# Advances in Data Center Power Supplies

IEEE Presentation  18 May 2016

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# Introduction

## Cisco Power Presentation

- Customer Power Requirements and Facility Power Distribution
- Efficiency and Power Savings with Facility Power Distribution
- FEP (Front-End-Power) Supplies Road Map
  - Digital power revolution in Power
- BMP (Board-Mounted-Power) Supplies

# Cisco Power Culture and Goals

Provide World Class Power Systems to Meet Customer Needs

1. **Reliability:** Provide best-in-class quality and reliability for system integrity with single-piont-of-failure tolerance
2. **Efficiency:** Energy saving and meet Green Energy Initiatives
3. **Cost:** Lowest cost of ownership and ROI
4. **Size:** Save space in systems and boards for important features in data performance
5. **Technology:** Leadership in advanced technology balanced with mature designs
6. **Leadership:** Work with meeting customers requirements and with supplier partners

# Facility Power and System Power Efficiency

## Data Systems Meet Power Savings and Green Power Needs

- Efficiency and power cost-of-ownership dictate facility voltages
- Power density limit power versus data rate system floor space
- Front-End-Power (FEP) supplies advanced technologies
  - Cost lowers with fewer supplies needed for N+1 & N+N redundancy with multiply input lines
  - Multiple input voltages and distributed power distribution voltages, i.e. 48VDC and 12VDC typical
  - Digital control with DSP/DSCs
  - Standardization with 1RU supply height and multi-use designs
- Board-Mounted-Power (BMP) supplies with advanced technologies
  - Intermediate-Bus-Converter (IBC) supplies and Point-Of-Load (POL) supplies
  - Power-Block POLs and digital control systems
  - 48:1V POL converters without IBC

# Front-End Power (FEP) Supply Tech History

Customer Facility Power Distribution Voltages and FEP Supply Input Voltages

## Contemporary Power Distribution Efficiencies

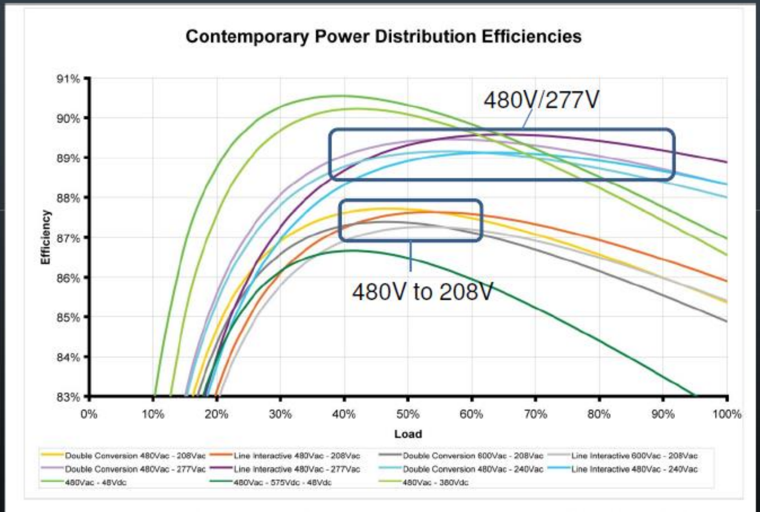
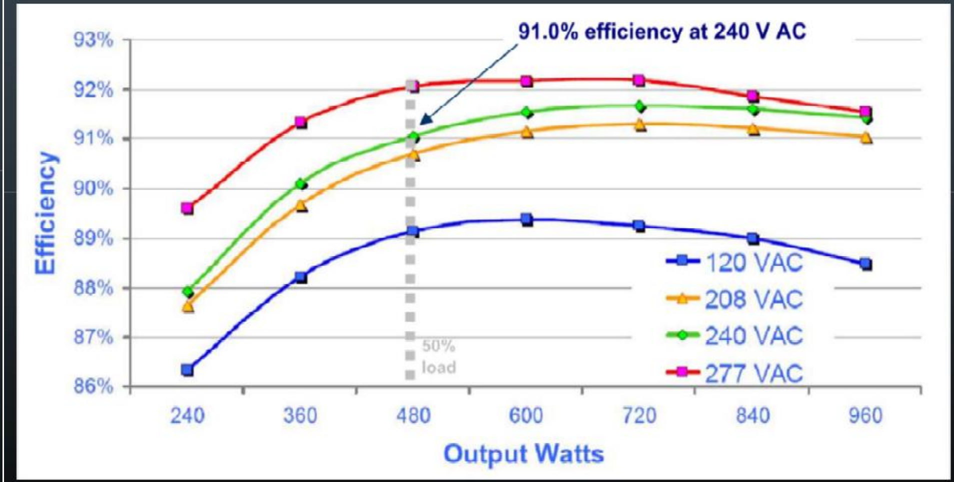



FIGURE 28. END-TO-END EFFICIENCY COMPARISON, EXCLUDING LEGACY 480VAC – 208VAC

The Green Grid, White Paper #16

## HP Power Supply Efficiency Curves




Marcoux and Sumrell, 7x24 Exchange, "277V Power Supplies"

("Efficiency Gains with 480/277V Power at the Cabinet Level" paper by Server Technology)

# Front-End Power (FEP) Supply Tech History

Customer Facility Power Distribution Voltages and FEP Supply Input Voltages

## Comparison

| Circuit Capacity | De-rated Value | 208 VAC 3-Phase | 415 VAC 3-Phase | 480 VAC 3-Phase |
|---|---|---|---|---|
| 20 A | 16 A | 5.8 kW | 11.5 kW | 13.3 kW |
| 30 A | 24 A | 8.6 kW | 17.3 kW | 19.9 kW |
| 50 A | 40 A | 14.4 kW | 28.8 kW | 33.2 kW |
| 60 A | 48 A | 17.3 kW | 34.6 kW | 39.9 kW |

415 VAC 3-phase delivers twice the power of a 208 VAC 3-phase system, while 480VAC delivers 2.3 times

- 208 VAC: 208V (phase to phase) x 24A x 1.732 = 8,646 W
- 415 VAC: 240V (phase to neutral) x 24A x 3.0 = 17,280 W
- 480 VAC: 277V (phase to neutral) x 24A x 3.0 = 19,944 W

("Efficiency Gains with 480/277V Power at the Cabinet Level" paper by Server Technology)

