One of the most famous firework festivals in Japan is held in Nagaoka on begin of August every year.

Phoenix (width 2000m)

Sho-sanjaku
Diameter 600m, altitude 600m

Power Electronics Lab.

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1. Introduction
   - Importance of minimization of passive components
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   - Matrix converter in Market: general purpose drive/air conditioner/quick charger
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   - Principle
   - Integrated to PFC or Inverter
   - Integrated to Chopper
4. Approach III: Discontinuous Current Mode converter
   - Principle: Robustness for inductor
   - Single-phase inverter with DCM
   - Three-phase inverter with DCM
5. Approach IV: FRT capability of grid-tied inverter with minimized inductor
   - Mr. Nagai presents his projects
6. Conclusion
Road to **Innovation**

- Innovation is born when convenience is more important than price; such as LCD, Smart phone, LED light

- High power density converter has possibilities;
  - New applications will be invented by size reduction
  - Size reduction realizes cost reduction because of decrease of material cost.

  **The door will be opened to new world!**

---

**Toward High power density**

- **Break through technologies**
  1. Loss reduction with SiC
  2. High temp. operation
  3. Size reduction and high temp. for passive components and heat think
  4. High current density: DLB, DCB

- **High efficiency = low loss = small heat think**

  **High power density**

  **This is not true!** Passive components can not be neglected
High power density in product –Switching Power Supply–

- TDK Lambda HFE2500-48 semiconductor

Control PCB

Air flow

Passive components

Passive components dominates large ratio of power system

---

Items for size reduction of passive components

- Development of new material
  Magnetic and capacitive materials are developing; however…

- High frequency switching by WBG device (SiC, GaN)
  - Maximum frequency is limited by passive components materials
  - Cooling method will be difficult
  - Implementation of PCB will be difficult because parasitic capacitance and inductance can not be neglected.

Consideration of best circuit topology is important.
(Two level inverter is not best way in all purpose)
High frequency technique with circuit topology

- Interleave topology (parallel connection)

Four-phase

- Input current is composed by triangle waveforms of four-phase current

Equivalent switching frequency: Four times

- Multi-level topology (series connection)

T-type 3-level

- Three-level output voltage waveform

Equivalent switching frequency: Double

Reduction of switching loss and filter loss are achieved by circuit topology

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**Approach I: Matrix converter**

- Direct power conversion from line frequency AC to other AC

- **Circuit type: four types**

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>Three</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The matrix converter can be applied to three-phase and single-phase input and/or output.

**Output voltage: composed by chopping three-phase input voltage with AC switches**

---

**Feature 1: Simple AC to AC direct conversion**

<table>
<thead>
<tr>
<th>Diode Rec. +Inverter</th>
<th>Matrix converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial charge unit</td>
<td>Ditto</td>
</tr>
<tr>
<td>DCL</td>
<td>Ditto</td>
</tr>
<tr>
<td>Smoothing Capacitor</td>
<td>Ditto</td>
</tr>
<tr>
<td>Breaking unit</td>
<td>Ditto</td>
</tr>
</tbody>
</table>

**Initial charging unit, DCL, Breaking unit, and Smoothing capacitor:**

*Not necessary for MC*

**Drastic size reduction will be achieved**
Feature 2: Low input current harmonics

- Sinusoidal input current waveform as well as PWM rectifier
- Input current THD
  (less than 20th)
  \[
  \text{THD} \leq 5\% 
  \text{at rated load}
  \]
- Input power factor
  \[
  \text{Input power factor} 
  \geq 99\% 
  \text{at over 50\% load}
  \]

Feature 3: Bidirectional power flow

- Regenerated power of motor can be returned to power line with sinusoidal current

Realizing drastic energy saving for the applications
which has regenerating power flow such as lifts, cleans and rapid adjustable speed drives with large inertia load
Comparison among AC-AC converters

