Static Power Converters
Past, Present and Future

Petar Grbović

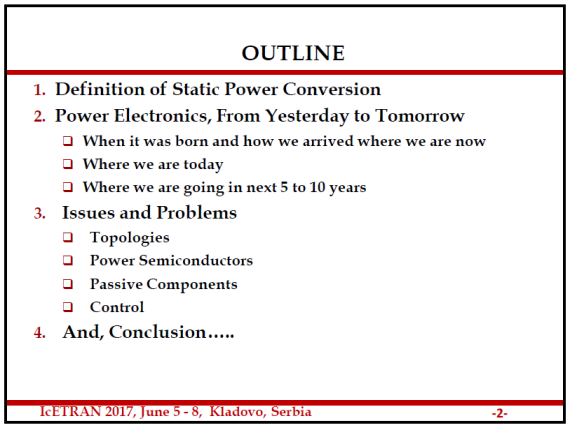
***Abstract*—Static power converters and power electronics play significant role in industrial applications, power generation and transmission, home appliance, transportation, etc., etc. Today, power converters are part of our life and everything will be completely different without power converters. How we arrived here where we are now and when static power conversion started? Is it a new discipline or not really? Where we are going in next years and decades? What is future of static power converters?**

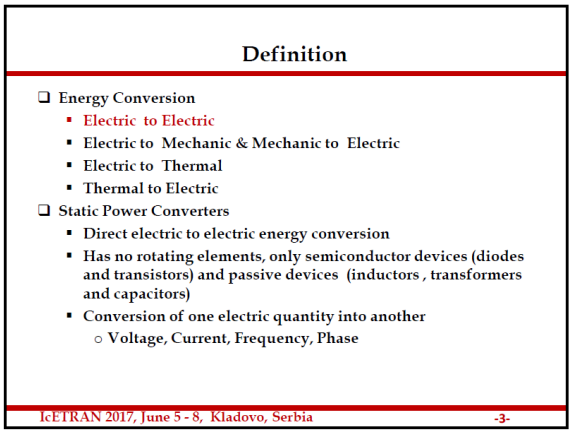
In the first part of the talk we will briefly go through the history of static power conversion starting from very first "power converters" such as Herz's Oscillator and Tesla's Transformer, then very first "Power Devices" such as mercury arc rectifiers, megatrons, thyratrons, and then finally real power devices, SCRs, BJTs, MOSFETs and IGBTs.

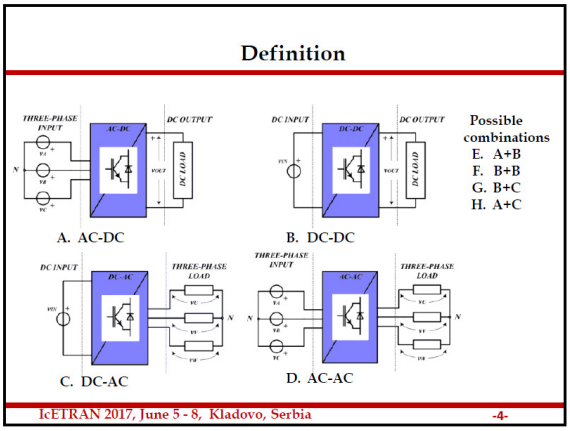
In the second part of the talk, influence of static power converters on our everyday life will be addressed. The latest development results in the field of power converters will be discussed too.

The third part of the talk will address future of power converters and some open issues that need urgent solution. We will intensively discuss: New power semiconductor devices such as SiC and GaN, "New" topologies, New material for passive devices (magnetics and capacitors) and System integration including power devices, passives and gate drivers. At the end, converters control aspects, hardware as well as strategies will be briefly addressed.

***Keywords*—Power, Converters, Static power converters**







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Long time ago…Yesterday

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- Long time ago, static power conversion was simple and "primitive"….no yet power electronics

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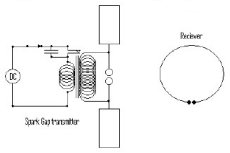
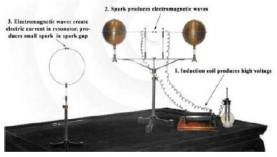
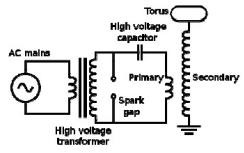


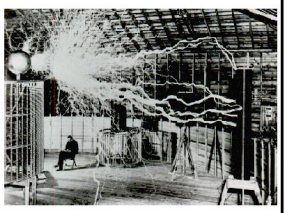


- Heinrich Hertz's oscillator, 1887…
  - "Static " Resonant Power Converter
  - Electromechanical switch

Long time ago…Yesterday…

- Long time ago, static power conversion was simple and "primitive"….no yet power electronics





- Tesla's high frequency high voltage transformers for wireless power transmission, 1890s
  - **Multi-resonant Static Converter**

Long time ago…Yesterday…

- Very first controlled power converter was mercury arc rectifier developed in 1902 by Peter Cooper Hewitt.