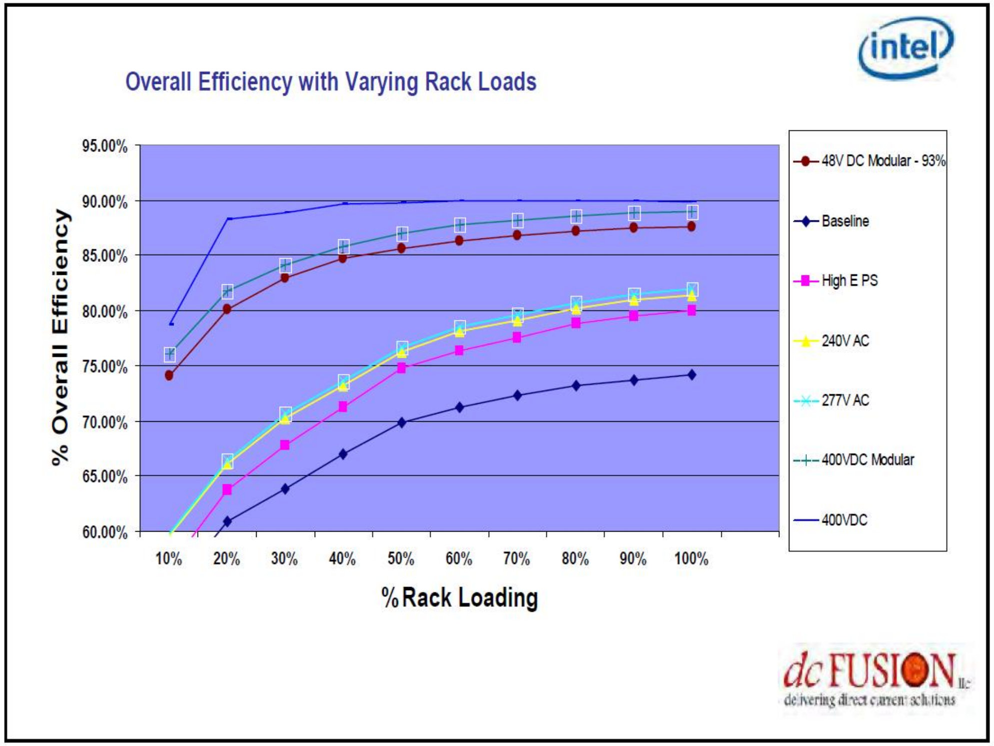
# Front-End Power (FEP) Supply Tech History

## Customer Facility Power Distribution Voltages and FEP Supply Input Voltages

### Why Direct 400Vdc Data Centers?

1. **~7% Facility energy savings, incl. cooling when compared to best-in-class AC system**
   - 7.7% at 50% load; 6.9% at 80% load
   - Much higher efficiency gains when compared to typical present day AC power topologies
2. **33% Space Savings**
   - No PDUs, simplified switchgear
3. **200% Reliability improvement**
   - 2x lower probability of failure in 5 years
   - 1000% reliability improvement if direct connect to batteries
4. **15% Electrical facility capital cost savings**
   - Electrical is ~40% of total facility cost, i.e. saves 15% of 40% ~ 6% of total
5. **Overall heat load reduction reduces overall cooling requirement**
6. **Using fewer of the earth's resources**
   - 15% Component volume reduction in every server power supply (PFC)

dcFUSION llc
delivering direct current solutions




("The Transition Path to DC" paper by dcFUSION, llc)

# Front-End Power (FEP) Supply Tech History

Customer Facility Power Distribution Voltages and FEP Supply Input Voltages

## End to End Efficiency

| Power | UPS | | Distribution | | IT Power Supply | | Overall Efficiency |
|---|---|---|---|---|---|---|---|
| 480/277 VAC | 96.20 | X | 99.50 | X | 92.00 | = | 88.10% |
| 400/230 VAC | 96.20 | X | 99.50 | X | 90.25 | = | 86.39% |
| 480 to 208VAC | 96.20 | X | 96.52 | X | 90.00 | = | 85.00% |
| 48V DC | 92.86 | X | 99.50 | X | 91.54 | = | 84.58% |
| 380V DC | 96.00 | X | 99.50 | X | 91.75 | = | 87.64% |
| Hybrid 575V DC | 95.32 | X | 92.54 | X | 91.54 | = | 80.75% |

(“Efficiency Gains with 480/277V Power at the Cabinet Level” paper by Server Technology)

# Efficiency Improvement Value Example

The following chart shows the importance of every percent of efficiency improvement as we get closer to 100% efficiency

| Efficiency | Losses | eff Saving Improvement | Improvement Net Effect |
|---|---|---|---|
| 80% | 20% | 1% | 5.00% |
| 81% | 19% | 1% | 5.26% |
| 82% | 18% | 1% | 5.56% |
| 83% | 17% | 1% | 5.88% |
| 84% | 16% | 1% | 6.25% |
| 85% | 15% | 1% | 6.67% |
| 86% | 14% | 1% | 7.14% |
| 87% | 13% | 1% | 7.69% |
| 88% | 12% | 1% | 8.33% |
| 89% | 11% | 1% | 9.09% |
| 90% | 10% | 1% | 10.00% |
| 91% | 9% | 1% | 11.11% |
| 92% | 8% | 1% | 12.50% |
| 93% | 7% | 1% | 14.29% |
| 94% | 6% | 1% | 16.67% |
| 95% | 5% | 1% | 20.00% |
| 96% | 4% | 1% | 25.00% |
| 97% | 3% | 1% | 33.33% |
| 98% | 2% | 1% | 50.00% |
| 99% | 1% | 1% | 100.00% |
| 100% | 0% | | |

# FEP Supply Input Power Requirements

World-Wide Input Voltage Requirements to Support

- -48/60VDC Telco input models (40-75VDC)
- 120VAC input models (85-132VAC)
- 120/240VAC input models (85-264VAC)
- 240VAC input models (170-264VAC)
- 277VAC input models (200-305VAC)
- 240VDC (China Narrow Range) (220-240VDC)
- 240VDC (China HVDC Standard) (192-288VDC)
- 260-400VDC (Emerge Standard) wide range
- 380VDC (Emerge Standard) narrow range (360-400VDC)
- 120/240/277VAC and HVDC 192-400VDC universal input

# Front-End Power (FEP) Supply Tech History

- Cisco HVAC, HVDC, & HVAC/HVDC FEP Supplies as of March 2016 are in development and production with 80 PLUS Gold, Platinum, and Titanium, 12V and 54VDC outputs, 500W to 3500W power output in 1RU high form factors.
- Samples of Cisco HVAC/HVDC FEP Supplies (March 2015)

