DC–DC Converter for DC Distribution and DC Microgrids

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Outline

Background
–DC distribution in telecom buildings and data centers–

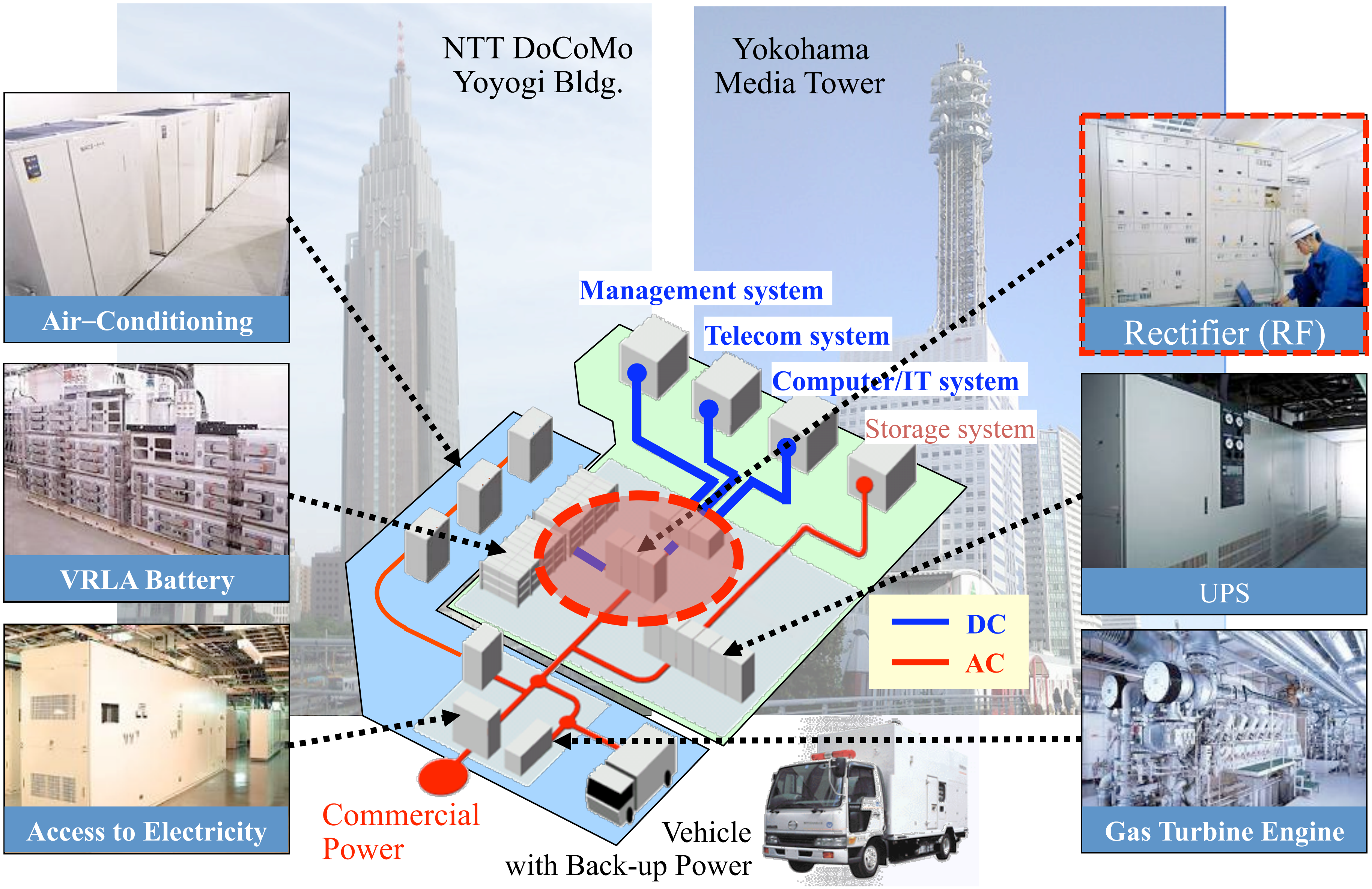
Issues to be resolved
–Energy saving toward low carbon society–

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.



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History of Rectifier in NTT

DC distribution is applied for telecom buildings and data centers.

	1950	1960	1970	1980	1990	2000	2010
Switching Equipment	Step by Step Switching	Crossbar Switching	Electric Private Branch Exchange		Digital Switching (D70/ISM/RT)	ASM/SBM /RSBM	NGN

DC Power Supply Technology

- ***48V Centralized Power Supply***: Se, Si, Thyristor; Flood–type Lead Acid Battery
- ***48V Distributed Power Supply***: Power Transistor, IGBT; Valve Regulated LA
- ***380V Power Supply***: Si–SJ, SiC; Lithium–ion
- Voltage Compensation: End Cell, Silicon Dropper, Booster Converter, Voltage Compensator

Rectifier for "Centralized" Power Supply based on Thyristor Technology

From "**Centralized**" to "**Distributed**"

Rectifier for "Distributed" Power Supply based on Power Transistor technology

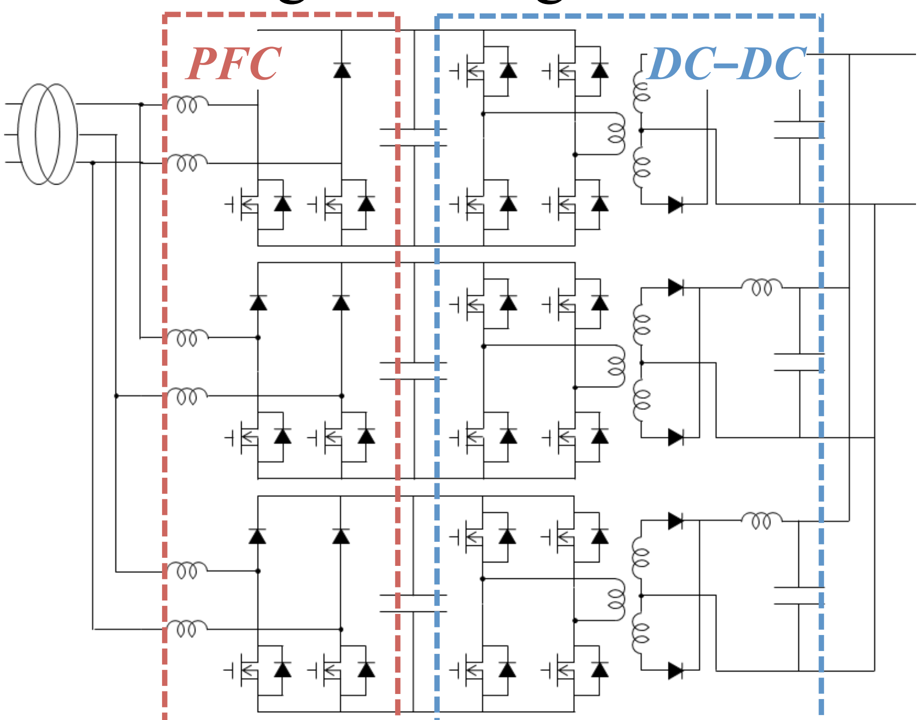
From "**48 V**" to "**380 V**"