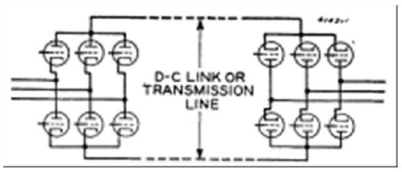
Mercury-arc valve

Siemens 560V 1300A Mercury-arc valve

GE hydrogen thyratron for radar applications

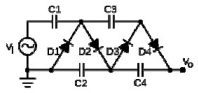
Long time ago…Yesterday…

- Very first controlled power converter was mercury arc rectifier developed in 1902 by Peter Cooper Hewitt.
- General Electric Company and engineer Alexanderson developed first controlled inverter to drive a three-phase motor in 1934



Long time ago…Yesterday…

- The **Cockcroft–Walton** (CW) generator/Voltage Multiplier, 1932



- The "key part" of particle accelerators
- The Nobel Prize in Physics (1951) for "Transmutation of atomic nuclei by artificially accelerated atomic particles"

Development of the atomic bomb, 1937 by Philips.

Cascade multiplier for TV set

Long time ago…Yesterday…

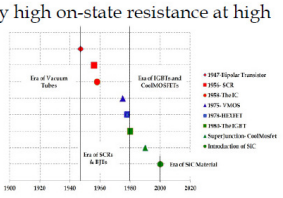
- 1940s and 1950s, Solid State Power Conversion as a real discipline started
- Shockley invented BJT in 1947…. Nobel Prize in Physics (1956)
- Silicon Controlled Rectifier (SCR) invented in 1956

A replica of the first bipolar transistor

High power SCR

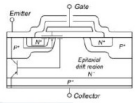
Long time ago…Yesterday…

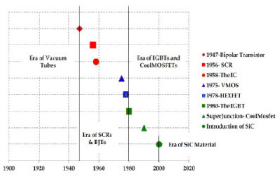
- From 1950s to 1980s SCR, BJT and MOSFET were a major player in power electronic applications
- But, not possible to run high power at high voltage and high switching frequency
  - BJT and SCR very slow,
  - MOSFET fast but very high on-state resistance at high voltage



Long time ago…Yesterday…

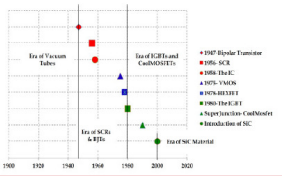
- Invention of Insulated Gate Bipolar Transistor-IGBT at the end of 1970s and begin of 1980s
  - **B. J. Baliga or ?????**
- The IGBT solved all problems of BJT and MOSFET
- **Power Electronics was born the second time**





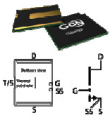
Long time ago…Yesterday…

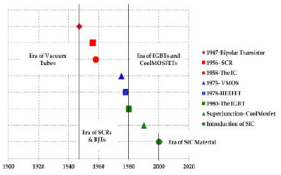
- But, MOSFET is still an important player in the Game of Power Electronics
- Super-Junction Si MOSFET invented in 1990s. Target applications up to 900V
  - Infineon –*CoolMOS*
  - ST- *MDmesh*™



Long time ago…Yesterday…

- But, MOSFET is still an important player in the Game of Power Electronics
- Super-Junction Si MOSFET, 1990s. Target applications in voltage range up to 800V
- At the end of 20 century, new materials (SiC and GaN) are in the game

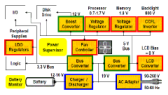




…Today…

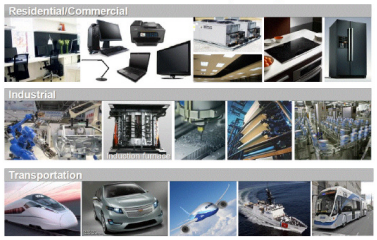
…….Today…

- **Thanks to introduction of the IGBT and the SJ-MOSFET, power electronics is today part of our everyday life**
- Home appliance, audio/video, communication…..
- Industrial Applications….
- Transportation…
- Wherever we need to control power flow without (significant) losses, we have to use power electronics.....
- Invention of the IGBT has contribution of >20 trillion (10^{12}) US$ to global economy due to energy saving!



…….Today…

- POWER ELECTRONICS IS EVERYWHERE
- **Without Power Electronics everything will be different**



❖ *D. Boroyević, I.Cvetković, D. Dong,"* INTERGRID: A FUTURE ELECTRONIC ENERGY NETWORK? 16th INTERNATIONAL SYMPOSIUM on POWER ELECTRONICS - Ee 2011 NOVI SAD, REPUBLIC OF SERBIA, October 26th - 28th, 2011

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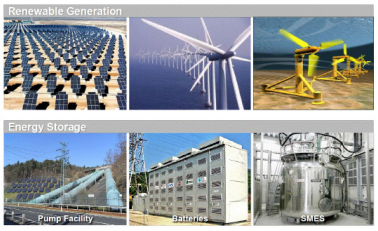