<table>
<thead>
<tr>
<th>Items</th>
<th>Diode rec. + Inv.</th>
<th>PWM rec. + Inv.</th>
<th>Matrix converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit configuration</td>
<td><img src="image1.png" alt="Circuit diagram" /></td>
<td><img src="image2.png" alt="Circuit diagram" /></td>
<td><img src="image3.png" alt="Circuit diagram" /></td>
</tr>
<tr>
<td>Num. of arms</td>
<td>Rec:6, INV:6, DB:1</td>
<td>Rec:6, INV:6</td>
<td>CONV:18</td>
</tr>
<tr>
<td>Circuit stricture</td>
<td>Simple</td>
<td>Complicate</td>
<td>Complicate</td>
</tr>
<tr>
<td>Regeneration</td>
<td>Impossible</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>Semiconductor loss</td>
<td>Low</td>
<td>Large</td>
<td>Middle</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Middle</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Input current harmonics</td>
<td>Large</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Input voltage distortion</td>
<td>Large</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td>Size</td>
<td>Small</td>
<td>Large</td>
<td>Middle</td>
</tr>
<tr>
<td>Cost</td>
<td>Low</td>
<td>High</td>
<td>Middle?</td>
</tr>
</tbody>
</table>

Performance of MC is the same to PWM rectifier although smaller size

Limitation of Matrix converter

- **Maximum Output voltage:** 0.866 of Input voltage
  - Output voltage is composed by three-phase input voltage within envelope curve
  - Output voltage is limited to less than 0.866 of input voltage
  - Output voltage becomes 170V at 200V input voltage
  - Output voltage can be increased by over modulation technique; however input current harmonics will be increased.

- **Instantaneous power interruption**
  - Not continuing the operation for instantaneous power interruption due to no large energy storage.
  - Possible to stop and automatic restart without trip
  - Speedy restart after power return due to no initial charging.
  - Control power supply have to keep during interruption with larger capacitors in control board.

- **Input voltage drop**
  - Maximum output voltage is decreased in input voltage drop due to no boost up capability.
  - PWM rectifier can keep DC voltage even voltage drop.
  - Possible to keep the performance for input voltage distortion, voltage imbalance

It is important to use MC to the applications which can neglect these limitations
Main circuit configuration

- 9-switch matrix converter
- Indirect Matrix converter
- Three-phase to single-phase

Matrix converter topology is separated into direct type and indirect type
- Indirect matrix converter has no DC link capacitor although snubber capacitor
- 3-1 matrix converter is used for high power application with modular structure and for medium frequency changer

Isolated AC-DC converter with matrix converter

- Three-types converters according to location of inductor

<table>
<thead>
<tr>
<th>Circuit configuration</th>
<th>Output voltage</th>
<th>Inductor</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Step-down</td>
<td>Output side DC</td>
<td>Simple</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Input side AC</td>
<td>Simple</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transformer Side AC</td>
<td>Complicate</td>
</tr>
</tbody>
</table>

One of disadvantage of matrix converter does not appear in this application because output voltage is adjusted by turn ratio of transformer
Step-down isolated matrix converter with DC inductor

- Problems: current ripple reduction with small DC inductor
- Solution 1: PWM method considering large DC current ripple [4]
- Solution 2: DC current ripple reduction with zero vector distribution of matrix converter [5]

**Dual active bridge type Isolated Matrix converter**

- Basic operating concept is the same to dual active bridge converter
- Low EMI and size reduction are achieved by soft switching and increase of frequency
- Suitable for high-power isolated power supply, EV charger, aircraft applications etc.
- However, the input voltage is fluctuated by three-phase ac voltage
Simple duty ratio calculation method by approximation

Output voltage of MC
Output voltage of inverter
Transformer current

Easy to calculate duty ratio
Possible to power transfer stiffing soft switching conditions
Error between ideal voltage and approximate waveform depending on load conditions = difficult to compensation

Use of approximation to square waveform

Problems occur such as increase of output power error, input current distortion, etc.


Asymmetry modulation method

Output voltage of MC
Output voltage of inverter
Transformer current

The current ripple in positive period is cancelled by ripple in negative period in transformer

Sinusoidal input current, high power factor in MFT, and Soft switching operation

S. Takuma, K. Kusaka, J. Itoh, Y. Ohnuma, S. Miyawaki:
General Purpose Motor Drive: U1000 Yaskawa Electric

YASKAWA

- Power Range of U1000:
  - From 200V, 9kVA (output current 28A)
  - up to 400V, 770kVA (output current 930A)

- The biggest motivation to use matrix converter is the input current harmonics reduction.