Rectifier for "380V" Power Supply based on SiC technology

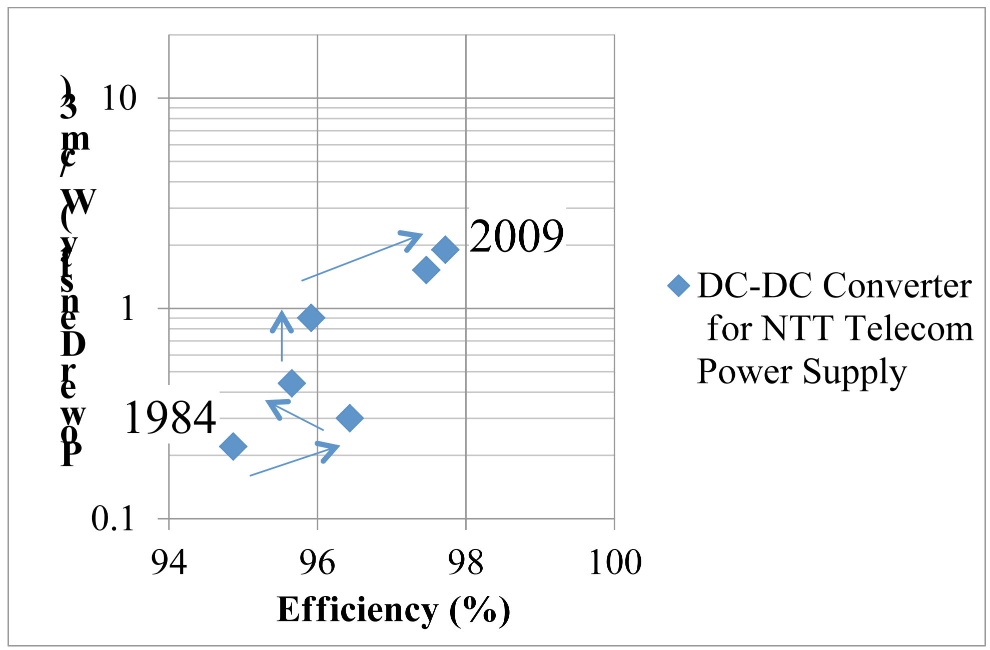
NTT (Nippon Telegraph and Telephone) History Center of Technologies: http://www.hct.ecl.ntt.co.jp/index.html

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

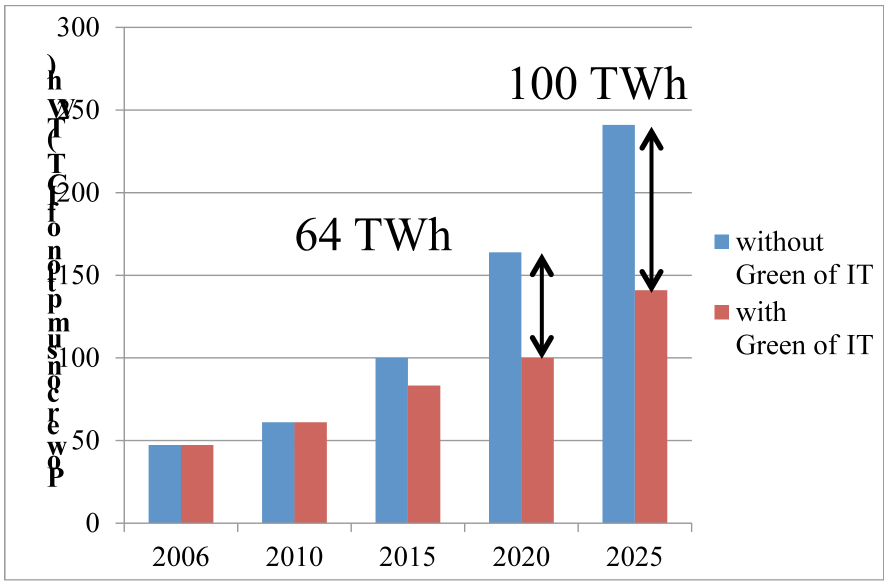


Power density V.S. efficiency of DC–DC converter in rectifier

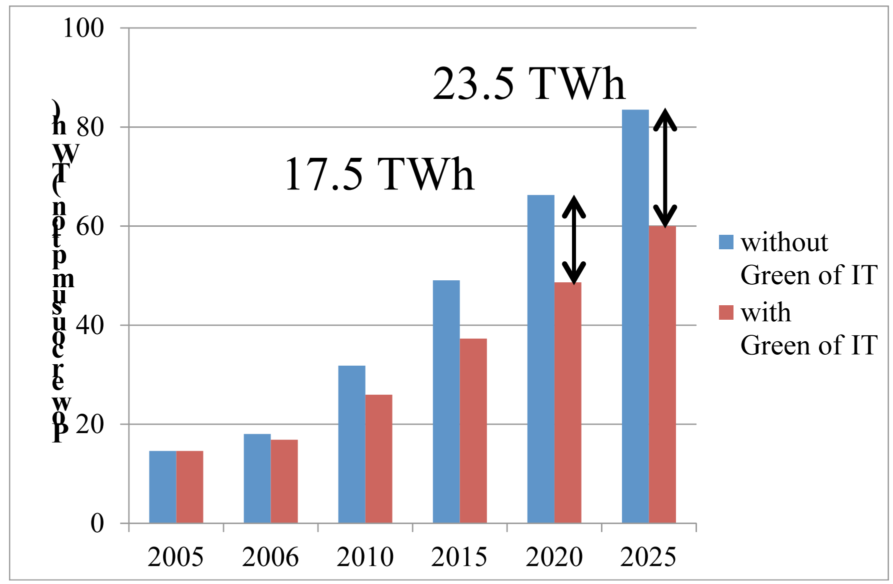
Issues to be resolved
–Energy saving toward low carbon society–

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.



Power consumption in whole ICT fields



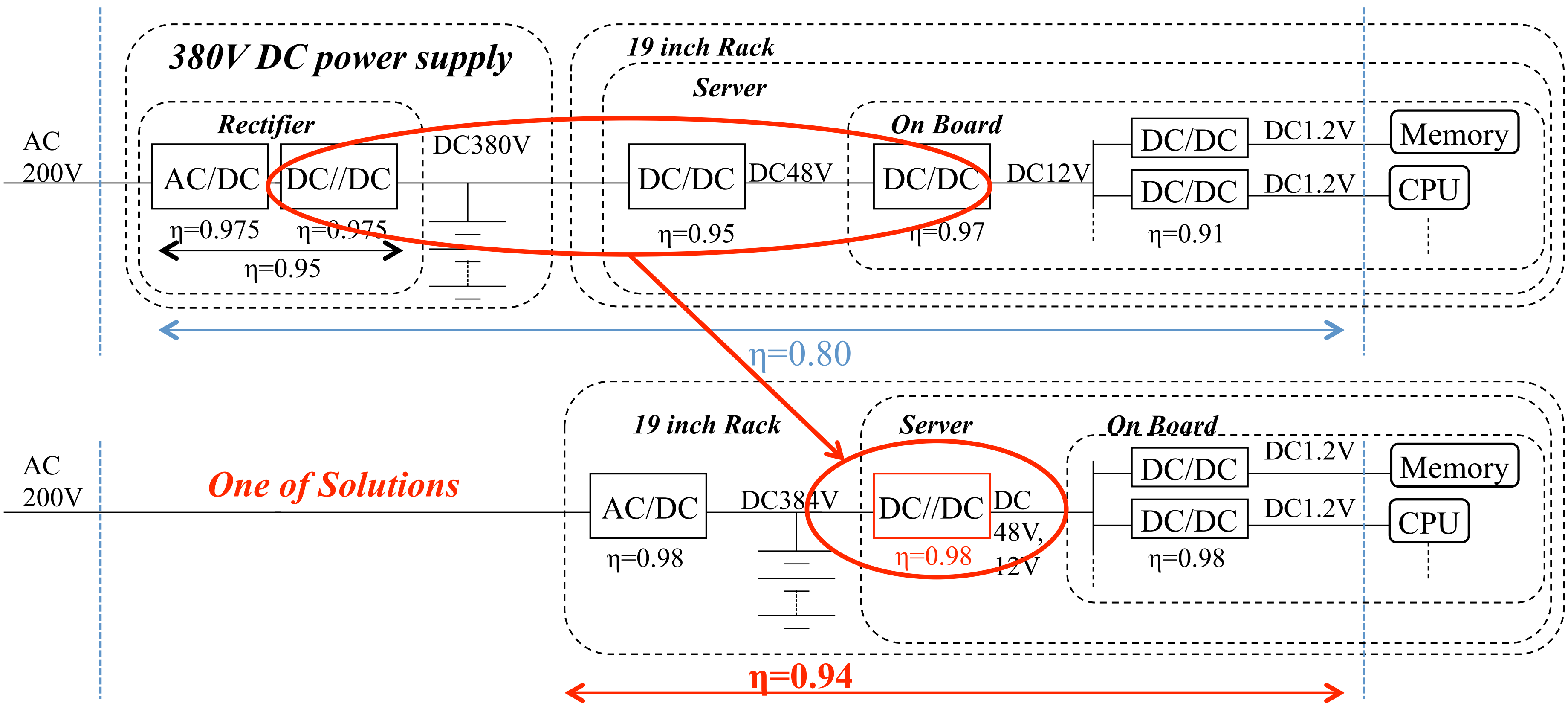
Power consumption in telecom buildings and data centers