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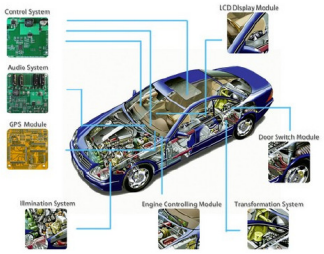

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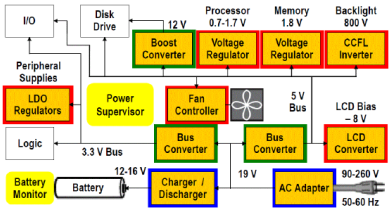

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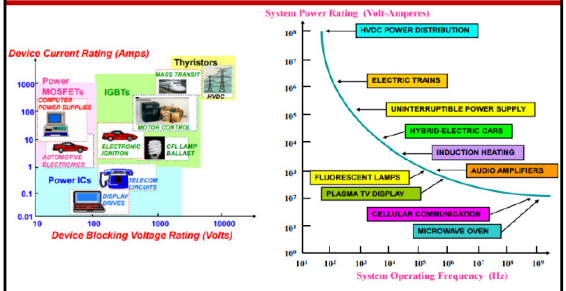


…Tomorrow…

-Where we are going?-

…Tomorrow…

I. Where we are going in next 5 to 10 years?
II. What is future of power electronics?
III. What are the research challenges? Are there any main ones?
IV. Isn´t industry already "leading" the area and defining the "useful" systems?
V. Aren´t we just using components which other people research for us?
VI. Isn´t the progress only incremental, i.e. to go e.g. from 98% efficiency to 99%?

…Tomorrow…

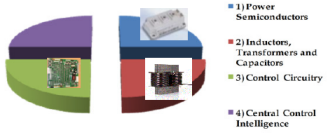
Major objective of future R&D

A. Cost, Cost, Cost, Cost…☹
B. Size, weight and footprint….
C. Losses…
   a) Energy saving
   b) Cooling effort=Size, weight & Cost
D. But, Some times reliability and only reliability….
   a) Fault tolerance….

…Tomorrow…

The Main "Four Elements" of a power converter

1) A Matrix of Power Semiconductor Switches
2) A bunch of Inductors, Transformers and Capacitors (and Resistors ☹)
3) Control Circuitry
4) Central Control Intelligence



…Tomorrow…

1) **What is a power semiconductor?**

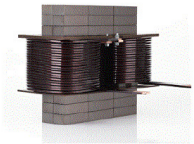
- **And, what it would be in the future?**

...Tomorrow...

1) What is a power semiconductor?
- From material perspective!
  - A power semiconductor is just a piece of roasted sand
- 27.7% of the planet is silicon!!

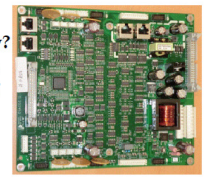
...Tomorrow...

2) What about inductors and transformers?
- Very costly and dirty technology!
- Limited resources!
  - Today and it will be even worst tomorrow?



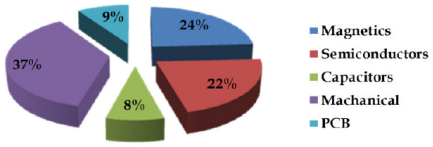
...Tomorrow...

3) Control Circuitry is also Si?
   - Today and will be tomorrow?
4) Central Control Intelligence is just certain number of lines of C code?
   - When you have it, does not cost anything?
   - But you need to have it, and it costs ?



...Tomorrow...

Magnetics and Mechanical are dominant factor in the converter cost



...Tomorrow...

- In future, we MUST use more and more Si, SiC, GaN...
- More intelligence...

- And, Less and Less iron and copper

... Issues...Today and Tomorrow

...Current Issues...

I. Power Semiconductors
   - Materials (Si, SiC, GaN), Devices, Packaging and Control
II. Topologies
   - If something new is possible
III. Passives
   - Magnetics, Capacitors and Energy Storage
IV. Digital Signal Controllers
   - DSP, FPGA, ASIC
V. High Level Control
   - Plug and Play, Grid Integration
VI. and....more

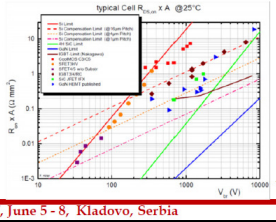
...Power Semiconductors...

...Power Semiconductors...

More Semiconductors, Less Iron and Copper .....

But what kind of Semiconductors???

Si  SiC  GaN 



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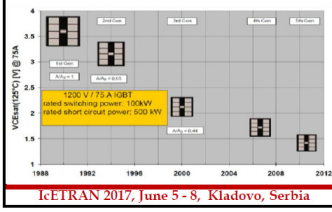
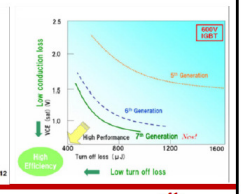
...Power Semiconductors...