- Input current harmonics is suppressed to 5%


Size reduction

- Matrix converter has big contribution to size reduction of panel in practically.

Panel size can be reduced by 1/2

The number of components: drastically reduced. The wiring is only 6

Main circuit
- Current source rectifier: unidirectional power flow

400V/50Hz, 5.7kW

Active Clamp circuit:
- Serial/parallel switching operation according to current direction
- To absorb reactive current at low load power factor
- To reduce inrush current at initial charge


Comparison of overview between PWM Rec. and IMC

- PWM rectifier + Inverter
- Indirect matrix converter

Additional noise filters are not necessary

Same PCB size although the number of switching device is increased.
The weight is reduced by 30% from 12kg to 8.2kg
Performance evaluations(1)

- Operation waveforms

Vdc: DC link voltage, Vs: Input phase voltage
Is: Input current, Iu: Output current

Sinusoidal input and output current
Unity power factor

Meeting IEC 61000-3-2 Class A

Performance evaluations(2)

- Conducted emission

Meeting CISPR14-1 (QP) without additional noise filters

Note: PWM rec. switching frequency: 15kHz
Indirect matrix converter: 5.9kHz

Efficiency

Improved by 1.5 - 2% in maximum and by 6% in light load condition
(Air conditioner has long operation time in light load)
Rapid Charger for EV

- Conventional charger
- Matrix converter charger

**Power Electronics Lab.**

Volume: reduced by 50%
Cost: reduced by 30% to the conventional charger.

The number of products: over 6000 units

Three-phase Isolated AC-DC converter

**Conventional circuit**
- Medium frequency transformer
- 50 or 60 Hz
- Bulky
- PWM rectifier
- inverter
- Rectifier
- Three-phase DC
- AC
- DC

**Advantages**
- Downsizing of a transformer
- Sinusoidal input current

**Disadvantages**
- Increasing of power loss
- Bulky electrolytic capacitor and input inductor

**Matrix converter**
- Small
- MC Obtains medium frequency AC from line frequency directly

**Advantage:**
No electrolytic capacitor and small AC inductors compared to that of conventional circuit

**Power Electronics Lab.**
The sinusoidal input current is obtained with 2.5% THD. The efficiency is over 90% in products level.

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Approach II: Active power decoupling

- Single-phase grid tied systems such as PCS for PV, On Board Charger for EV etc… have mismatching between input and output power.

![Power conversion system diagram]

- Bucky electrolytic capacitors are connected to DC-link to absorb power ripple of double frequency of power grid.

Principle of Active power decoupling

- How to reduce the capacitor in DC-link
  - Capacitor voltage is actively oscillated instead of use of large capacitor.

![Diagram showing capacitor energy]

- Film capacitors or ceramic capacitors will be used instead of electrolytic capacitors
  - Long life time will be achieved due to no electrolytic capacitor

---

### Passive decoupling

- No cooling system
- No inductor

### Active decoupling

- Small capacitance
- Low rated voltage switches

### Pros

- No cooling system
- No inductor

### Cons

- Electrolytic capacitors are needed.
- High rated voltage switches
- Large capacitance

#### Comparison of these circuits in terms of efficiency and power density

<table>
<thead>
<tr>
<th>Power density [kW/dm³]</th>
<th>Efficiency [%]</th>
<th>Boost type</th>
<th>Buck type</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.8</td>
<td>99</td>
<td>Si-MOSFET 20 kHz</td>
<td>IGBT 15 kHz</td>
</tr>
<tr>
<td>17.0</td>
<td>99.9%</td>
<td>Si-MOSFET 20 kHz</td>
<td></td>
</tr>
</tbody>
</table>

#### Maximum parameter

- Passive: 18.8 kW/dm³
- Active: 17.0 kW/dm³

#### Efficiency

- Passive: 99.9%
- Active: 99.5%

Power density of conventional APD is 90% of that of passive topology.
Boost type vs. Buck type

- Minimum volume point is calculated in each rated power.

