DC–DC Converter for DC Distribution and DC Microgrids

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Outline

Background
–DC distribution in telecom buildings and data centers–

Issues to be resolved
–Energy saving toward low carbon society–

Approach to high power density DC–DC converter
–ISOP and IPOS topology of modular converters–

Conclusions
Background
–DC distribution in telecom buildings and data centers–
Facilities in NTT Telecom. Bldg.

- NTT DoCoMo Yoyogi Bldg.
- Yokohama Media Tower
- Management system
- Telecom system
- Computer/IT system
- Storage system

- Air Conditioning
- VRLA Battery
- Access to Electricity
- Commercial Power
- Vehicle with Back-up Power
- Rectifier (RF)
- UPS
- Gas Turbine Engine
- DC
- AC

- Access to Electricity
DC distribution is applied for telecom buildings and data centers.

- **1950**
  - **Switching Equipment**: Step by Step Switching
  - **DC Power Supply Technology**: Flood–type Lead Acid Battery

- **1960**
  - **Switching Equipment**: Crossbar Switching
  - **DC Power Supply Technology**: Thyristor

- **1970**
  - **Switching Equipment**: Electric Private Branch Exchange
  - **DC Power Supply Technology**: End Cell, Silicon Dropper

- **1980**
  - **Switching Equipment**: Digital Switching (D70/ISM/RT)
  - **DC Power Supply Technology**: Booster Converter, Voltage Compensator

- **1990**
  - **Switching Equipment**: ASM/SBM/RSBM
  - **DC Power Supply Technology**: Valve Regulated LA

- **2000**
  - **Switching Equipment**: NGN
  - **DC Power Supply Technology**: Lithium–ion

- **2010**
  - **Switching Equipment**: None
  - **DC Power Supply Technology**: None

From “Centralized” to “Distributed”

- **48V Centralized Power Supply**
  - Voltage Compensation
  - End Cell
  - Se
  - Power Supply for “Centralized” based on Thyristor Technology

- **48V Distributed Power Supply**
  - Voltage Compensation
  - Silicon Dropper
  - Si
  - Power Supply for “Distributed” based on Power Transistor technology

- **380V Power Supply**
  - Voltage Compensation
  - Booster Converter
  - Si–SJ, SiC
  - Power Supply for “380V” based on SiC technology

NTT (Nippon Telegraph and Telephone) History Center of Technologies: [http://www.hct.ecl.ntt.co.jp/index.html](http://www.hct.ecl.ntt.co.jp/index.html)
Power density of DC–DC converters in NTT

- A Rectifier consists of PFC (Power Factor Correction) circuits and isolated DC–DC converters.

- Power density of DC–DC converters has been increasing
  - Higher switching frequency by using power transistors
  - Higher voltage and lower supply current by SiC power devices

![Circuit configuration of rectifier](image)

![Power density V.S. efficiency of DC–DC converter in rectifier](image)
Issues to be resolved
–Energy saving toward low carbon society–
Energy saving in telecom bldg. and data centers

- NTT has proposed “THE GREEN VISION 2020” toward low carbon society.
  - Energy saving of 100 TWh per year will be achieved in 2025 (Green of ICT).
  - In telecom buildings and data centers, energy saving of 23.5 TWh (30% in 2025) has to be accomplished.

*ICT: Information and Communication Technology

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**Power consumption in whole ICT fields**

Energy saving in DC distribution system

- To realize 30% energy saving in telecom buildings and data centers, highly efficient power supply system is indispensable.
- Conversion efficiency of 94% is required from the front–end converter to the point of load converter.

Necessity of high performance converter

- High performance isolated DC–DC converters (or DC transformer: fixed voltage transfer ratio) are necessary.

<table>
<thead>
<tr>
<th></th>
<th>Target</th>
<th>DC–DC in rectifier</th>
<th>Aim</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>98%</td>
<td>97.5%</td>
<td>For Energy saving</td>
</tr>
<tr>
<td>Power density</td>
<td>10 W/cm³</td>
<td>2 W/cm³</td>
<td>To be installed into 19 inch rack with customer equipment</td>
</tr>
<tr>
<td>Transformer ratio</td>
<td>384 V–12 V and / or 48 V</td>
<td>384 V–384V</td>
<td>To connect POL (Point of Load) converters</td>
</tr>
</tbody>
</table>

- To achieve highly efficient and ultra compact converters,
  - Ultra–low loss and high–speed novel power devices such as SiC and GaN are attractive.
  - High frequency operation of novel power devices contributes to minimizing passive components.
    - Series–parallel connection topology of highly integrated DC–DC converters is one of options.

- To realize flexible transformer ratios,
  - Series–parallel connection topology of modular DC–DC converters is one of options.
Approach to high power density DC–DC converter—ISOP and IPOS topology of modular converters—
ISOP–IPOS topology

- Higher input voltage can be injected in ISOP (Input Series and Output Parallel) topology.
- IPOS (Input Parallel and Output Series) topology makes higher output voltage.
  - Conversion efficiency depends on an isolated DC–DC converter (low-voltage and low-power) module.
DC–DC converters in R&D