-http://www.ntt.co.jp/csr/2010report/special/vision01.html
-Y. Sugiyama, "Green ICT toward Low Carbon Society-Green R&D Activities in NTT",
- Proceedings of 4th International Workshop on Green Communications, Kyoto, Japan, 2011.

*ICT: Information and Communication Technology

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.



-T. Ninomiya, Y. Ishizuka, R. Shibahara and S. Abe, "Energy–saving technology using next–generation power electronics", Proceedings of 2012 IEE–Japan Industry Applications Society Conference, Chiba, Japan, 2012 (in Japanese).

Necessity of high performance converter

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

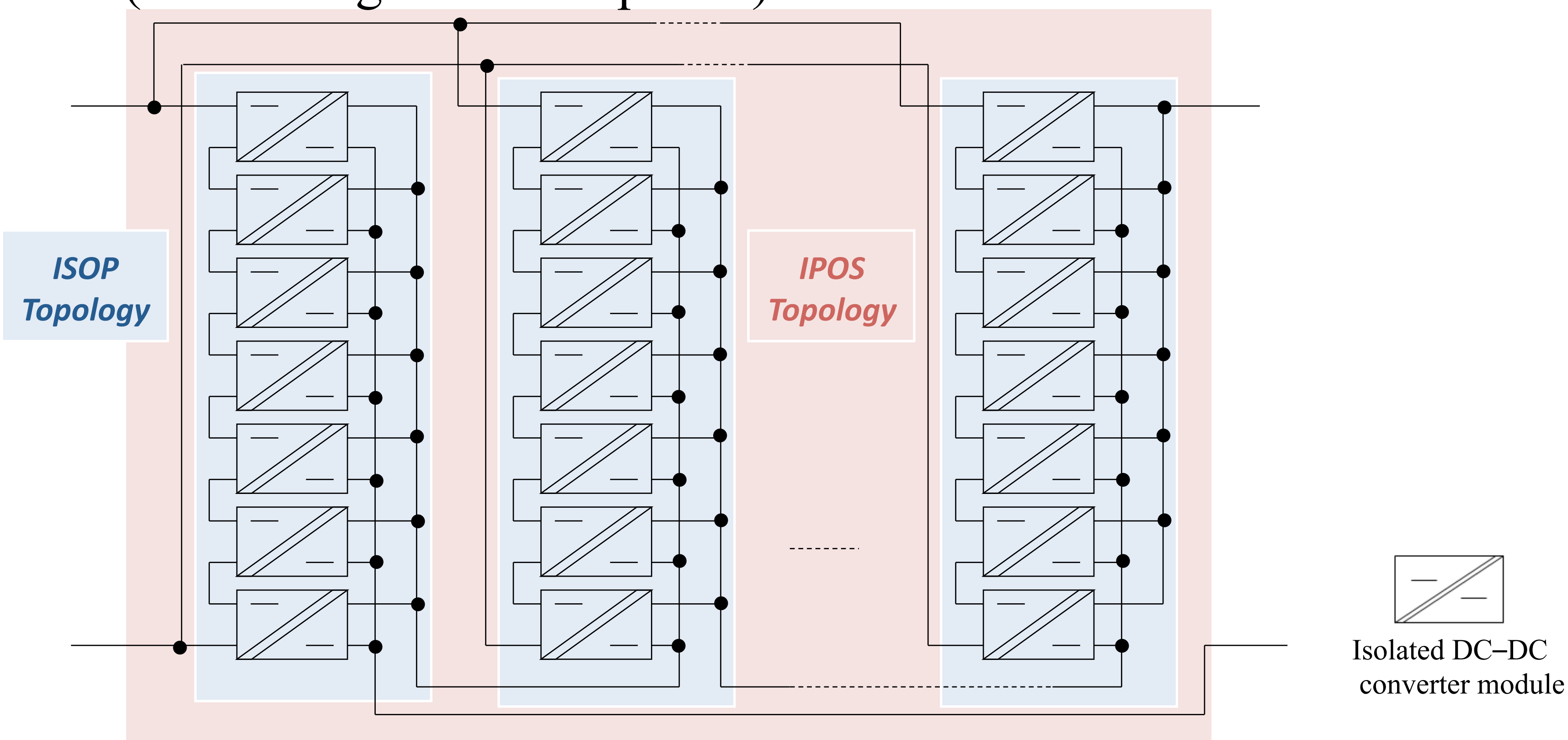
	Target	DC–DC in rectifier	Aim
Efficiency	**98%**	97.5%	For Energy saving
Power density	**10 W/cm^3**	2 W/cm^3	To be installed into 19 inch rack with customer equipment
Transformer ratio	**384 V–12 V and / or 48 V**	384 V–384V	To connect POL (Point of Load) converters

- 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.**

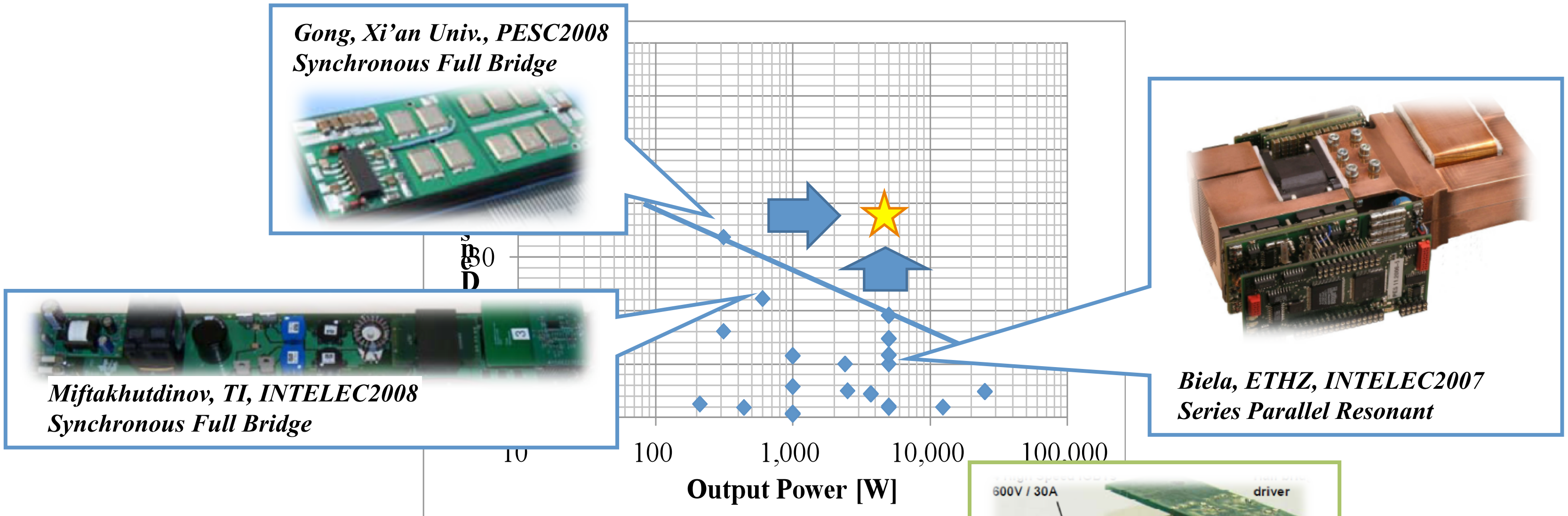
Approach to high power density DC–DC converter
–ISOP and IPOS topology of modular converters–