**Buck type < Boost type**
- CSPI = 3 °C/dm³ (Natural cooling)
- Switching frequency: 25 kHz

**Buck type > Boost type**
- CSPI = 3 °C/dm³ (Natural cooling)
- Switching frequency: 30 kHz

Best topology depends on rated power.
In high power, boost type is superior

Volume analysis

- Total volume of APD components is compared to electrolytic cap.

Boost inductor is dominated by 30% of total volume even though SiC device is used in APD.
Proposed circuit I: APD with indirect matrix converter

- Active clamp snubber in indirect matrix converter is used for APD operation
- APD is integrated to PFC

Points of the proposed circuit

- Only requiring a small capacitor and no additional a boost inductor
- The buffer switch (Sc) achieves the zero current switching


Operation principle

- Separating three parts
- Load current becomes current source for DC side
- Inverter becomes single-switch which is operated by zero vectors
- Switch Sc controls buffer capacitor voltage

Operation condition: $v_c > v_{IN}$

Charging: Inverter regenerates the power from load.
Discharge: Sc is turned ON

Input current is controlled by switch Sc and zero vectors of inverter
Operation waveforms at 1 kW

- **Conventional circuit**
  - C: 50μF only
  - Output current can not keep sinusoidal waveform (THD 49.8%)

- **APD circuit with IMC**
  - C: 50μF + SW
  - Input current THD 3.9%
  - Output current THD 5.1%
  - Sinusoidal output current waveform although the DC capacitor is only 50μF

---

**Experimental verifications**

- **Input power factor**
  - Input power factor of over 99% although diode rectifier is used
  - 99%

- **THD of input and output currents**
  - The minimum value
  - Input current THD 3.3%
  - Output current THD 6.7%
Proposed circuit II: APD integrated to chopper

- Proposed inverter achieves MPPT, grid connection and power decoupling capability

- Feature of proposed circuit
  - Small ac filter because proposed converter is current source type.
  - Capacitance value is reduced by controlling the voltage variation
    Capacitor voltage variation is not influence to the ripple of input and output

  Additional components are minimized for APD


Operation principle I: chopper mode

- Proposed converter is operated as boost chopper

- Mode1
  Input power is directly transferred to ac side

- Mode4
  Short circuit mode to keep input inductor current

APD circuit current pass does not appear in these modes
Operation principle II: Energy management mode

- Buffering power is controlled by mode 2 and 3

- **Mode 2**
  - Buffer capacitor is charged by connecting in parallel to input voltage

- **Mode 3**
  - Buffer capacitor is discharged by connecting in series to input voltage.

Buffer voltage is independently controlled.

---

Experimental verifications

- **Operation waveforms**

![Operation waveforms](image)

- Constant input current is obtained with 9.33% of input ripple.
- Sinusoidal output current is obtained with 4.2% of THD.
- Output power factor **99.9%**  Maximum efficiency **94.9%**
**Comparison of power density**

- Maximum power density of 1.8 times is obtained.
- Volume of buffer capacitor becomes 1/10 due to use of ceramic capacitor.
- Heat sink will be smaller if SiC device applied to proposed circuit.

---

**Proposed circuit III: APD integrated to chopper with DCM**

- Boost inductor is shared to APD operation.
- DCM is used for discharge of buffer capacitor $C_{buf}$.

Buffer voltage becomes higher than DC-link voltage = boost type.

※Current source: Single-phase VSI

**Average current of $i_l$ keeps constant**

Because DC input current $i_{in}$ should be constant direction, constant value.

---

Operation waveform

- **Without APD operation**
- **With APD**

Buffer capacitor voltage oscillates at 100 Hz.

100 Hz components in input current is suppressed by 96.8%.

Output power: 600 W

---

Volume comparison

DC-DC converter with power decoupling capability

- **Proposed circuit** achieves 1.1 times higher power density
- However total loss becomes 1.5 times higher
- BCM will be applied to improve the efficiency because conduction loss is dominated in total loss
Proposed circuit IV: APD integrated to chopper with DCM

- Boost inductor is shared to APD operation.
- Same concept to proposed circuit III
- Buffer voltage becomes lower than DC-link voltage = buck type

\[ C_{buf}: \text{Charging mode} \]

\[ C_{buf}: \text{Discharging mode} \]

- Only one switch from input voltage to DC-link
- Low voltage devices applied to APD
  - Low conduction loss


Operation waveforms

- Without APD operation
- With APD

- Buffer capacitor voltage oscillates at 100 Hz.