# Digital Evolution of FEP

Large simple analog supplies

~1200 Components
~10 W/cu-in
~$100%/W

2002
80+ Bronze/Silver

80 PLUS | 80 PLUS BRONZE | 80 PLUS SILVER | 80 PLUS GOLD | 80 PLUS PLATINUM | 80 PLUS TITANIUM

Efficiency improvements 80% to 96%+

Higher power density & lower cost evolving with uP/uC

~1000 Components
~15 W/cu-in
~$67%/W

2007
80+ Silver/Gold

2012
80+ Gold/Platinum

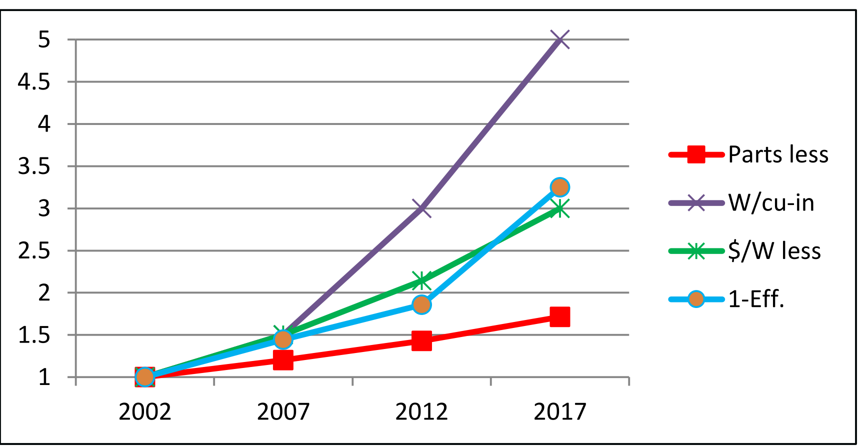
DSP/DSC takes over most control today

~840 Components
~30 W/cu-in
~$47%/W

2017
80+ Titanium

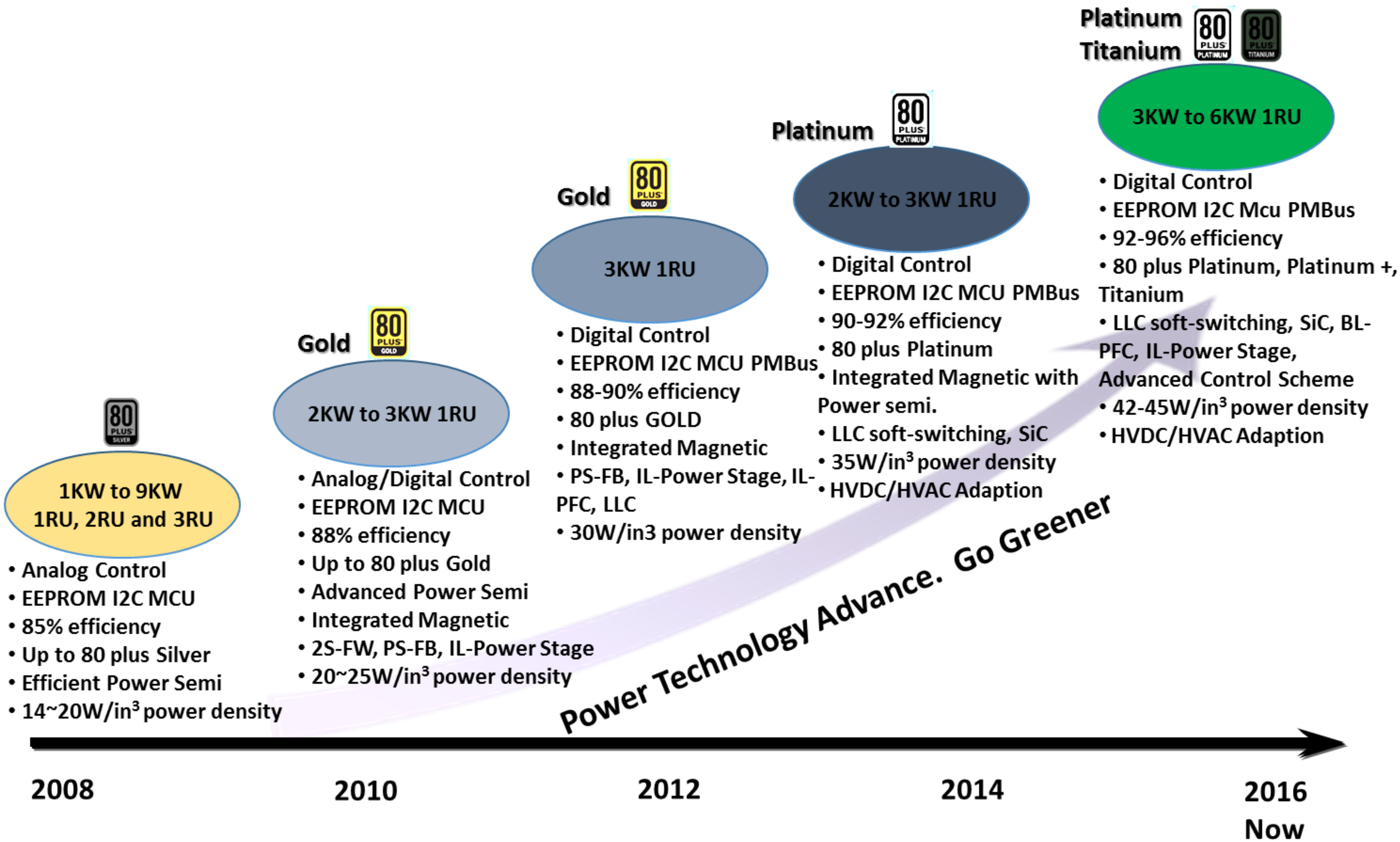
Smarter supplies complex digital future sub-systems

~700 Components
>50 W/cu-in
~$33%/W




Estimates of 3KW AC/DC
Note: Not all due to DSP

# Front-End Power (FEP) Supply Tech History



# FEP Supply Efficiency Road Map

- Topology advances
  - Interleaved power circuits, Resonant switching (HB-LLC and quasi-resonant PS-FB) , Totem pole or Bridgeless PFC.
- Controller advances
  - Advanced PWM control ICs, Adaptive Digital control to maximize efficiency at different Line/Load conditions, Variable switching frequency, pulse skipping, phase dropping etc. for improved light load efficiency.
- Component technology advance
  - High Voltage Schottky, SiC, GaN, Sync FETs. Thermal efficient packaging.
  - Planar Magnetics, Bus-Bar conductors, integrated assemblies.
  - New magnetic materials, new geometries, integrated magnetics.
  - Low loss Aux power and low loss fans.

**2016 Now** — Platinum & Titanium (80 PLUS PLATINUM, 80 PLUS TITANIUM)

92%-96% peak efficiency Platinum, Platinum+ (flat), Titanium

**2018** — Platinum & Titanium (80 PLUS PLATINUM, 80 PLUS TITANIUM)

94%-96% peak efficiency Platinum+ and Titanium

**2020** — Titanium (80 PLUS TITANIUM)

96% + peak efficiency Titanium and Titanium+ (flat)

# FEP High Power Density Road Map

- 97%+ efficiency with advanced topology, Controller Scheme and new Semi.
- Packaging and assembly improvements.
  - Thermal efficient packaging for Semi and power supply.
  - Planar Magnetics with hi Bsat materials.
  - Modular designs with BMP assemble tech used in the module.
  - Bus-Bar conductors, new geometries magnetics
- New circuit between PFC and DCDC to minimize the Bulk capacitance.
- Real time monitor and reporting to minimize design margin for components.
- Battery Backup in system to reduce the Holdup requirement.
- GaN to boost Switching frequency and reduce size.
- HVAC/HVDC

**2016 Now**

- **42-45W/in$^3$ power density**

**2018**

- **55-60W/in$^3$ power density**

**2020**

- **65W+/in$^3$ power density for routing and 70W+/in$^3$ for Server**

# Digital Smart Front-End Power (FEP) Supplies

- **Digital control has replaced analog control in recent years**
- **Digital Signal Processor (DSP) and Digital Signal Controller (DSC) CPUs** make the **FEP supplies smarter subsystems** of the system platforms
- **DSPs** in the last 5-6 years **have taken over most control** functions of the FEP
- **System demands for smart control, data, and features** from the power supply are increasingly **more complex**
- **FW design is** now a major part with the **HW design**