- Si IGBTs has almost achieved the limit, but it is still alive
- Only incremental improvement is possible
  - Higher operating temperature, **BUT is it beneficial?**
  - Switching /Conduction Losses Reduction
- High voltage IGBTs possible improvement





...Power Semiconductors...

More Semiconductors Less Iron an Copper.....

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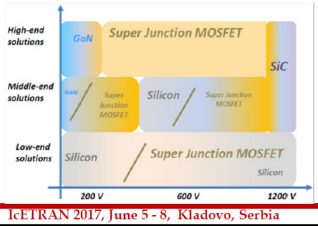

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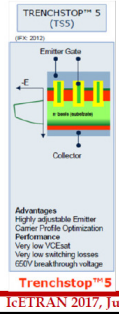
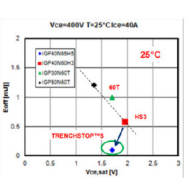
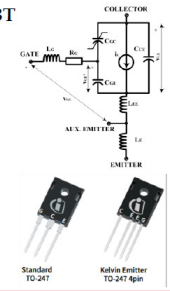
...Power Semiconductors...

- Si IGBTs is still alive

Infineon TS5 650V IGBT







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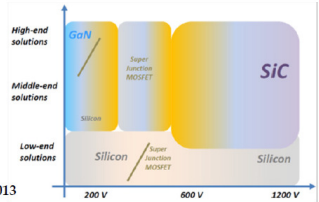

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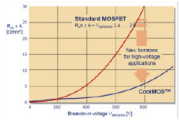
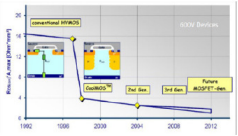
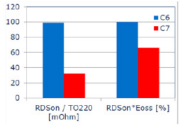
...Power Semiconductors...

- Si MOSFET is still alive but at the limit
- Super-Junction MOSFET
  - Up to 900V,
  - Above 900V still no significant progress







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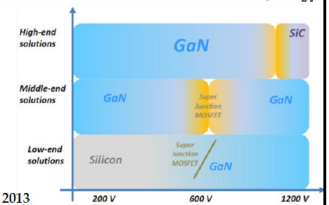

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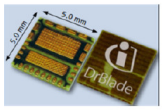
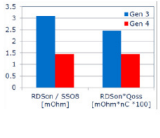
...Power Semiconductors...

- Si MOSFET is still alive but at the limit
- Super-Junction MOSFET
  - Up to 900V,
  - Above 900V still no significant progress
- OptiMOS
  - Low voltage Applications, up to 250V

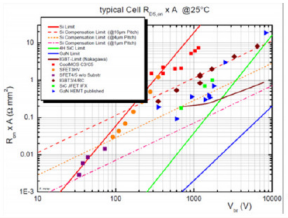




J. Sanchez, " Figure-of-merits of Todays LV MOSFETs in Comparison to HV MOS and GaN " ECPE Workshop "Advanced Multi-cell / Multi-level Power Converters", 1-2 July, 2014, Toulouse, France

...Power Semiconductors...

- WBG Devices are very promising
  - Extremely High Operating Temperature Tj
  - Very Low On-State Resistance R_{ON}
  - Very High Switching Speed



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- WBG Devices are very promising
  - Extremely High Operating Temperature Tj
  - Very Low On-State Resistance R_{ON}
  - Very High Switching Speed
- SiC SBDs on market for years 1200V 50A, etc., etc
  - Zero recover losses, but still expensive…

...Power Semiconductors...

- WBG Devices are very promising
  - Extremely High Operating Temperature Tj
  - Very Low On-State Resistance R_{ON}
  - Very High Switching Speed
- What About Active Switches?
  - SiC JFET is developed, BUT!?
  - SiC MOSFET already on market, BUT many open issues
  - GaN 600V MOSFET is also there….
  - BUT…Many open questions

...Power Semiconductors...

600V Devices

	Si IGBT	Si SJ MOSFET	SiC MOSFET
Conduction Losses	Low	Low	Low
Switching Losses	Moderate/Low	Low	Low
Cost/A (mΩ)	Low	High	Very High
Reliability	High	High	Still not good enough
Chip Size	Small	Large	Small
Body Diode	No	Issue, complex external circuit	Moderate, simple external SiC SBD

...Power Semiconductors...

1200V Devices

	Si IGBT	Si SJ MOSFET	SiC MOSFET
Conduction Losses	Low	Very High	Low
Switching Losses	High/Moderate	Low	Low
Cost/A (mΩ)	Low	High	Very High
Reliability	High	High	Still not good enough
Chip Size	Small	Large	Small
Body Diode	No	Issue, complex external circuit	Moderate, simple external SiC SBD

...Power Semiconductors...

1700V Devices

	Si IGBT	Si SJ MOSFET	SiC MOSFET
Conduction Losses	Moderate/Low		Low
Switching Losses	High		Low
Cost/A (mΩ)	Low		Very High
Reliability	High		Still not good enough
Chip Size	Small		Small
Body Diode	No		Moderate, simple external SiC SBD

...Power Semiconductors...