100 Hz components in input current is suppressed by 90.2 %.
Efficiency

- Efficiency is larger than 94% in region over 10% of rated power
- Max. efficiency is 96.0% at 600 W output

Comparison of each DC-DC converter with APD

- Pareto-front curve of power density and efficiency

Proposed circuit achieves:
- Volume of capacitors is reduced by 42.7%.
- 1.26 times higher power density is obtained
Neutral point voltage control in T-type inverter is used as APD capability. DCM is applied to ac current control.


Operation principle

Neutral point current is controlled for APD. Fundamental frequency of neutral point current is the same to grid frequency.

Output current is sum of APD current and reactive current. Time shearing to achieve both control at the same time.

Sum of APD and reactive current become zero at around 0 and π of grid voltage phase.
Operation waveforms

Without power decoupling

With power decoupling

2nd order harmonics in DC input current is reduced by 77%

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Motivation to use DCM

Problems: Inductor is bulky and expensive

Advantages of DCM are;
1) Use of small inductance with small volume
   - Peak current becomes double average current in boundary condition
   - Example: 1/10 of inductance, double peak current then, amount of energy 2/5
   - Volume is reduced by 60%

2) Low inductor loss due to optimum design
3) Small RMS current in light load under same average current

DCM is suitable for high power density converters

Problem and solution

Conventional method
- Nonlinear characteristic is compensated by inverse model of Transfer function
- Disadvantages:
  - Inductance-dependent
  - Difficult to design cut-off frequency
  - DCM Regeneration/Powering transition control has not been realized.

Proposed method
- Advantages:
  - Inductance-independent
  - Easy to design cut-off frequency
  - DCM Regeneration/Powering transition control is realized.

Experimental verifications

- Current command response

Powering and Regeneration

- Same current response is obtained with both CCM and DCM

CCM/DCM Syn. Switching: obtains maximum efficiency of 99.0% and Eff. over 98.7% at all load

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>200V</td>
</tr>
<tr>
<td>Output Power</td>
<td>1kW</td>
</tr>
<tr>
<td>Inductance</td>
<td>1.08 mH</td>
</tr>
<tr>
<td>Switching Freq.</td>
<td>20kHz</td>
</tr>
<tr>
<td>Cutoff Freq.</td>
<td>500Hz</td>
</tr>
</tbody>
</table>

Applying DCM to Single-phase inverter

- Single-phase Grid-Tied Inverter

- Mixed PWM using both CCM and DCM is used to suppress the peak current

- Input current distortion becomes higher because loop gain from command to current is different to each modulation.

- Modulation mode should be changed smoothly

Mode detection between CCM and DCM

**Conventional Method**
- Use $L$ to calculate $I_{BCM}$
- Use $I_{BCM}$ to detect mode

$$I_{BCM} = \frac{1}{L} \left( \frac{V_{in}}{V_{out}} - \frac{V_{in}}{2f_{sw}V_{out}} \right)$$

$\frac{I_{in}}{I_{BCM}} > 1$ : CCM, $\frac{I_{in}}{I_{BCM}} < 1$ : DCM

**Proposed Method**
- Use relationship between $Duty_{DCM}$ and $Duty_{CCM}$ to detect mode

Calculation of $Duty_{DCM}$ and $Duty_{CCM}$ does not require $L$.

Inductance-independent mode detection

**Relationship between duties in DCM and CCM**

<table>
<thead>
<tr>
<th>Duty ratio</th>
<th>Inductance Current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>0.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Transition point

Current value at boundary of CCM and DCM

**Control block diagram of proposed modulation**

Conventional CCM PI Controller

DCM Duty Generation

Current Mode Determination

Pervious duty value is used instead of induction value for nonlinear compensation.