# DSP Advantages for FEP Supplies

- **Replacement** of many discrete analog and digital **circuits** and **components**
- **Reduces board space for higher power density, lowers costs, improves reliability, and improves efficiency**
- Provides added **functionality and features** including **advanced power topology control techniques** and **more smart control**
- Allows **fast cut-n-try problem solving**
- **Higher efficiency** optimization with adaptive control from input, output, and temperature dynamic variables and tighten **tolerances** and lower **drift**
- **Transient response improved** with hysteretic or predictive and adaptive control technique options

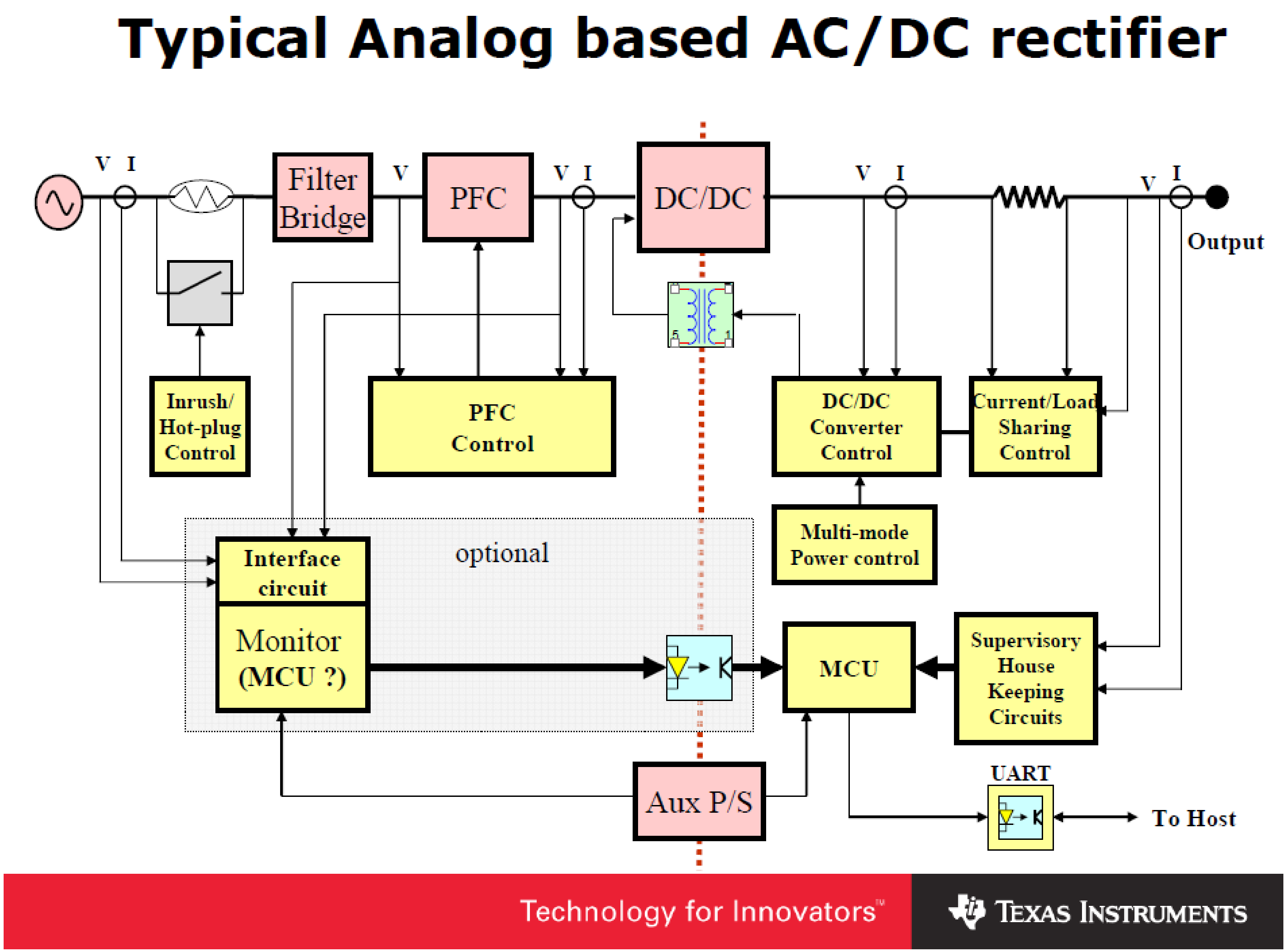
# DSP Advantages for FEP Supplies

- **Eliminates $I^2C$ communication chip sets** that are included in the DSPs
- **Reliability** with self-test, self calibration, and prognosis
- **EMI reduction** by noise cancellation & frequency dithering ability
- **Reusable FW code** to **simplify and speed development** of new designs
- **Easy design changes** with **FW** and to mitigate HW changes to upgrade supplies without PCB re-spins
- Allowing **field FW upgrades** with **boot-loader** through system or Internet to avoid returning supplies

# DSP Disadvantages for FEP Supplies

- **Disadvantages** include **schematic review and traditional circuit analysis tools no longer available** to understand the design
- **Need special attention with design review, logic diagrams, and testing** of control functions, modes, levels, timing, and decisions of power supply responses under dynamic line, load, and temperature conditions
- **Black-Box analysis needed** but limited with **traditional design review and design validation testing (DVT)**
- **More smart systems interface and communications problems** between the FEP supplies and the system **than power problems**

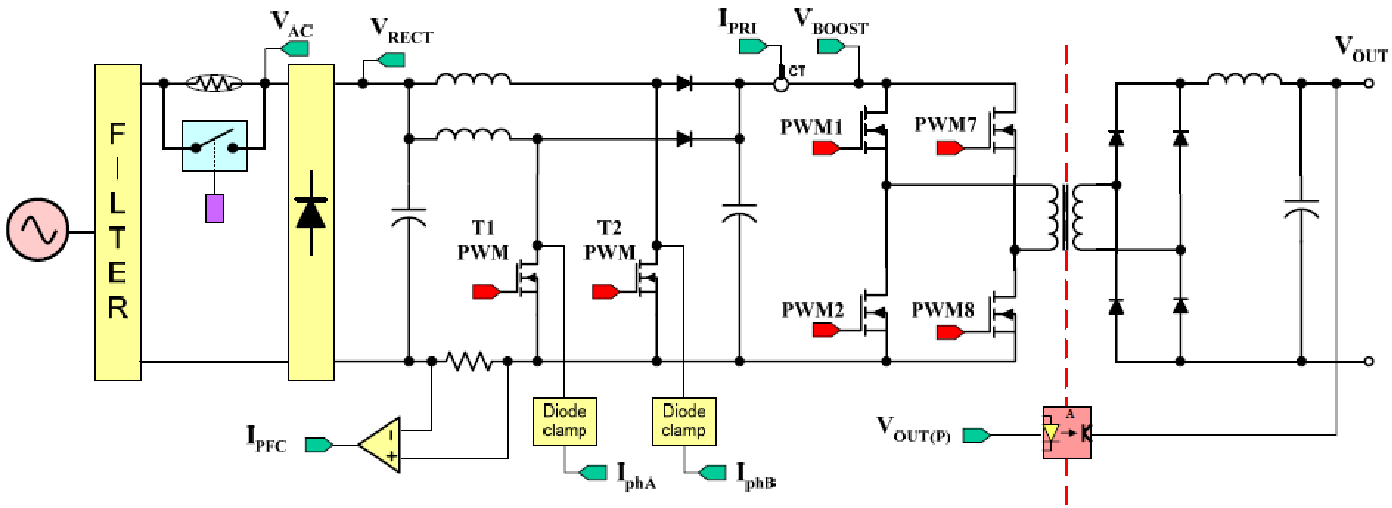
# Typical FEP Analog/Digital Design 5-10 Years Ago