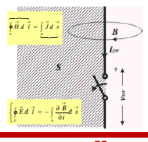
The system approach is a MUST, no way to use all the benefits of WBG devices without the system approach

- High Temperature **WBG devices** require new packaging concept,
  - Package for 200-300°C,
  - Thermal cycling
- High Speed **WBG devices** require new packaging concept,
  - Minimized inductance and capacitance

...Power Semiconductors...

The system approach is a MUST, no way to use all the benefits of WBG devices without the system approach

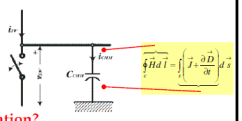
- A new WBG switch **1200V&1000A @ 25ns**
  - It sounds very good and promising, almost no switching losses. … BUT Not easy as it looks like….
  - Typical commutation inductance L_ζ=15+10+5=30nH
  - $\Delta v_{stv} = L_\zeta di_{stv}/dt$=1200V!!!!! DOES NOT WORK!!
- An active gate driver to limit the voltage?
  - Not only, it does not make sense!
- New packaging technology is a MUST,
- **But not enough, new Control and topology of the device is also a MUST!**



...Power Semiconductors...

The system approach is a MUST, no way to use all the benefits of WBG devices without the system approach

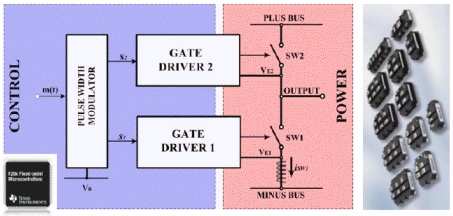
- A new WBG (SiC MOSFET) switch **10kV&120A @ 100ns**
  - It sounds very good and promising, almost no switching losses. … BUT Not easy as it looks like….
  - dv_{SW}/dt=80kV/μs
- DOES it WORK?
  - What about parasitic capacitance and displacement current?
  - What about the machine insulation?
- Does an active gate driver solve the problem?



...Control & Protection of Power Semiconductors...

...Control of Power Semiconductors...

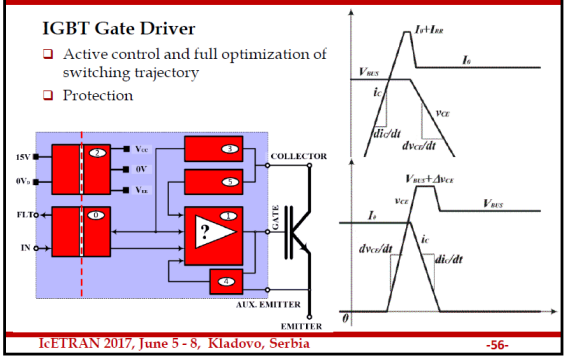
- Gate driver is the necessary link between the power and control,
- Must, not nice to have feature…



...Control of Power Semiconductors...

IGBT Gate Driver

- Active control and full optimization of switching trajectory
- Protection



... Magnetics & Power Capacitors ...

...Magnetics...

Magnetic materials are progressing slowly

- Amorphous and Nanocristallyn
  - High saturation B and relatively low loses
  - <20kHz
  - Acoustic noise is a BIG Issue-Still Unsolved
- Iron-Powder Material
  - High saturation B but relatively high loses,
    - Only very low ac B (0.1T)….CCM inductors
  - <100kHz
- Ferrites
  - Low losses, but
  - Very low sat B<0.45T

...Magnetics...

A. **What material in range 15kHz to 40kHz, especially at high ac flux density?**

- Amorphous and Nanocrystallyne
  - Relatively High losses!!!

- Ferrite
  - Low saturation B ⇒Big core!!!

- Iron-Powders (Koll Mμ, MPP, High Flux, XFlux, Sendust,….)
  - High losses!

- What Else??

...Magnetics...

A. **What is the material in range 15kHz to 30kHz, especially at high ac flux density?**

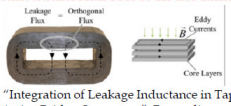
B. **What about acoustic noise**

- **<16kHz @ LF bias**
  - **Transformers with high leakage inductance, ICTs**
  - **Normally, the noise frequency is twice switching, but with bias is same as the switching !!**

$$\approx \left(\frac{B_{BIAS}}{LF} + \frac{B_{AC}}{SWITCHING} \right)^2$$

...Magnetics...

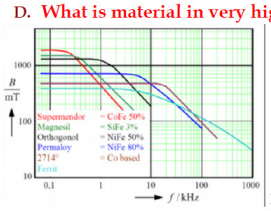
A. **What is the material in range 15kHz to 30kHz, especially at high ac flux density?**
B. **What about acoustic noise**
C. **What about orthogonal flux losses?**
   - The flux flow is not well controlled
   - High leakage inductance transformers and ICTs
     - **Significant additional losses in the lamination!!**



❖ **B. Cougo and J. Kolar,** "Integration of Leakage Inductance in Tape Wound Core Transformers for Dual Active Bridge Converters", Proceedings of the International Conference of Integrated Power Electronics Systems (CIPS 2012), Nuremberg, Germany, March 6-8, 2012

...Magnetics...