ISOP–IPOS topology

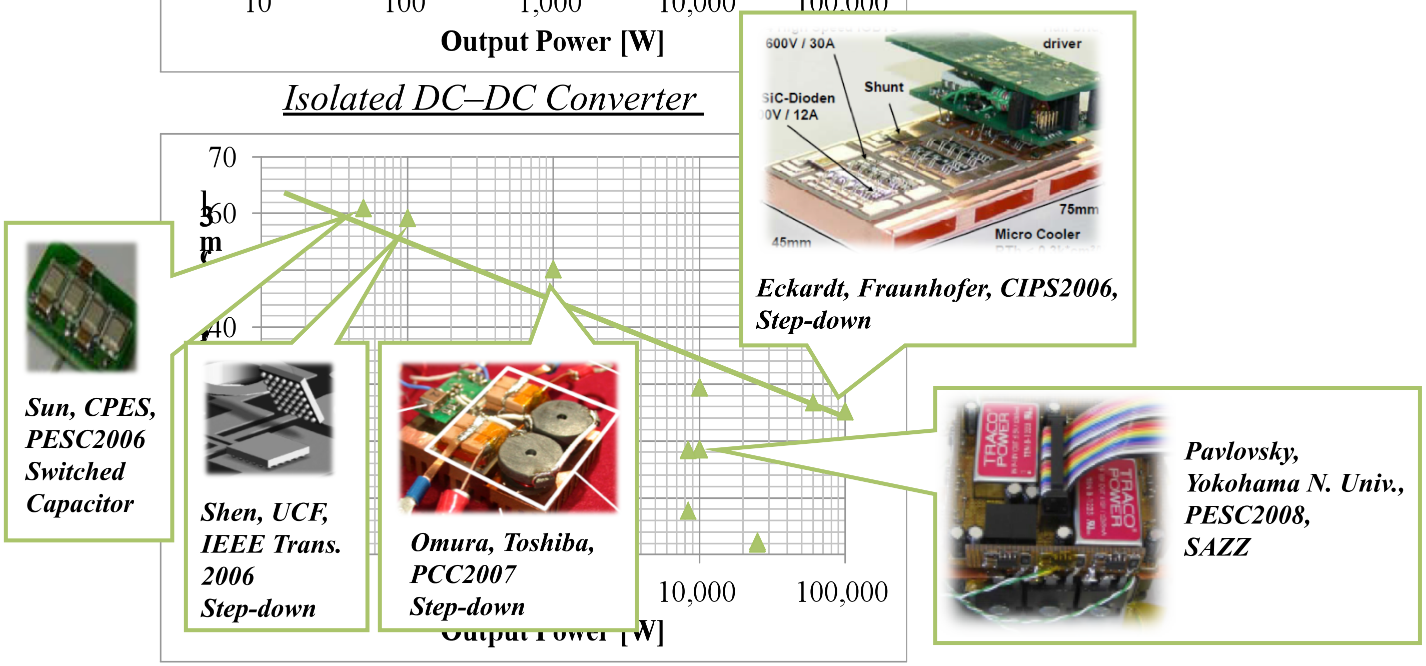
- Higher input voltage can be injected in ISOP (Input Series and Output Parallel) topology.
- IPOS (Input Parallel and Output Series) topology makes higher output voltage.
  - Conversion efficiency depends on an isolated DC–DC converter (low–voltage and low–power) module.