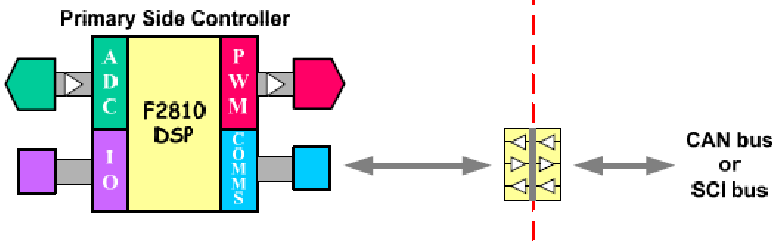
# Typical DSP Primary-Side Design Today with DSP

Digital control example shown with 1 DSP, but most FEP supplies use 2 or more DSPs.

**Digital approach with Single Device example for AC/DC Rectifier**




- 1000W / 48 V
- F2810 DSP based
- 2 Phase PFC-IL
- Phase shifted ZVS-FB
- 200 KHz PWM (DC/DC)
- 100 KHz PWM (PFC)

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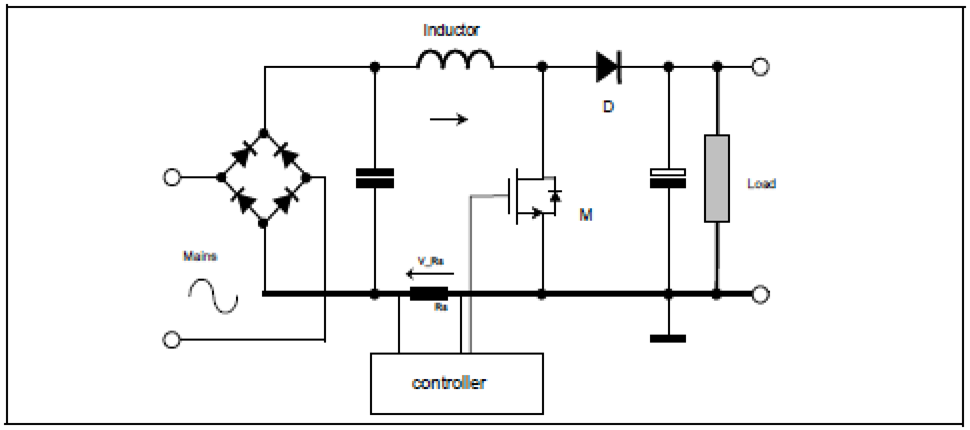
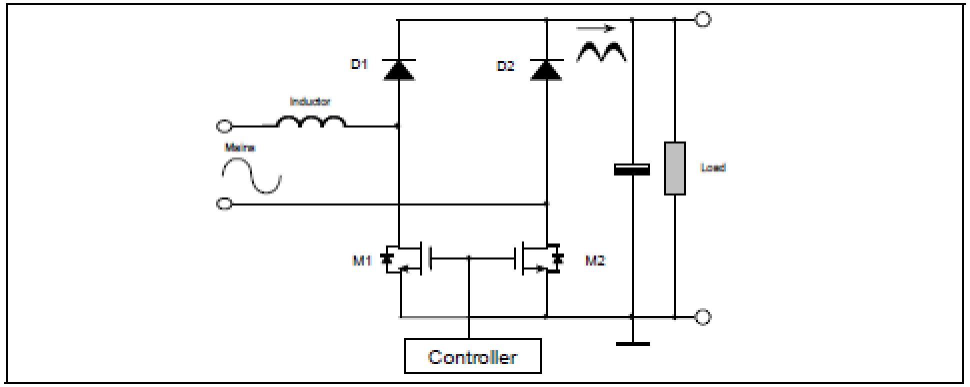
# Power Factor Correction (PFC) Circuit Design

PFC Rectifier Stage Topology with High Efficiency Example




Typical Bridge Rectifier PFC stage with PWM Controller
(STMicroelectronics AN1606 Application Note)




Bridgeless Rectifier PFC stage with PWM Controller
(STMicroelectronics AN1606 Application Note)

# Series/Parallel Resonant (LLC) Converter Design

## LLC DC/DC Converter (typical for high efficiency)

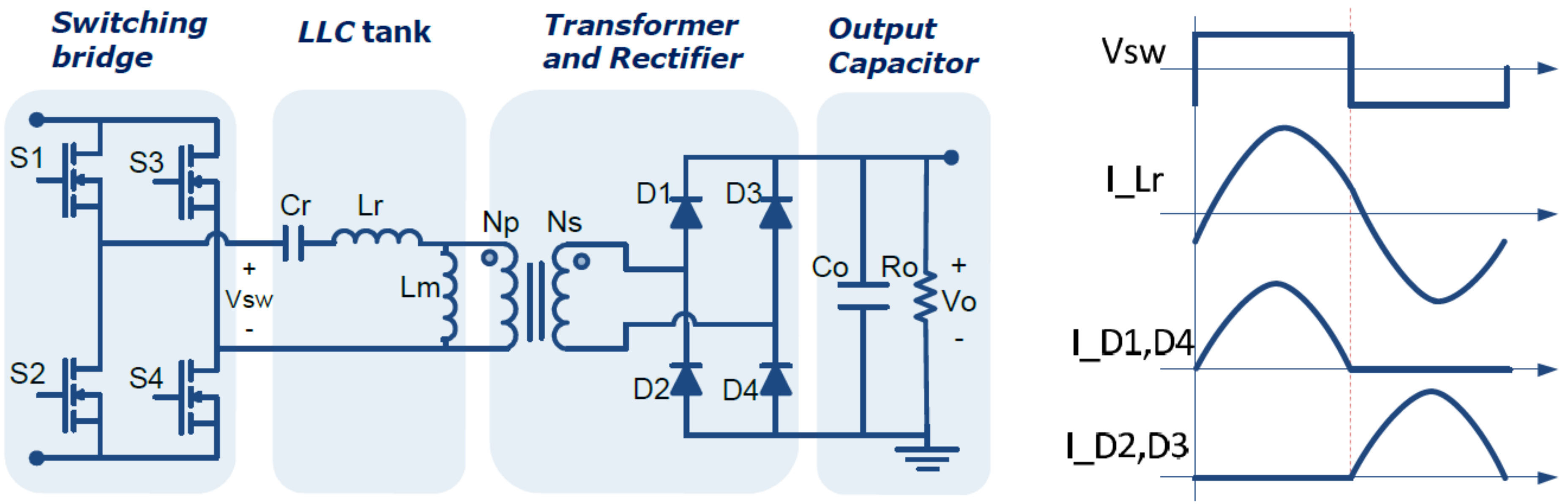



**Figure 2.1 Full-Bridge LLC converter with Full-Bridge rectifier**

(From Infineon Application Note AN 2012-09)