- Gong, Xi’an Univ., PESC2008
  Synchronous Full Bridge

- Biela, ETHZ, INTELEC2007
  Series Parallel Resonant

- Miftakhutdinov, TI, INTELEC2008
  Synchronous Full Bridge

- Sun, CPES, PESC2006
  Switched Capacitor

- Omura, Toshiba, PCC2007
  Step-down

- Eckardt, Fraunhofer, CIPS2006,
  Step-down

- Pavlovsky, Yokohama N. Univ.,
  PESC2008, SAZZ

Isolated DC–DC Converter

Non–Isolated DC–DC Converter
Example

- Power density and conversion efficiency of a high voltage high power converter are compared with low voltage low power one.
- Single 256 V–384 V converter with SiC power devices
- A 256 V–384 V converter using eight 32 V–48 V converters with GaN power devices

\[ \eta = \frac{P_{OUT}}{P_{IN}}, \quad P_d = \frac{P_{OUT}}{VOL_{CONV}} \]

\[ \eta' = \frac{N \cdot P_{OUT}'}{N \cdot P_{IN}'}, \quad P_d' = \frac{N \cdot P_{OUT}'}{N \cdot VOL_{CONV}'} = \frac{P_{OUT}'}{VOL_{CONV}'} \]
Experiments of non–isolated converters

**SiC Power Devices**
- TO247 packages
- 1200V, 80mΩ

**Input Inductor**

**Output Capacitor**

**Experimental Results of a 256V–384V converter using SiC–MOSFET (CREE)**

- Gate to Source Voltage (0 V-5 V)
- Drain to Source Voltage (0 V-48 V)
- Input Current (9.0A)
- Output Current (6.0A)

**GaN Power Devices**
- Bare chips
- 100V, 7mΩ

**Input Inductor**

**Output Capacitor**

**Experimental results of a 32V – 48V converter using GaN–FET (EPC)**

- Gate to Source Voltage (0 V-5 V)
- Drain to Source Voltage (0 V-48 V)
- Input Current (14.1A)
- Output Current (9.3A)
Input voltage balance in ISOP topology

- Input voltages of converters balances ideally.
  - Mismatch of output impedances causes the input voltage unbalance under real circuit operation conditions.
- Imbalance of input voltages were calculated when output impedances vary from 1% to 5% in eight converters.
  - Input voltages vary 2% from the rated voltage (48 V ± 1V), and the influence is negligible.

![Schematic Diagram of Series-Parallel Connected Converters](image-url)

\[
\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (Z_i - Z_{\text{ave}})^2
\]

- \(\sigma^2\): Variance
- \(N\): Number connected in series
- \(Z_i\): Output Impedance of converter No.i
- \(Z_{\text{ave}}\): Average of output impedances

Input Voltage Unbalance in Series Input Parallel Output Converter

Variation from Initial 3% Impedance [%]

Variation from Rated Voltage [%]

0 0.5 1 1.5 2 2.5

97 98 99 100 101 102 103

Conv. Voltage (Max.) Conv. V. (Min.) Output Voltage

+2% -2%
ISOP and IPOS converter prototypes

- A 384 V–384 V 2.4 kW consists of eight 384 V–48 V modules connected in IPOS.
  - Maximum efficiency was 95.5% at full load.
- A 384 V–48 V 2.4 kW consists of eight 48 V–48 V modules connected in ISOP.
  - Maximum efficiency was improved from 95.5% to 96.7%
Sixty four 48 V–48 V 300 W converter modules (VICOR, V048F480T006) were utilized.

- A 384 V–48 V 2.4 kW consists of eight modules connected in ISOP.
- A 384 V–384 V 19.2 kW consists of eight 384 V–48 V 2.4 kW converters in IPOS.

Maximum conversion efficiency was 96.6% and the power density was 10 W/cm³ without fans.

- Maximum efficiency of each 48 V–48 V module is 96.7%.
• Start-up waveforms were measured under no load condition.
  • No input voltage unbalances were observed.
• Transient characteristics in rapid load variation were shown.
  • Input voltage fluctuation was within 100 ± 5 %.
84 V–12 V 98% Converter

- Eight 48 V–12 V converter modules (VICOR, IB048E120T40N1-00) were utilized to fabricate a 384 V–12 V 2.4 kW ISOP converter.
  - Maximum efficiency of each converter module is 98.2%.
- Maximum conversion efficiency was 98.1%.
  - Output voltages of 12 V, 48 V, 384 V are obtained by IPOS with 98% efficiency.
• In DC–DC converters for NTT telecom power supply, output power density has been increasing.
  • Higher conversion efficiency has been also achieved.
• The 384 V–384 V converter using 48 V–48 V converter modules connected in ISOP–IPOS achieved higher power density.
  • Higher efficiency has been also achieved by using 48 V–12 V converters
Conclusions

- DC distribution for telecom buildings and data centers was introduced.
  - Highly efficient DC power supply is indispensable to realize low carbon society.
- Availability of ISOP–IPOS topology was shown to realize highly efficient and ultra compact converters.
  - A 19.2 kW 384 V–384 V converter was fabricated by using sixty-four 48 V–48 V converter modules with the efficiency of 96.6%.
  - A 2.4 kW 384 V–12 V converter was fabricated by using eight 48 V–12 V converter modules with the efficiency of 98.1%.
  - I/O voltages are arbitrarily selected in ISOP–IPOS topology.
- DC–DC converters with ISOP–IPOS topology contribute to realizing highly efficient DC microgrids.
Thank you for your attention.
Power density and efficiency estimation

- Calculation results of efficiency and power density are shown.
  - Ideal circuit condition: Stored energy in $C_{OSS}$ is only considered to calculate switching loss energy
  - Real circuit condition: Parameters in the experiment is taken into account
- Higher power density will be achieved in the low voltage and low power converter

*Power density V.S. switching frequency*  
*Power density V.S. conversion efficiency*