DC–DC converters in R&D



Isolated DC–DC Converter

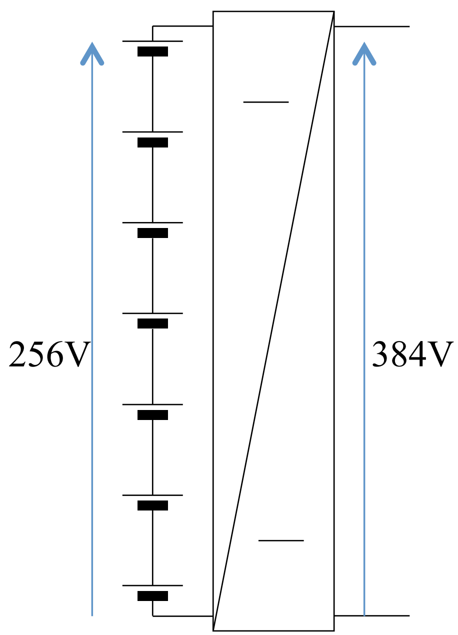


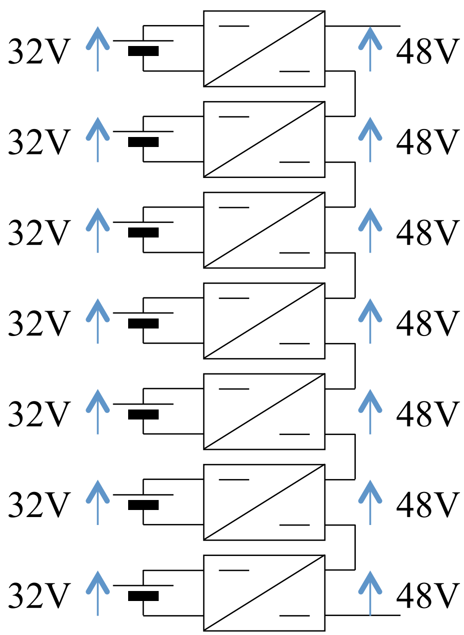
Non–Isolated DC–DC Converter

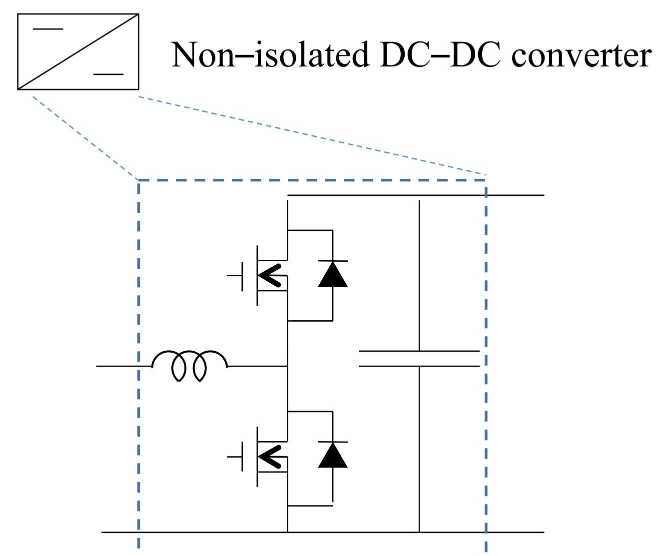
Example

- 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

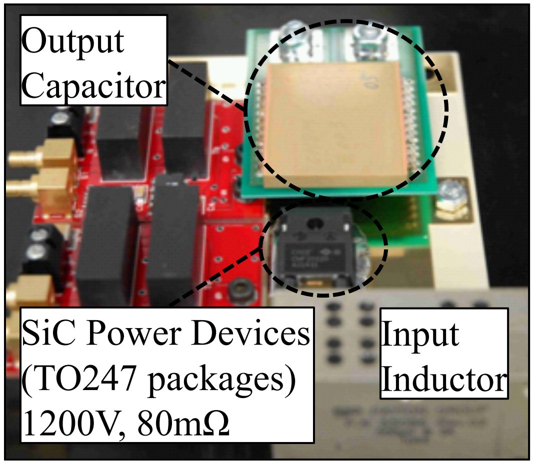
$$\eta = \frac{P_{OUT}}{P_{IN}}, \quad Pd = \frac{P_{OUT}}{VOL_{CONV}} \qquad \eta' = \frac{N \cdot P_{OUT}'}{N \cdot P_{IN}'} = \frac{P_{OUT}'}{P_{IN}'}, \quad Pd' = \frac{N \cdot P_{OUT}'}{N \cdot VOL_{CONV}'} = \frac{P_{OUT}'}{VOL_{CONV}'}$$

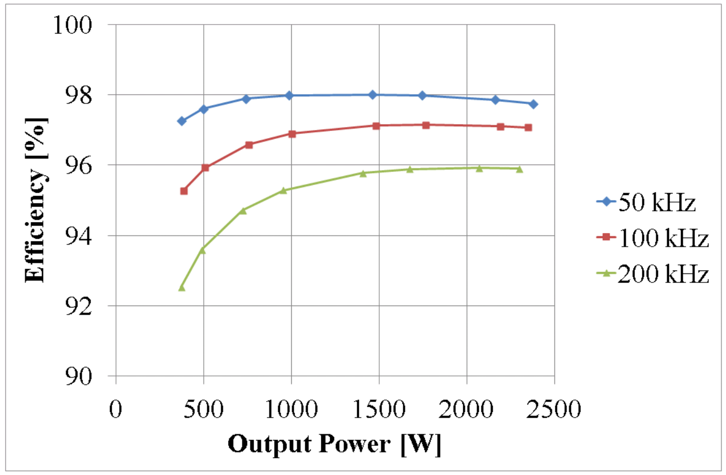


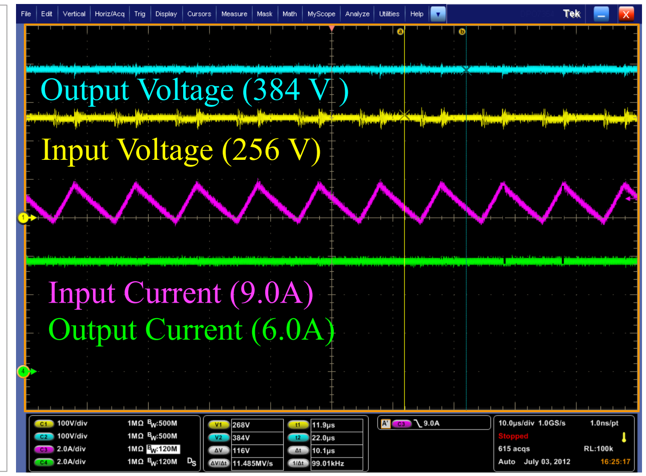




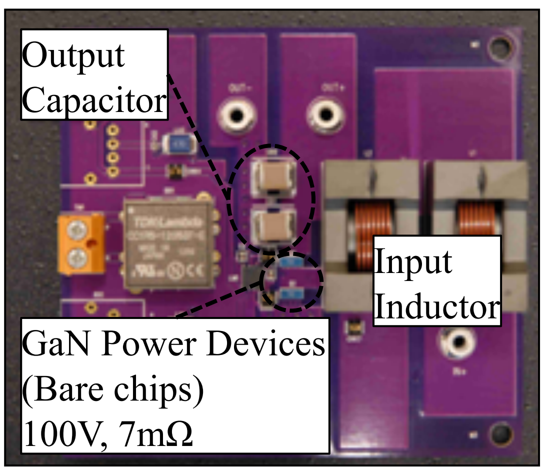
Experiments of non–isolated converters

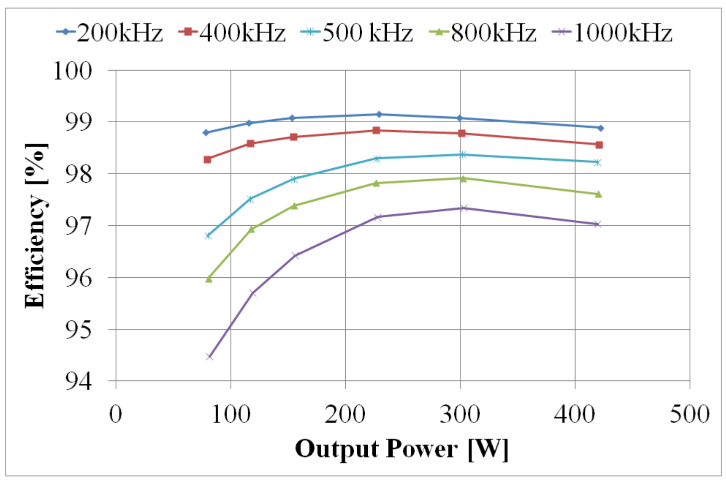


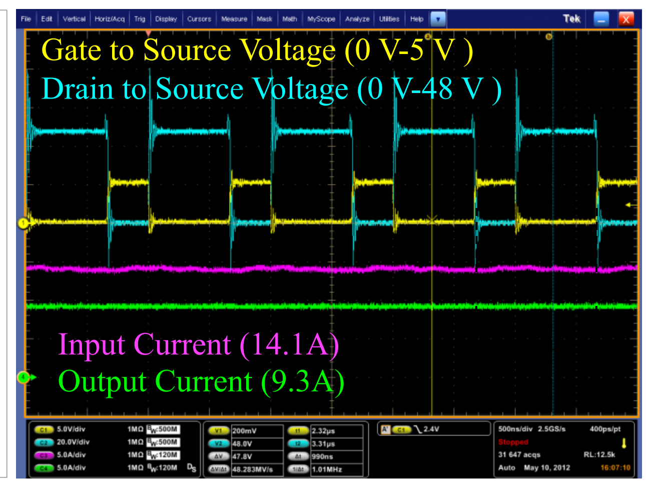




Experimental Results of a 256V–384V converter using SiC–MOSFET (CREE)



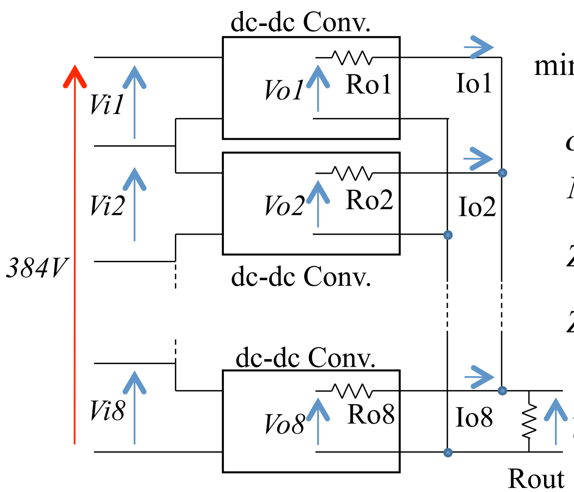




Experimental results of a 32V – 48V converter using GaN–FET (EPC)