# Board Mount Power

- Present state of BMP technology
- What next?
- Advanced semiconductors
- Other components

# Now:

## On-Board Power Regulators

### CPU Power, On-Board & Discrete

- 12 V Input, non-isolated
  - To 320 A output current
  - 4 Φ to 8 Φ

### Power Modules

- 12 V Input, non-isolated
  - 25 A to 130 A output current
  - High Power Density (> 200 A/in$^2$, > 450 A/in$^3$)
  - High cost

### On-Board, discrete

- 12 V Input, non-isolated, single / dual phase
  - 4 A to 80 A output current
  - High Power Density (to > 80 A/in$^2$)
  - Low cost

# Next Generation:

## On-Board Power Regulators

### 48 V Input, non-isolated

- Lower distribution losses
- Enables higher power systems

### Power Modules

- 48 V Input, isolated
  - Higher output power (> 1200W, ¼ Brick)
  - Higher output current

### On-Board, discrete

- 48 V Input, non-isolated, single / dual phase
  - Higher output current
  - Smaller, increased Power Density

# Advanced Semiconductors

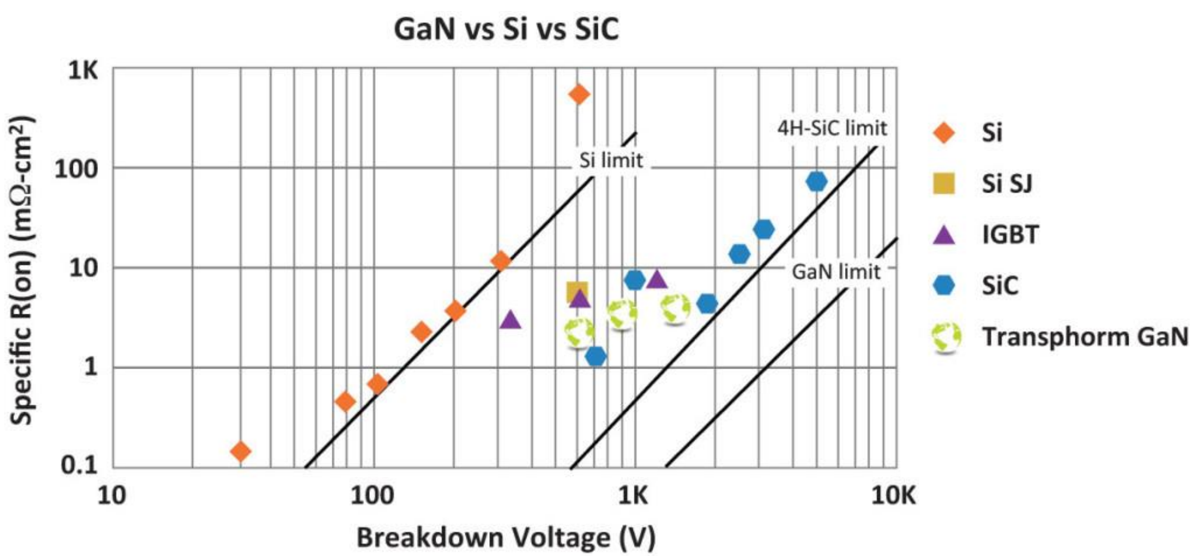
| Characteristic | Unit | GaN | Si | SiC |
|---|---|---|---|---|
| Bandgap | eV | 3.49 | 1.1 | 3.26 |
| Electron mobility | $cm^2/Vs$ | 2000 | 1500 | 700 |
| Peak electron velocity | $x10^7 cm/s$ | 2.1 | 1.0 | 2.0 |
| Critical electric field | MV/cm | 3.0 | 0.3 | 3.0 |
| Thermal conductivity | W/cm * K | >1.5 | 1.5 | 4.5 |
| Relative dielectric constant | er | 9.0 | 11.8 | 10.0 |

**GaN**

- Typically 600 V – 800 V, some Low V
- High Switching Speed
    - Low Capacitances / Gate Charge
- No D-S parasitic Diode
- No Avalanche mode
- High Temperature
- Basic structure: Normally On
- Moderate Cost (GaN on Si)

**SiC**

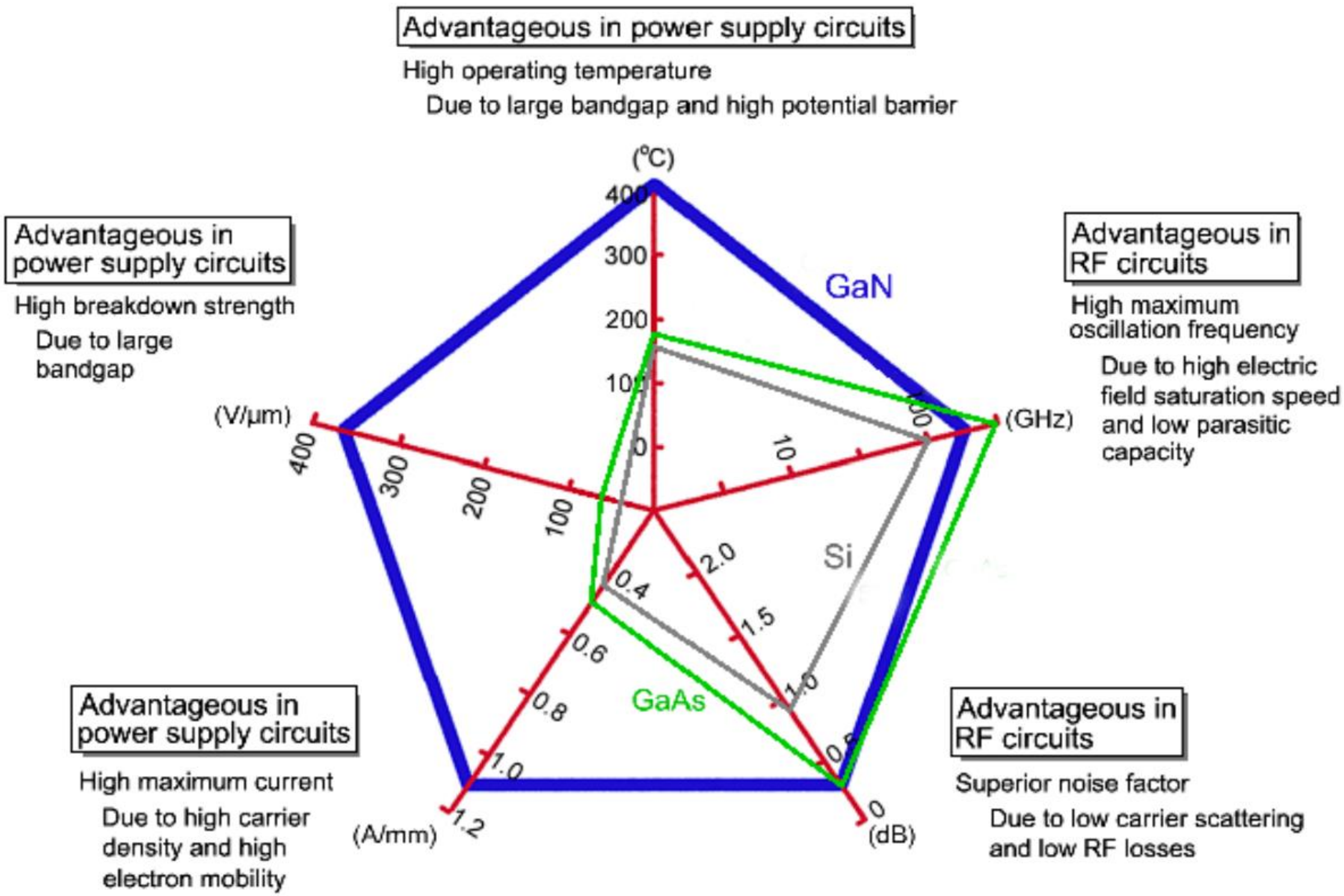
- Typically 600 V – 1200 V
- Generally High Current
- High Switching Speed
    - Low Capacitances / Cg
- No D-S parasitic Diode
- No Avalanche mode
- High Temperature
- High Cost