A. **What is the material in range 15kHz to 30kHz, especially at high ac flux density?**
B. **What about acoustic noise**
C. **What about orthogonal flux losses**
D. **What is material in very high frequency range?**



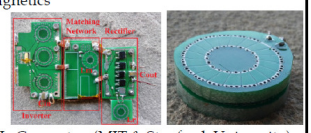
Prof. Kolar CIPS 2014

...Magnetics...

A. **What is the material in range 15kHz to 30kHz, especially at high ac flux density?**
B. **What about acoustic noise**
C. **What about orthogonal flux losses**
D. **What is material in Very High Frequency range?**
   - Key direction for future high level integration
     - High power density but @ high efficiency
       - Isolated dc-dc, **170kW/L**, extraordinary density !!
       - The key issue magnetics material and design

...Magnetics...

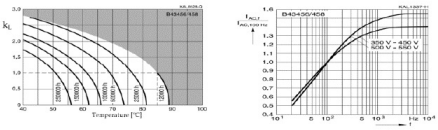
A. **What is the material in range 15kHz to 30kHz, especially at high ac flux density?**
B. **What about acoustic noise**
C. **What about orthogonal flux losses**
D. **What is material in Very High Frequency range?**
E. **What is material in Ultra High Frequency range?**
   - Most likely air-core magnetics



27.12MHz Converter (MIT & Stanford University)

...Power Capacitors...

Also, not progressing well
A. Electrolytic capacitors,
   - Life time and current capability



   - In some applications not very welcomed
     - PV Inverters
   - In some applications Electrolytic Caps are Must
     - Single phase converters

...Power Capacitors...

Also, not progressing well
A. Electrolytic capacitors,
B. Film capacitors,
   - Energy density
   - Current capability much better than Elec. Cap, but not enough

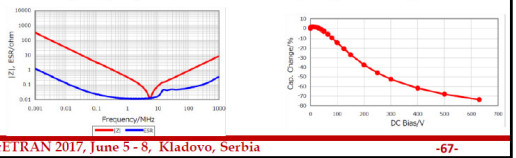
DC link capacitors, MKP-PBC-DG, B25832*

High-power DC capacitors, MKK, B25840, B25650, B25750

Low-inductance high-power capacitors, MKV LBI, B25856

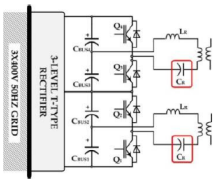
...Power Capacitors...

Also, not progressing well
A. Electrolytic capacitors,
B. Film capacitors,
A. MLCC capacitors (**Dielectric X6S, X7T, C0G**)
   - Energy density better than Film Capacitors but not good enough
   - Good Current Capability
   - Frequency dependent ESR and Voltage dependent Capacitance!



...Power Capacitors...What We Need?

- **Very high current capability @ moderate capacitance is required for resonant and switched capacitor converters**



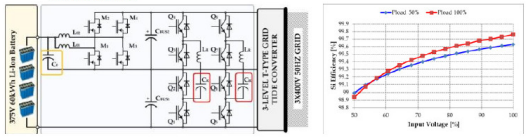
Series Resonant Converter (SRC)

I. **"Profi" Portable Welding Supply**
   - 500A 40V
   - 98% Efficiency
   - 2kW/kg
II. **"HV"DC Date Center Power Supply**
   - 54V 200A
   - 98.5% Efficiency
   - 3kW/kg

...Power Capacitors...What We Need?

Partial Power Rated Converter (PPRC)

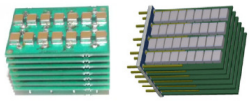
- Very high current capability @ moderate capacitance is required for resonant and switched capacitor converters



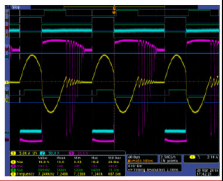
I. Energy Storage Interface DC/DC Converter
- 25kW
- 99.5%
- 25kW/kg & 50kW/dm^3

...Power Capacitors...What We Need?

- Very high current capability @ moderate capacitance is required for resonant and switched capacitor converters
  - 20kW Isolated dc-dc converter: 10-20μF, 450V & 30A RMS current capability (1.5-3 A/μF)
  - 25 kW balancing RSC converter: 5-10μF, 450V & 40A RMS current capability (4-8 A/μF)



23uF /100A @100kHz



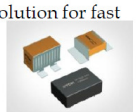
...Power Capacitors...What We Need?

- Very high current capability @ moderate capacitance is required for resonant and switched capacitor converters
  - 20kW Isolated dc-dc converter: 10-20μF, 450V & 30A RMS current capability (1.5-3 A/μF)
  - 25 kW balancing RSC converter: 5-10μF, 450V & 40A RMS current capability (4-8 A/μF)
- Electrolytic capacitors with significantly higher capacitance density, current capability and life time at low frequency is a MUST
  - For Single phase applications… Google-Little Box Challenge?