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.



$$\min.\quad \sigma^2 = \frac{1}{N}\sum_{i=1}^{N}\left(Z_i - Z_{ave}\right)^2$$

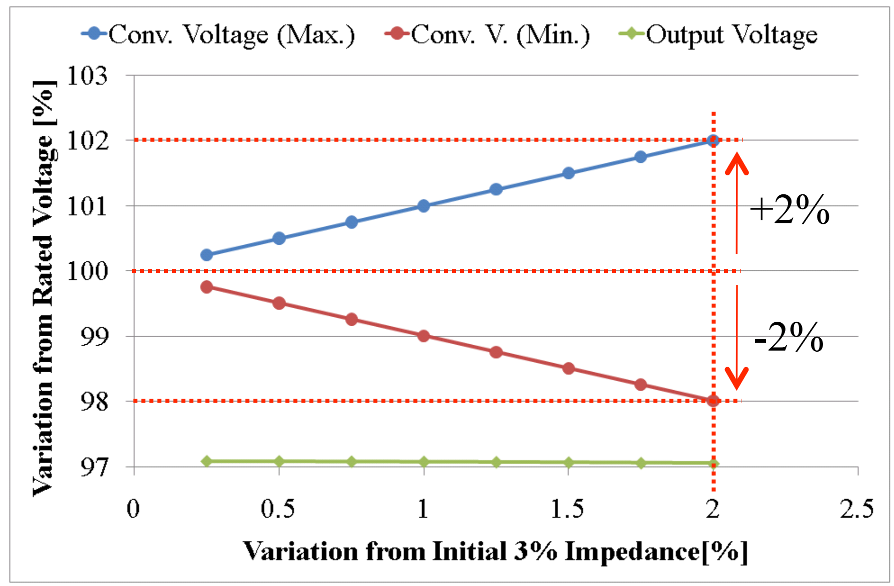
σ^2 : Variance

N : Number connected in series

$Z_i = \dfrac{Voi}{Ioi}$: Output Impedance of converter No.i

Z_{ave} : Average of output impedances

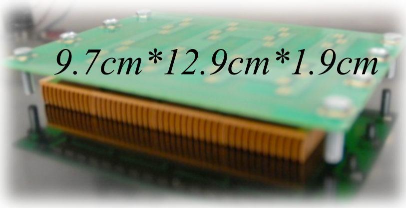
Schematic Diagram of Series-Parallel Connected Converters

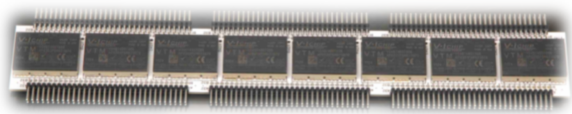


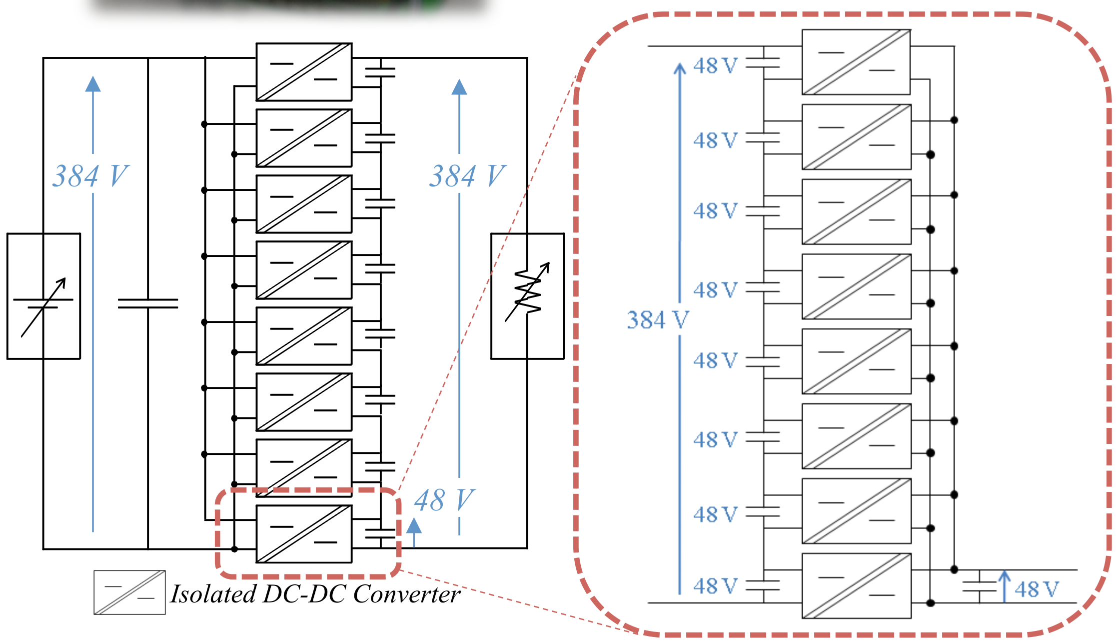
Input Voltage Unbalance in Series Input Parallel Output Converter

