}$
- $v_{pb}$
- $v_{pc}$
- $\delta_{[xy]}$
- $s_{T_{dc},h}$
• **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

![3-ϕ Buck-Boost CSI System Diagram]

### DC/AC Operating Point

<table>
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<tr>
<th>Description</th>
<th>Value</th>
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<tr>
<td>Input Current</td>
<td>( i_{dc} )</td>
</tr>
<tr>
<td>Output Power</td>
<td>( P_{out} )</td>
</tr>
</tbody>
</table>

DC-Link: \( V \) vs. \( I \)  
2G MB GaN e-FET  
3-ϕ bB CSI System  
HW & Measurements
Hardware Design

3-ϕ Buck-Boost CSI System

![Circuit Diagram]

DC/AC Operating Point
- Input Current: $i_{dc}$
- Output Power: $P_{out}$
- Values:
  - $i_{dc}$: 20A
  - $P_{out}$: 7.5kW

1-ϕ Half-Bridge

DC/DC Operating Point
- Output Current: $i_{dc}$
- Value: 20A

- Additional information:
  - DC-Link: V vs. I
  - 2G MB GaN e-FET
  - 3-ϕ bB CSI System

HW & Measurements
## Hardware Design

### 3-φ Buck-Boost CSI System

#### 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

### 1-φ Half-Bridge

#### DC/AC Operating Point
- **Output Current**: $i_{dc}$ 20A
- **Input Voltage**: $V_{ba}$ 400V

#### DC/DC Operating Point

---

DC-Link: V vs. I

2G MB GaN e-FET

3-φ bB CSI System

HW & Measurements 49
Hardware Design

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

Top-View

Bottom-View
Hardware Design

3-\(\phi\) 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

DC-Link: V vs. I
2G MB GaN e-FET
3-φ bB CSI System
**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](image1)

![Bottom-View](image2)
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

Graph showing measured waveforms with time on the x-axis and voltage and current on the y-axis.
## Measurements

### 1-φ Half-Bridge

**DC/DC Operating Point**

- Input Voltage \( V_{ba} \) \( \quad 400V \)
- Output Current \( i_{dc} \) \( \quad 5A \)

**Measured Waveforms**

- DC-Link: \( V \) vs. \( I \)
- 2G MB GaN e-FET
- 3-φ bB CSI System

---

**Graphs:**

- \( v_{na} \) vs. \( t \) for \( u_{na} \) and \( i_{dc} \)
- Waveforms for various stages: \( T_{b,ln} \), \( T_{b,lp} \), \( T_{a,ln} \), \( T_{a,lp} \)
Measurements

1-φ Half-Bridge

DC/DC Operating Point

Input Voltage \( V_{\text{ba}} \) 400V
Output Current \( i_{\text{dc}} \) 5A

Measured Waveforms
## Measurements

### 1-φ Half-Bridge

**DC/DC Operating Point**

- **Input Voltage** $V_{ba} = 400V$
- **Output Current** $i_{dc} = 5A$

**Measured Waveforms**

- DC-Link: $V$ vs. $I$
- 2G MB GaN e-FET
- 3-φ bB CSI System

**Graphs**

- $v_{na}$ vs. $i_{dc}$
- Measured waveforms for $T_{b,ln}$, $T_{b,lp}$, $T_{a,lp}$, $T_{a,ln}$

**Diagram**

- Circuit diagram of 1-φ Half-Bridge

---

* ETH Zürich Power Electronic Systems Laboratory*
**Measurements**

### 1-ϕ Half-Bridge

![Half-Bridge Circuit Diagram]

**DC/DC Operating Point**

- **Input Voltage** \( V_{ba} \): 400V
- **Output Current** \( i_{dc} \): 5A

**Measured Waveforms**

- **DC-Link: V vs. I**
- **2G MB GaN e-FET**
- **3-ϕ bB CSI System**
- **HW & Measurements**
## Measurements

### 1-φ Half-Bridge

**DC/DC Operating Point**

- **Input Voltage** \( V_{ba} \) 400V
- **Output Current** \( i_{dc} \) 5A

**Measured Waveforms**

- DC-Link: \( V \) vs. \( I \)
- 2G MB GaN e-FET
- 3-φ bB CSI System
### Measurements

**1-φ Half-Bridge**

![Diagram of 1-φ Half-Bridge](image)

**DC/DC Operating Point**

- **Input Voltage** $V_{ba} = 400V$
- **Output Current** $i_{dc} = 5A$

**Measured Waveforms**

![Measured Waveforms](image)
Outlook

Conclusion
Future Work
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**
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
\section*{Outlook}

\subsection*{Conclusion}

\textbf{Inverter:}
- Continuous Output Voltage
- Wide Input Voltage Range

\textbf{Panasonic 2G MB GaN e-FET:}
- Dual-Gate - Gate Injection
- Monolithic Bidirectional
- Switching Performance

\textbf{Two-Third Modulation (TTM):}
- Operating Principle
- Synergetic Control
- \(-8\%\) Conduction Losses
- \(-86\%\) Switching Losses

\subsection*{Future Research}

\textbf{3-Φ Buck-Boost CSI System: Optimization}
Outlook

Conclusion

Inverter:
- Continuous Output Voltage
- Wide Input Voltage Range

Panasonic 2G MB GaN e-FET:
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Future Research

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

Investigate Different Concepts

► Normally-On
Thank You!
Tack så mycket!
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