**Characteristics of proposed control:**

1. *Does not use inductance value* to calculate $D_{DCM}$ \& $D_{CCM}$
2. *Use relationship between duties* to detect mode

Inductance-Independent CCM/DCM control is achieved
**Experimental and simulation verification**

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC link Voltage</td>
<td>$v_{dc}$</td>
<td>350 V</td>
</tr>
<tr>
<td>Grid Voltage</td>
<td>$v_g$</td>
<td>200 Vrms</td>
</tr>
<tr>
<td>Nominal Power</td>
<td>$P_n$</td>
<td>4 kW</td>
</tr>
<tr>
<td>Grid Frequency</td>
<td>$f_g$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>$f_{sw}$</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Dead Time</td>
<td>$T_{deadtime}$</td>
<td>500 ns</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>$f_{samp}$</td>
<td>25 kHz</td>
</tr>
<tr>
<td>Crossover Frequency</td>
<td>$f_c$</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Phase Margin</td>
<td>$PM$</td>
<td>60°</td>
</tr>
</tbody>
</table>

**LCL Filter Design**

<table>
<thead>
<tr>
<th>Case</th>
<th>Grid Inductance</th>
<th>Inverter-side Inductance</th>
<th>Grid-side Inductance</th>
<th>Filter Capacitance</th>
<th>Capacitance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$L_g$ 160 H</td>
<td>$L$ 16 µH</td>
<td>$L_f$ 10 µH</td>
<td>$C$ 4 µF</td>
<td>$n$ 1.5</td>
</tr>
<tr>
<td>II</td>
<td>$L_g$ 10 H</td>
<td>$L$ 16 µH</td>
<td>$L_f$ 16 µH</td>
<td>$C$ 16 µF</td>
<td>$n$ 1.5</td>
</tr>
<tr>
<td>III</td>
<td>$L_g$ 10 H</td>
<td>$L$ 16 µH</td>
<td>$L_f$ 16 µH</td>
<td>$C$ 16 µF</td>
<td>$n$ 1.5</td>
</tr>
</tbody>
</table>

**Case I**

$L_g = 580 \mu H$ (%$Z_L = 1.8\%$)

$V_{ol} = 856 \text{ cm}^2 (1.0 \text{ p.u.})$

%$Z = 1.8\%$

**Case II**

$L_g = 160 \mu H$ (%$Z_L = 0.5\%$)

$V_{ol} = 401 \text{ cm}^2 (0.47 \text{ p.u.})$

%$Z = 0.5\%$

---

**Operation in normal grid**

Conventional controller, %$Z_L = 1.8\%$

- Grid voltage $v_g$ (500 V/div)
- Grid-side current $i_g$ (40 A/div)

Proposed controller, %$Z_L = 1.8\%$

- Grid voltage $v_g$ (500 V/div)
- Grid-side current $i_g$ (40 A/div)

Conventional controller, %$Z_L = 0.5\%$

- Grid voltage $v_g$ (500 V/div)
- Grid-side current $i_g$ (40 A/div)

Proposed controller, %$Z_L = 0.5\%$

- Grid voltage $v_g$ (500 V/div)
- Grid-side current $i_g$ (40 A/div)

Proposed controller reduces the zero-crossing current distortion
Operation in weak grid for case II & III

Pole trajectory

Filter design using pole trajectory enables achieve desired stability with lowest damping loss

Proposed controller, %ZL=0.5% R=16 ohm

Inverter Side Current

Inverter Side Current

Proposed controller, %ZL=0.5% R=8 ohm

Filter Capacitor Voltage

Filter Capacitor Voltage

Power Electronics Lab.

Applying DCM to Three-phase inverter

Inverter Output Current

Zero-crossing distortion occurs in output current as same to single-phase inverter because DCM appears by dead-time

Without dead time

With dead time

DCM employs whole period to reduce distortion

How to apply proposed DCM to three-phase

- **Time sharing control**

Considering interval $0^\circ$~$60^\circ$

Desired current waveform

Proposed method splits control of $i_u$ and $i_w$ into 2 intervals:

(i) $D_1$ and $D_2$ control $i_u$

(ii) $D_3$ and $D_4$ control $i_w$

Each phase current is individually controlled.