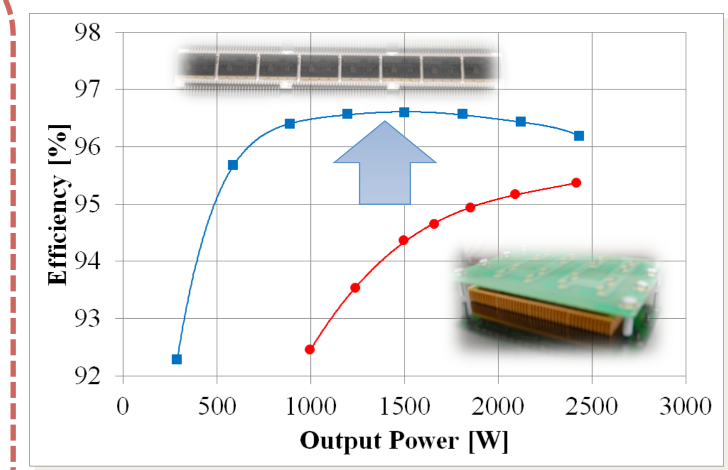
ISOP and IPOS converter prototypes

- 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 %







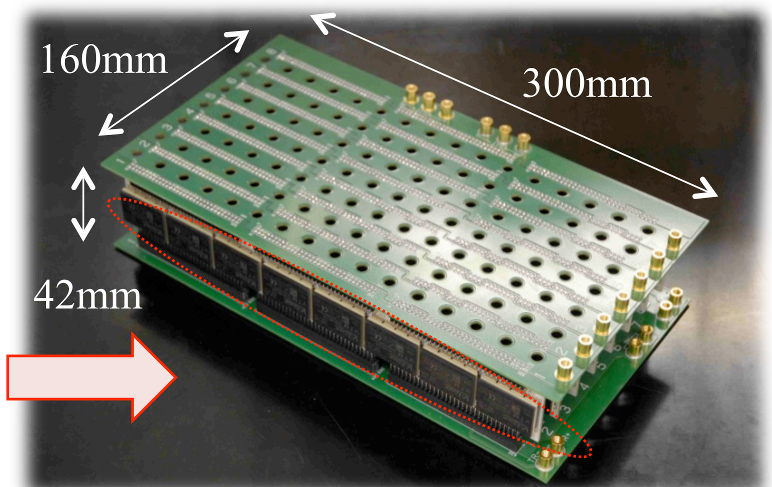


Conversion Efficiency

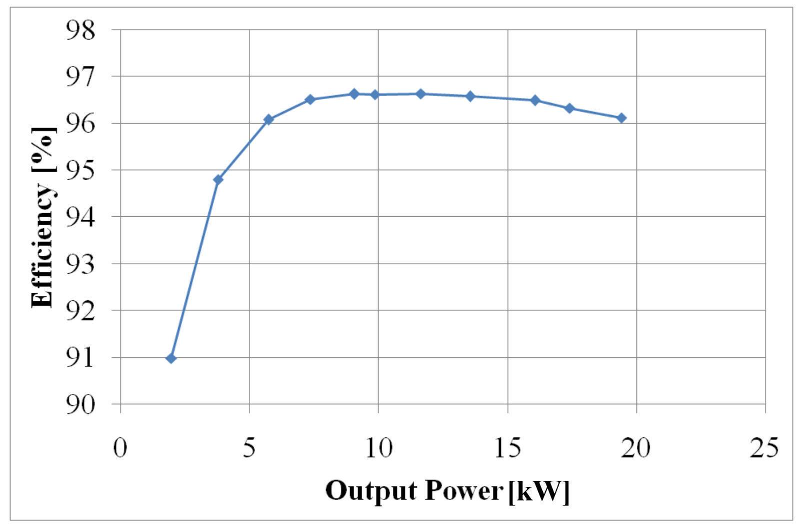
384 V–384 V 19.2 kW ISOP–IPOS Converter

- *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%.

384 V–48 V 2.4 kW ISOP converter



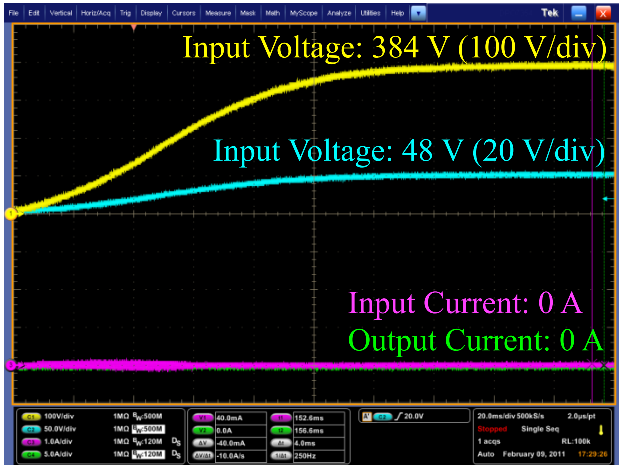
384 V–384 V 19.2 kW IPOS Converter using eight ISOP converters



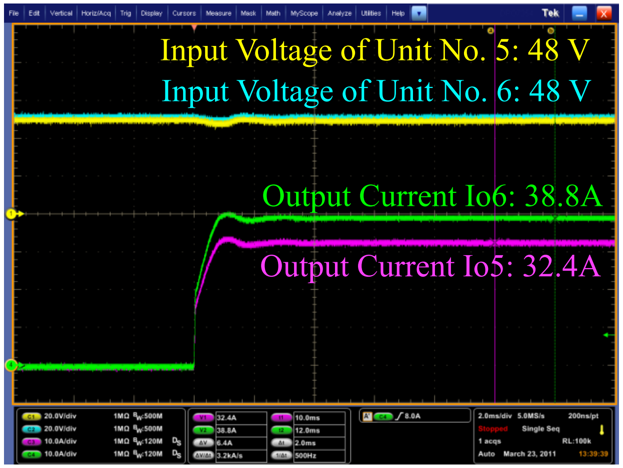
Conversion efficiency of 384 V–384 V 19.2 kW converter

Transient behavior of ISOP converter

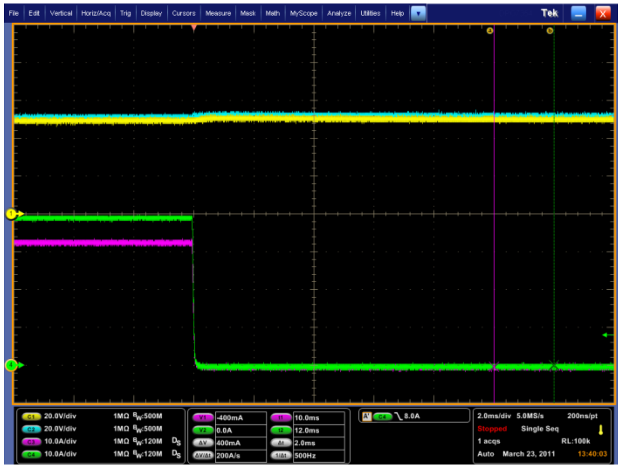
- Start-up waveforms were measured under no load condition.
  - No input voltage unbalances were observed.
- Transient characteristics in rapid load variation were shown.
  - Input voltage fluctuation was within 100 ± 5 %.



Start-up waveforms under no load condition



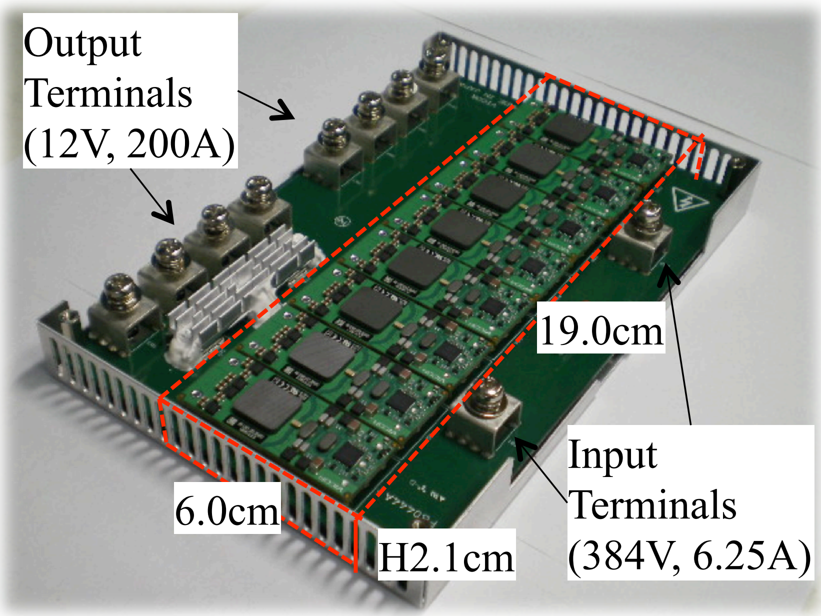
Rapid load variation (1ms, 0%→100%)



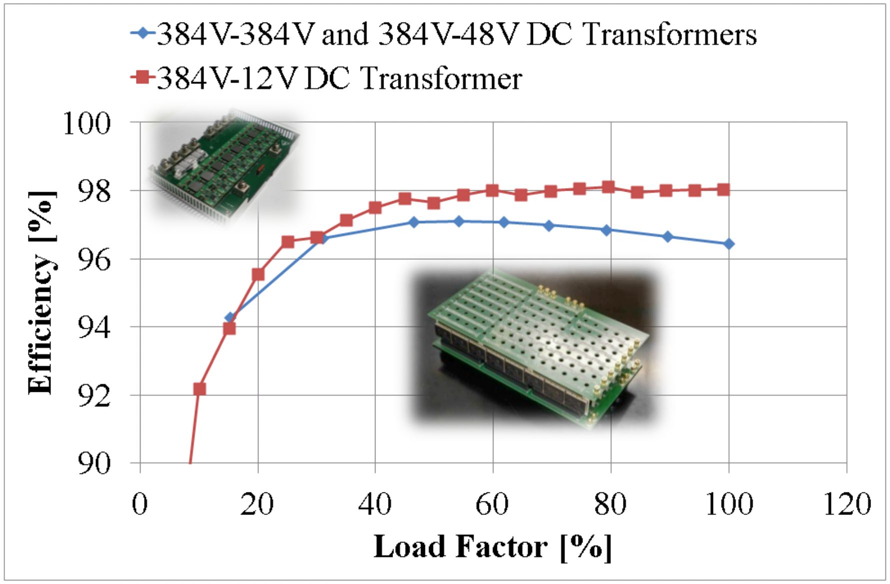
Rapid load variation (1ms, 100%→0%)

384 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.