*Ref. Transphorm Technology*

# Performance Comparison

**Si – GaAs - GaN**

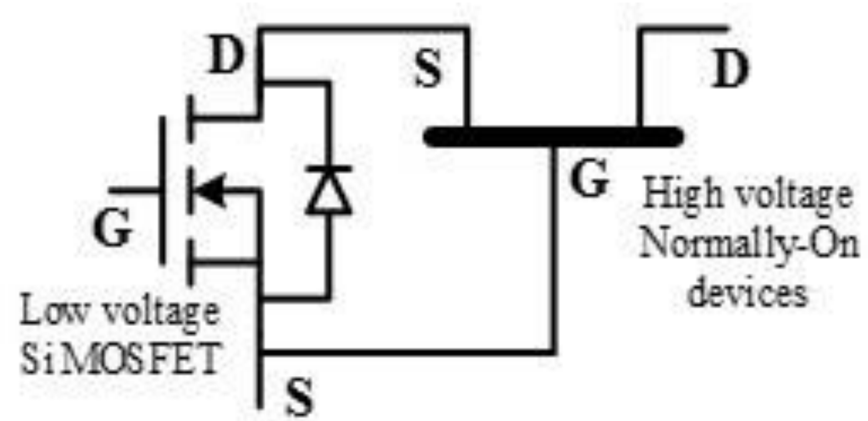



*Ref. GaN Systems website*

# Cascode Structure

Simple Depletion mode GaN FET with low Voltage series control Si MOSFET.

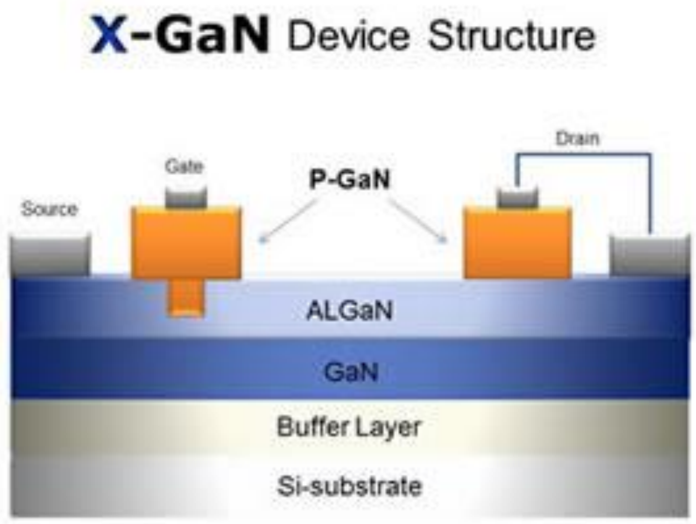
- Gate is a Si MOSFET
  - Small, low charge control FET
  - Rugged Si Gate structure
  - Complex dual-die structure
  - Higher packaging cost

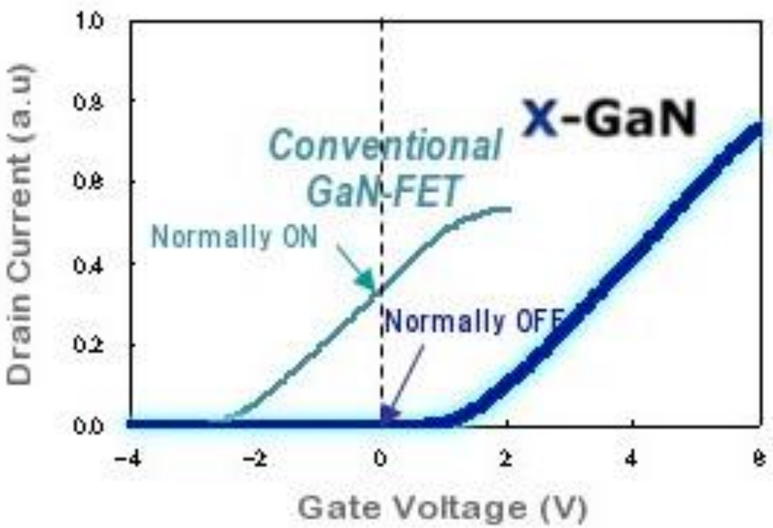



*Ref. Transphorm*

# Enhancement mode Structure

## Panasonic




Panasonic makes normally-off by using P type GaN on the gate and discharge in the channel under the gate.

Normally-off can be made to reduce the number of electrons in the transistor and modified the gate structure.