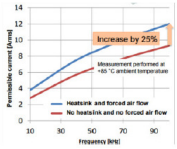
...Power Capacitors...Something New

EPCOS CeraLink™ Capacitors – The revolution for fast switching inverters

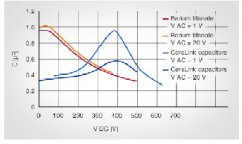
- Antiferroelectric capacitor technology



1μF 500V



- High Current Capability



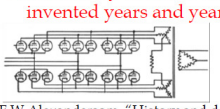
- High Capacitance at Operating Voltage

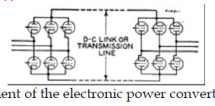
EPCOS AG 2015

... Topologies ...

...Topologies...

- Is there any new topology?
- Most likely NO…all "NEW" topologies have been invented years and years ago…

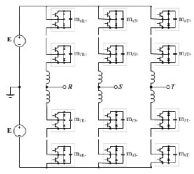


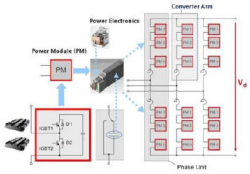


E.F.W Alexandersom, "History and development of the electronic power converter," Transaction on AIIE, Vol. 63, No. 9, 1944.

...Topologies...

- Is there any new topology?
- Most likely NO…all "NEW" topologies have been invented years and years ago…
- Modular Multilevel Converter is somehow new (already 10 years old)





...New (OLD) Topologies...
Multi-Cell Converters

-Split the load current into segments-

...Multi-Cell Converters...

Why we need to split the load (output) current into segments?

I. Good topic for (university) research,
II. Can we do something for passives (Inductors & Capacitors)?
III. Something else?
IV. And, is it a logical step?

...Multi-Cell Converters...

High power (and/or high performances) converters

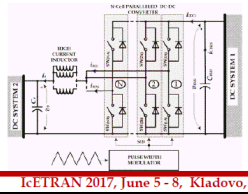
- Paralleling of power semiconductors is a need

...Multi-Cell Converters...

High power (and/or high performances) converters

- Paralleling of power semiconductors is a need

1. Direct Paralleling
   - Easy control, but
   - The current sharing is an issues..
   - No additional benefits

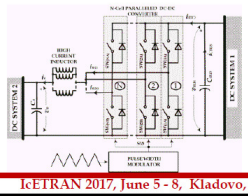


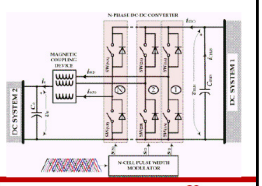
...Multi-Cell Converters...

High power (and/or high performances) converters

- Paralleling of power semiconductors is a need

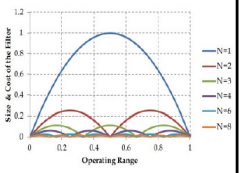
1. Direct Paralleling
   - Easy control, but
   - The current sharing is an issues..
   - No additional benefits
2. Paralleling with Interleaving
   - More expensive, but
   - Better performances (filter size/cost, losses, control...)

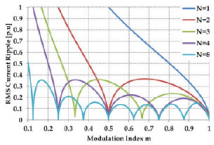


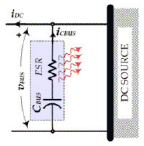


...Multi-Cell Converters...

- Harmonics Cancelation effect
- The input filter cost and size
- The DC Bus Current and DC Bus capacitor stress and losses

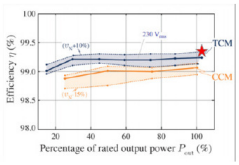


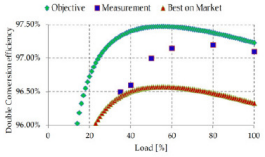




...Multi-Cell Converters...

- 99.3% Efficiency, single phase PFC/Inverter..
  - ETH /Professor J.W. Kolar
- 97.5 % Efficiency, double conversion 100kVA UPS
  - PCTL Huawei Technologies, Nuremberg
- All this would not be possible without Interleaving





...Multi-Cell Converters...

What ELSE?

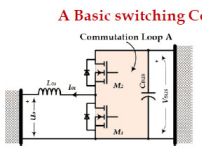
- Interleaving automatically means:

I. Reduced equivalent stray inductance of the switching cell, or
II. Reduced equivalent switching speed of a device
   - ⇒ Higher switching speed is possible
   - ⇒ Better utilization of WBG Devices

- Particularly case in low voltage high current applications
  - Even today with Si MOSFETs
  - In near future much more with WBG, particularly GaN

...Multi-Cell Converters...