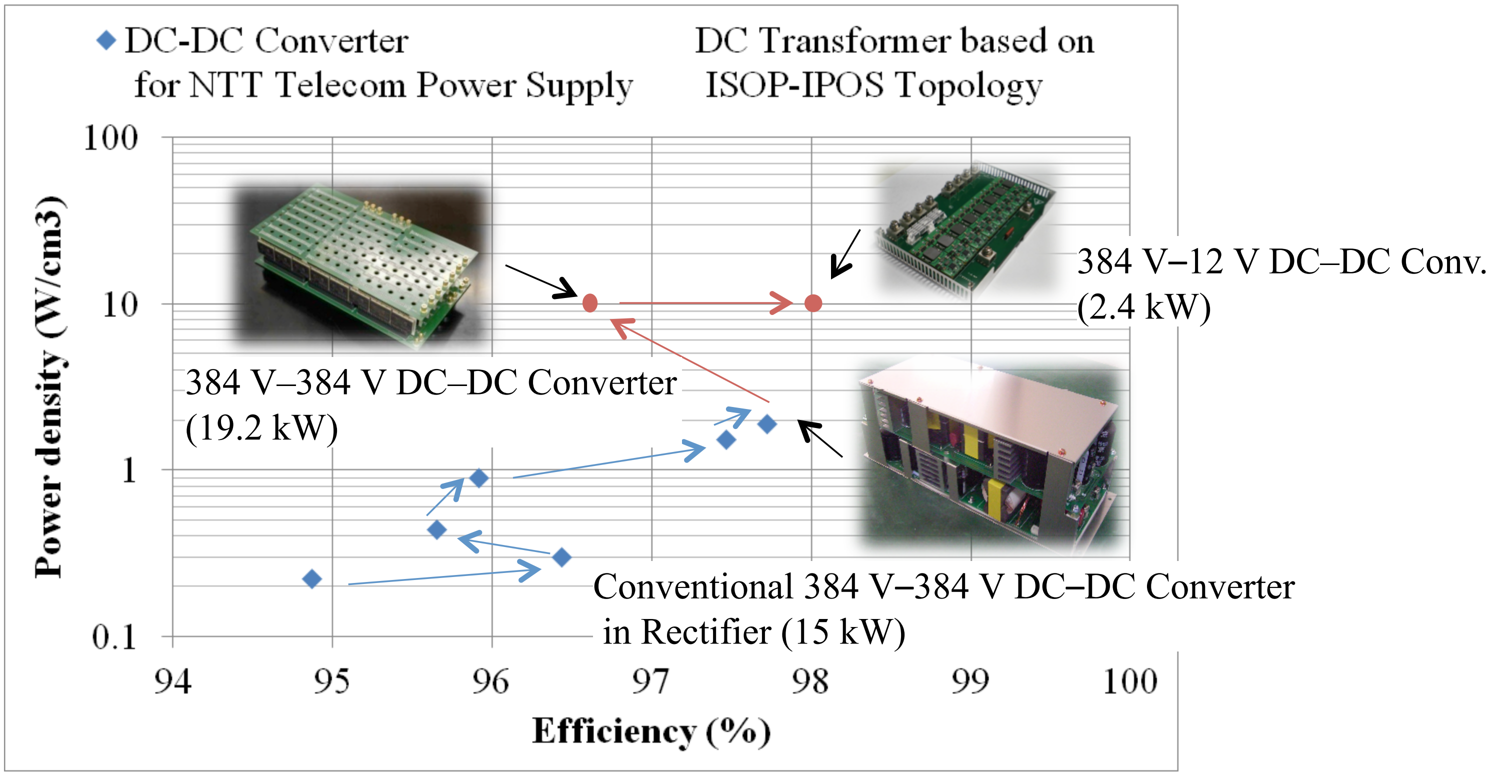
384 V–12 V 2.4 kW DC–DC Converter



Conversion efficiency of DC–DC Converter

Improvement of power density and 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



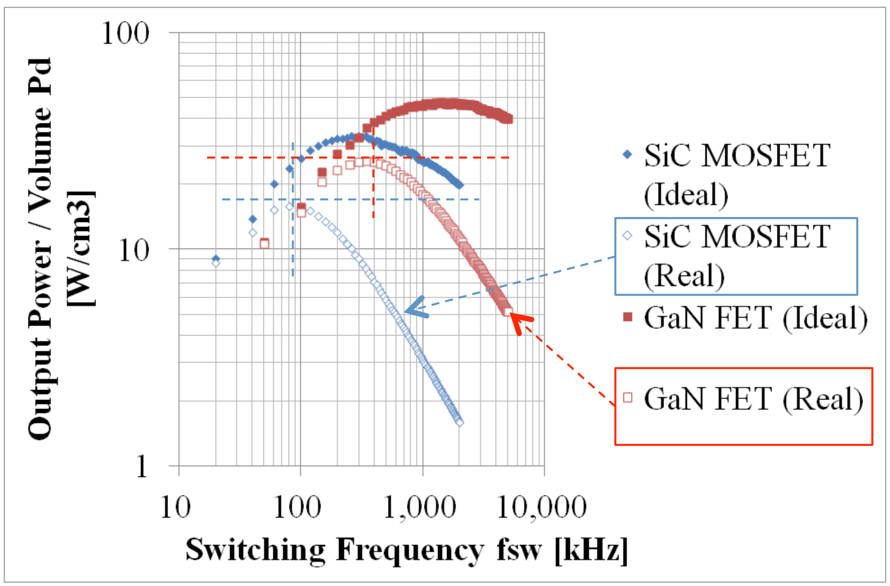
Conclusions

- 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.

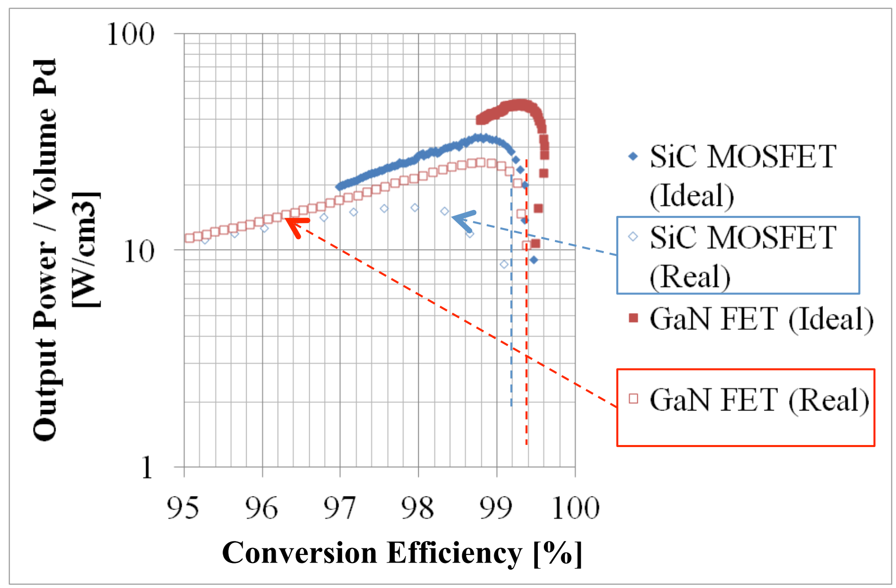
Thank you for your attention.

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