*Ref. Panasonic website*

# Example: PFC with GaN

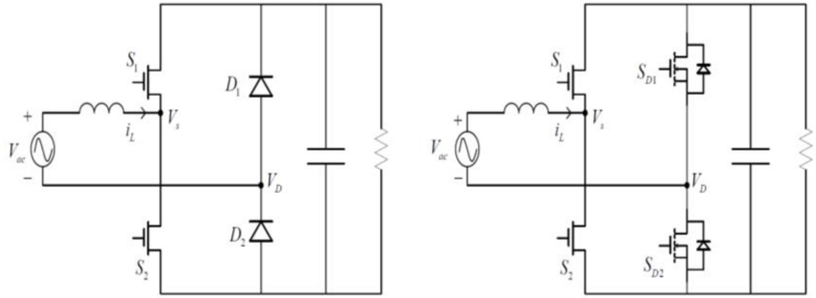
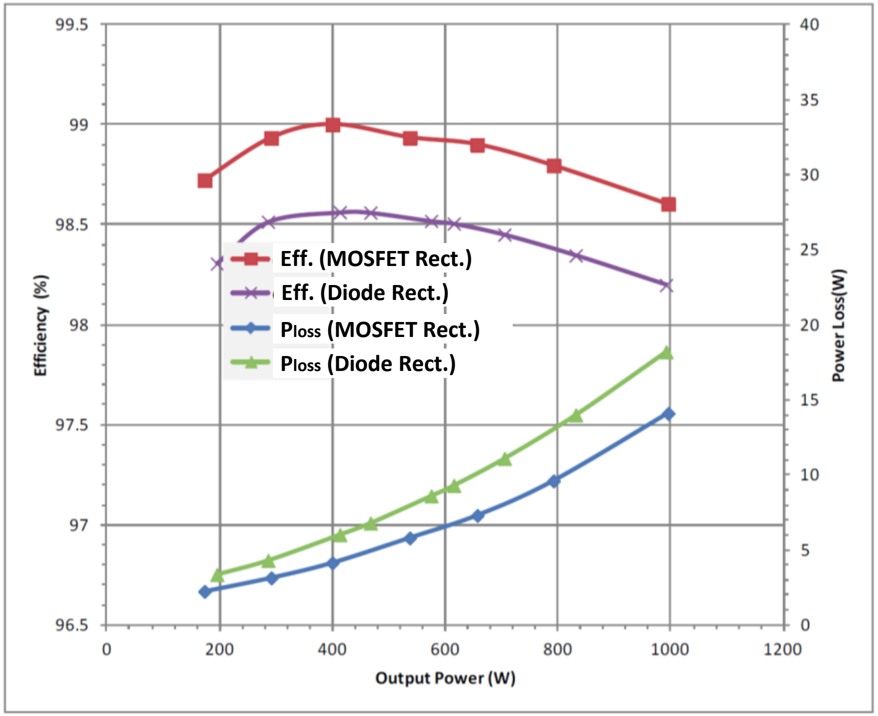
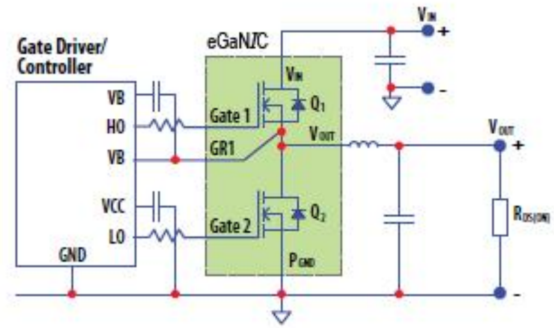


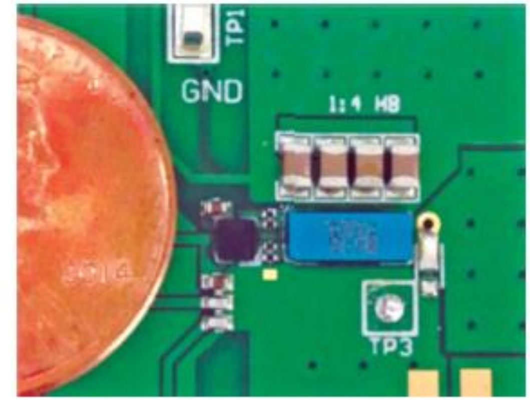

Fig.1 Totem-pole bridgeless PFC boost converter based on GaN HEMT (a) Diode for line rectification (b) MOSFET for line rectification




*Ref. Transphorm App. Note*

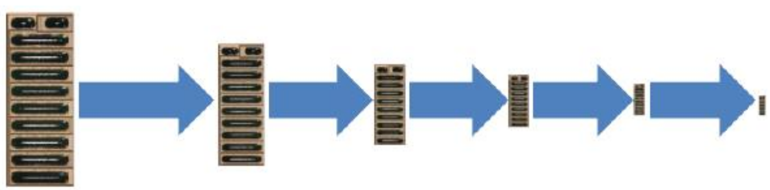
# GaN for 12 V PoL



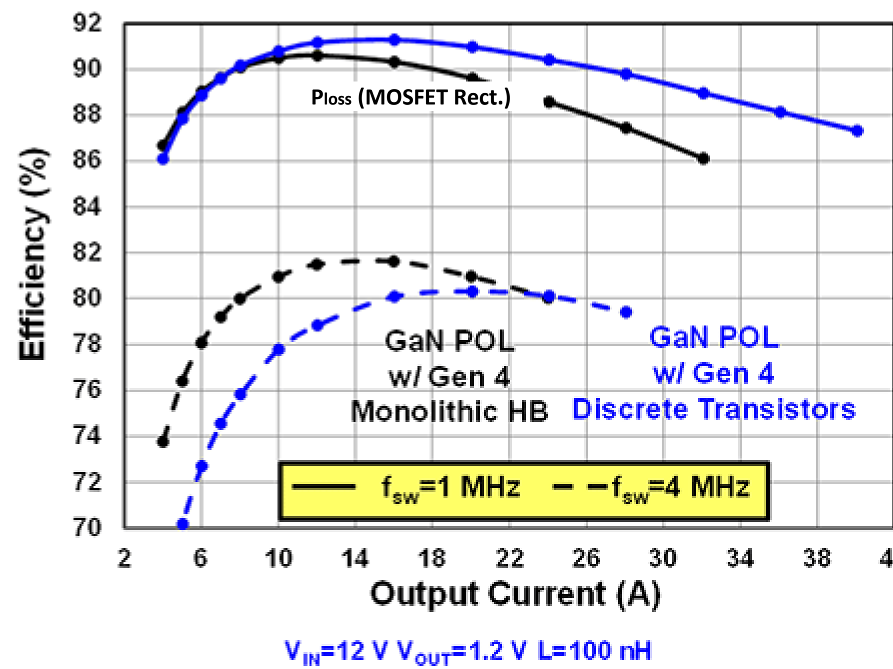




Increasing Frequency → Small!

New Technology → Further reduction over time



*The performance of eGaN FETs is expected to double every two years resulting in increased performance from a smaller form factor*






*Ref. EPC website*

# Passive components, materials

Higher switching frequencies

- Lower loss magnetic core materials
- Innovative core geometries
- Low inductance packaging
  - Semiconductors
  - Capacitors
- Improved ripple current capacitors
- Higher frequency PWM controllers
  - Reduced delay times

# Supplier links

GaN Systems: http://www.gansystems.com/why_gallium_nitride_new.php

EPC: http://epc-co.com/epc/Applications/DC-DCConversion/PointofLoadConverters.aspx

Transphorm: http://www.transphormusa.com/applications/#power-supply

Panasonic: http://www.semicon.panasonic.co.jp/en/products/powerics/ganpower/#chap5

TOMORROW starts here.