Datasheet Parameters

<table>
<thead>
<tr>
<th>Power Semiconductor</th>
<th>$V_{ss,MAX}$</th>
<th>$I_{ss,MAX}$</th>
<th>$R_{ss,on}$</th>
<th>$C_{oss,Q}$</th>
<th>$C_{rss,Q}$</th>
<th>$FoM = (R_{ss,on}Q_{oss})^{-1}$</th>
<th>Package Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panasonic Co. EDLS06SMD</td>
<td>±600 V</td>
<td>92 A</td>
<td>26 – 43 mΩ</td>
<td>190 pF</td>
<td>40 pF</td>
<td>506 MHz/v</td>
<td>2.3 cm²</td>
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<tr>
<td>GaN Systems Inc. GS66516</td>
<td>(1x) 650 V</td>
<td>(4x) 120 A</td>
<td>25 – 65 mΩ</td>
<td>281 pF</td>
<td>8 pF</td>
<td>355 MHz/v</td>
<td>1.0 cm²</td>
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<tr>
<td></td>
<td>±650 V</td>
<td></td>
<td></td>
<td>562 pF</td>
<td>16 pF</td>
<td>178 MHz/v</td>
<td>4.0 cm²</td>
</tr>
</tbody>
</table>

DC-Link: V vs. I

2G MB GaN e-FET

3-ϕ bB CSI System

HW & Measurements
### Monolithic Bidirectional Switch

#### Equivalent Circuit

- **ON**
  - ON
  - OFF

- **OFF**
  - ON
  - OFF

- **Bidirectional Voltage Blocking**
- **Bidirectional Current Flow**

#### Conventional 2G Driver

- **Gate Driver Features**
  - Separate On-Off Paths

---

**DC-Link: V vs. I**

<table>
<thead>
<tr>
<th>2G MB GaN e-FET</th>
<th>3-φ bB CSI System</th>
<th>HW &amp; Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>73</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Monolithic Bidirectional Switch

#### Equivalent Circuit

- **ON**
  - \( V_{gs,p} \)
  - \( V_{gs,n} \)
  - \( S_p \)
  - \( G_p \)
  - \( G_n \)

- **OFF**
  - \( D_{off} \)
  - \( R_{off} \)
  - \( C_g \)
  - \( V_{gs,n} \)

- **Gate Driver Features**
  - Separate On-Off Paths
  - Constant Current Path

- **Bidirectional Voltage Blocking**
- **Bidirectional Current Flow**

#### Gate-Injection 2G Driver

- \( V_{gs,p} \)
- \( V_{ss} \)
- \( S_n \)
- \( R_{on} \)
- \( R_g \)
- \( C_g \)
Conventional Pulse-Width Modulation (PWM)

Active States

\[
\begin{align*}
[ab] & \quad i_{ph} = [+i_{dc}, -i_{dc}, 0] \\
[ac] & \quad i_{ph} = [+i_{dc}, 0, -i_{dc}] \\
[ba] & \quad i_{ph} = [-i_{dc}, +i_{dc}, 0] \\
[bc] & \quad i_{ph} = [0, -i_{dc}, +i_{dc}] \\
[ca] & \quad i_{ph} = [+i_{dc}, 0, -i_{dc}] \\
[cb] & \quad i_{ph} = [0, +i_{dc}, -i_{dc}] \\
\end{align*}
\]

Zero States

\[
\begin{align*}
[aa] & \quad i_{ph} = [0, 0, 0] \\
[bb] & \quad i_{ph} = [0, 0, 0] \\
[cc] & \quad i_{ph} = [0, 0, 0] \\
\end{align*}
\]

3-φ Load Current Waveforms

\[ i_{dc} \]

SV Diagram
## Two-Third Modulation (TTM)

### Active States

- **[ab]** \[\vec{i}_{ph} = [+i_{dc}, -i_{dc}, 0]\]
- **[ac]** \[\vec{i}_{ph} = [+i_{dc}, 0, -i_{dc}]\]
- **[ba]** \[\vec{i}_{ph} = [-i_{dc}, +i_{dc}, 0]\]
- **[bc]** \[\vec{i}_{ph} = [0, -i_{dc}, +i_{dc}]\]
- **[ca]** \[\vec{i}_{ph} = [+i_{dc}, 0, -i_{dc}]\]
- **[cb]** \[\vec{i}_{ph} = [0, +i_{dc}, -i_{dc}]\]

### Zero States

- **[aa]** \[\vec{i}_{ph} = [0, 0, 0]\]
- **[bb]** \[\vec{i}_{ph} = [0, 0, 0]\]
- **[cc]** \[\vec{i}_{ph} = [0, 0, 0]\]

### 3-Φ Load Current Waveforms

![Graph showing 3-Φ load current waveforms]

**SV Diagram**

- [Diagram showing SV diagram]

---

**DC-Link: V vs. I**

**2G MB GaN e-FET**

**3-Φ bB CSI System**

**HW & Measurements**
- **Conventional PWM vs. TTM (2)**

  ![Graph showing comparison between Conventional PWM and TTM](image)

  **Conventional PWM**

  **TTM**

  DC-Link: V vs. I

  2G MB GaN e-FET

  3-φ bB CSI System

  HW & Measurements
Conventional PWM vs. TTM (3)

- **Conventional PWM**

- **TTM**

DC-Link: V vs. I

2G MB GaN e-FET

3-φ bB CSI System

HW & Measurements
- Conventional PWM vs. TTM

Equivalent Circuit

3-φ Line-to-Line Voltage Waveforms

1. $v_{ab}$
2. $v_{bc}$
3. $v_{ca}$
Thank You!

Tack så mycket!