Operation of proposed DCM control (700W prototype)

- **u-phase voltage and INV currents**

u-phase voltage (100 V/div)

Grid phase voltage (50 V/div)

THD = 2.4%

- **Grid voltage and grid voltage**

DCM operation is achieved in whole period.
Step response & Current THD characteristic

Quick, stable step response, and Current THD below 5% are obtained at rated load → Good control performance

Efficiency Characteristics Comparison

Compared to asynchronous switching, synchronous switching reduces loss by 33.3% at rated load
Contents

1. Introduction
   - Importance of minimization of passive components
2. Approach I: Matrix converter
   - Circuit topology and features
   - Latest technologies: Three-phase to Single phase-
   - Matrix converter in Market: general purpose drive/air conditioner/quick charger
3. Approach II: Active power decoupling for Single-phase converter
   - Principle
   - Integrated to PFC or Inverter
   - Integrated to Chopper
4. Approach III: Discontinuous Current Mode converter
   - Principle: Robustness for inductor
   - Single-phase inverter with DCM
   - Three-phase inverter with DCM
5. Approach IV: FRT capability of grid-tied inverter with minimized inductor
   - Mr. Nagai presents his projects
6. Conclusion

Current overshoot suppression during Fault Ride-through for Three-phase Grid-tied Inverter with Low Inductance

Satoshi Nagai, Jun-ichi Itoh
Nagaoka University of Technology, Japan

Abstracts

- Occurrence of current overshoot with low inductance
  => Update delay of inverter output at voltage drop and recovery

- Proposed method: Current overshoot is suppressed with the high-speed update of the inverter output voltage.

- The current overshoot is suppressed to less than 150% in the low inductance (%Z = 0.38%) with the proposed method.
Background

- Minimization of system volume with high switching frequency
- Applying SiC or GaN devices to grid-tied inverter

The inductor achieves small size by reducing the inductance.

**Problem**

- Low inductance
- Reduction of disturbance suppression performance

**Application**

- Solar cell*¹
- Power conditioning system

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*¹ https://biblion.jp/articles/ADTUP


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FRT requirements

- Grid-tied inverters stop at grid disturbance
- Black out
- Continuous operation is necessary without disconnection from grid

(FRT: Fault Ride Through)

**FRT requirements**

- Period of voltage sag less than 150 ms: FRT is necessary*³
- Current overshoot rate at voltage recovery: Less than 150%*⁴

**Decision of FRT / Disconnection (E. ON code)**


Problem for FRT with low inductance

- Requirement of grid-tied inverter
  - Continuing operation during grid fault
- FRT operation with low inductance
  - Inverter operation stops due to over current protection.

**Purpose**
- Minimization of inductor
- Suppression of current overshoot

Principal of current overshoot at voltage sag

- The inductor voltage \( v_L \) is increased due to an update delay of the inverter output voltage \( v_{inv} \) at the voltage drop and recovery.

**Steady state**

\[
\begin{align*}
  v_L &= v_{inv} \\
  i_L &= -\frac{v_{ac}}{L}
\end{align*}
\]

**At voltage drop**

\[
\begin{align*}
  v_L &= v_{inv} \\
  i_L &= -\frac{v_{ac}}{L} \Delta t
\end{align*}
\]

**At voltage recovery**

\[
\begin{align*}
  v_L &= v_{inv} - v_{ac} \\
  i_L &= -\frac{v_{ac}}{L} \Delta t
\end{align*}
\]

Inductor voltage \( v_L \): Large \(\Rightarrow\) Occurrence of inductor current overshoot

Conventional FRT: Large update delay of output voltage \( \Delta t \)

The current overshoot increases with the low inductance.

The update delay should be reduced to suppress the current overshoot.
Conventional FRT control (Command change)

- Reactive current control*3
  => Adjustment of reactive current toward voltage drop level

- Command limiter*5
  => Suppression of maximum current during voltage sag

Impossible to update inverter output with high-speed at voltage drop and recovery

The current overshoot is increased by applying the low inductance.


Current command limiter*5

Conventional FRT control (high-speed control)

- Current control with 1 MHz-PLL and dead-beat control*6

  Dead-beat control: Output current follows in one sampling period. (100 kHz sampling)

  1 MHz-PLL: Multi rate sampling (6.7 kHz to 1 MHz)

Achieving high-speed tracking to current command

=> It is impossible to suppress the current overshoot in less than the sampling period (10 μs).

Proposed current overshoot reduction during FRT

- Current overshoot reduction with high-speed update of inverter output at voltage drop and recovery

![Voltage vector diagram](image)

Current overshoot is reduced
=> Counter voltage vector
   (Achieving by gate-block operation)

Output vector: Same as grid voltage
=> Current slope becomes zero

The current overshoot is suppressed with the proposed vector at voltage drop and recovery.
=> Then, the high-speed voltage sag detection is necessary.

High-speed voltage sag detection method

- Voltage sag is detected by HPF and comparator.
- Voltage drop and recovery signals are generated in FPGA.

\[(x = a, b, c)\]

- Analog circuit: HPF \( V_{ac, in} \), comparator \( V_{ac, th} \), and high period of output signal \( V_{drop, det} \) for carrier period.
- FPGA threshold: 5 times for HPF maximum output during rated operation

Signal for the proposed operation is generated by HPF output overshoot at grid voltage drop and recovery.
Inductance design to meet FRT requirements

- Inductance is designed with proposed FRT operation.
- Inductor current overshoot rate is less than 150% for rated inductor current peak at voltage recovery.

**Rated current peak**

\[
i_{L-1} = -I_L
\]

**Transient current**

\[
i_{L-2} = \frac{V_{ac}}{L} t
\]

Inductor current overshoot

\[
i_L = -I_L - \frac{V_{ac}}{L} t
\]

Minimized inductance design

\[
L = \frac{V_{ac}}{I_{L-th} - I_L t_{bd}}
\]

Rated current peak: 4.0 A

Grid voltage peak: 163 V

\[u(t): \text{unit step function}\]

Inductance \(L\) is designed to 0.48 mH (\(\%Z = 0.38\%\))

<table>
<thead>
<tr>
<th>Design conditions</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>150% of rated current peak (I_{L-th})</td>
<td>6.0 A</td>
<td></td>
</tr>
<tr>
<td>Delay time of output voltage update</td>
<td>(t_{bd})</td>
<td>6.0 (\mu s)</td>
</tr>
</tbody>
</table>

Experimental condition

- Voltage sag: down to 0 V

- Using programmable power source: Voltage drop and recovery occur at voltage peak.

Experimental conditions

<table>
<thead>
<tr>
<th>Output power</th>
<th>(P_{out})</th>
<th>1 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier freq.</td>
<td>(f_{cry})</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Inductance ((%Z))</td>
<td>(L)</td>
<td>0.48 mH (0.38%)</td>
</tr>
<tr>
<td>GB delay time</td>
<td>(t_{delay})</td>
<td>(&lt; 6 \mu s)</td>
</tr>
</tbody>
</table>

Line to line: 200 V\(_{rms}\)

Programmable AC power source

Verification in maximum-current-overshoot condition
Comparison of current overshoot at voltage drop

Comparison between conventional and proposed FRT method

With only reactive current control

With prop. method

The current overshoot at the voltage drop is reduced to 230%.

Voltage recovery with prop. method (a phase peak)

With counter voltage vector (gate-block) => Current overshoot due to command tracking

With Prop. method

The current overshoot with prop. method is reduced to 46%.
Conclusion of FRT

Current overshoot suppression during Fault Ride-through for Three-phase Grid-tied Inverter with Low Inductance

- Considering current overshoot suppression at voltage drop and recovery with low inductance
  - The FRT operation was achieved with the proposed method without disconnection from grid.
  - The proposed method achieved the high-speed update of the inverter output voltage.
    - Inverter side inductance: 0.38%
    - Current overshoot rate: Less than 150%

Future work

Verification of asymmetrical voltage sag operation

Conclusion

1. Introduction
   - Minimization of passive components is important more and more to obtain high power density
2. Matrix converter is one of candidate to eliminate DC cap.
   - Products in market: general purpose drive/air conditioner/quick charger
3. Active power decoupling is effective for Single-phase converter
   - It is important to integrate APD to PFC, inverter, or chopper to realize high power density
4. Discontinuous Current Mode converter is good way to minimize inductors.
   - Inductance-Independent CCM/DCM control is achieved for single-phase and three-phase inverters
5. FRT capability of grid-tied inverter becomes important when minimized inductor is used.
   - High speed gate block method is one of solution to meet FRT standard.
Thank you for your kind attention

Thousand of Japanese sake bottles are waiting for you when you visit Japan.