A Basic switching Cell



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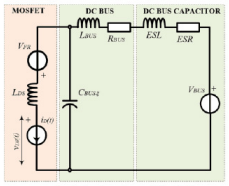


An Equivalent Model

The Switch Voltage Rating

A. Steady state
   1. Dc bus voltage,
B. Transient Over-voltage
   2. Total Commutation inductance,
   3. Commutation di/dt,
   4. Number of Cells N
   5. Forward recover voltage,
   6. Effect of resonance

$$V_{DS} = V_{BUS} + k_R \underbrace{\frac{L_\sigma}{N}\frac{di_D}{dt}}_{TRANSIENT} + V_{FR}$$

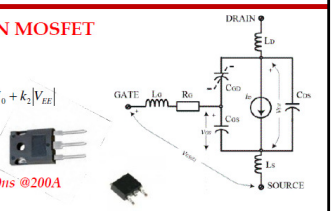
The Switch Total Voltage

...Multi-Cell Converters...

GaN MOSFET

Simplified linear model

$$\frac{di_D}{dt} = \frac{\frac{I_0}{g_m} + V_{GS(TH)} + |V_{EE}|}{\frac{R_G C_{ISS}}{g_m} + \frac{L_S}{N}} = k_0 + k_1 I_0 + k_2 |V_{EE}|$$



- $V_{GS(TH)}$=1-2V
- TO247 or TO220 Package
  - di/dt <0.5kA/μs ⇒ t_f>400ns @200A
    - *Losses ??*
- Even TO 252 and similar package makes no big difference

What is The Solution

I. Negative gate-source voltage V_{EE}
II. Kelvin Source, YES but not enough!
III. Reduced current per a chip-Interleaving

...Multi-Cell Converters...

- **Multi-Cell Conversion is a logical step for Low Voltage and High Currents applications!**
- **Only way to move forward with Si and**
- **Only way to use full benefit of WBG low voltage devices!!**

... New (OLD) Topologies... Multi-level Converters

-Split the input voltage into segments-

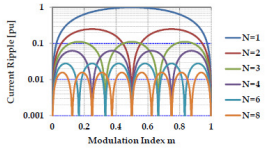
...Multi-level Converters...

Why we need to split the input (dc bus) voltage into segments?

I. Good topic for academic research, what else?
II. The filter size, mainly inductor

$$L \approx \psi = \Delta v_{L0} \Delta T \approx \frac{\Delta v_0}{f_{sw}} k_{op}$$

III. Reduce conversion losses
   a. Faster devices
   b. Lower voltage drop



...Multi-level Converters...

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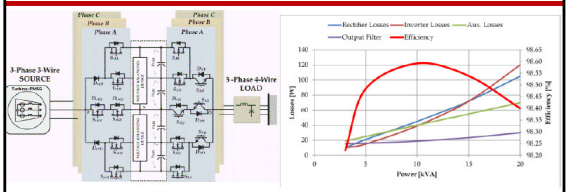
I. Good topic for academic research, what else?

...Multi-level Converters...



❖ M. Di Benedetto, P. J. Grbović, L. Solero, F. Crescimbini and A. Lidozzi, "**5-Level E-Type Back to Back Power Converters:** *A New Solution for Extreme Efficiency and Power Density*"
- 98.5% Double Conversion Efficiency
- 5.3kW/dm³
- 5kVA/kg
- Si Devices Only (no WBG)

...Multi-level Converters...

WHAT ELSE?

...Multi-level Converters...

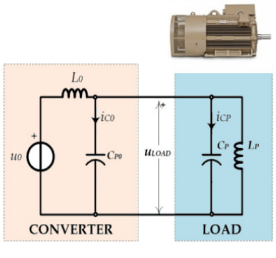
- **What about the load voltage and the load stress?**

C_P-The load parasitic capacitance

$$i_{CP} = C_P \frac{du_{LOAD}}{dt}$$

- Just an indication,
- Much more complex in the reality,

I. *dE/dt ≈ dv/dt* is critical for the load insulation
   - *dv/dt should be <10kV/μs*
II. Voltage reflection
III. The machine shaft parasitic current

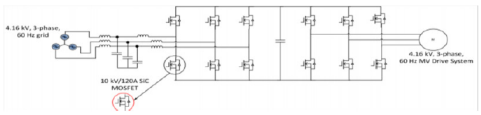


...Multi-level Converters...

- In General, electrical machines do not like high *dv/dt* stress
- BUT, what we are doing is completely opposite!!

...Multi-level Converters...

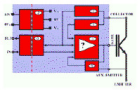
- In General, electrical machines do not like high *dv/dt* stress
- BUT, what we are doing is completely opposite!!
- SiC MOSFET, 10kV&120A @ 100-200ns
  - *35-70kV/μs*

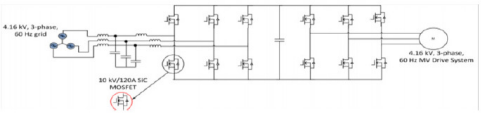


*Subhashish Bhattacharya, "High MegaWatt MV Drives", Dept. of ECE, FREEDM Systems Center NC State University

...Multi-level Converters...

- Can we use an active gate driver and slowdown the switching?





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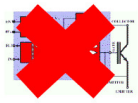

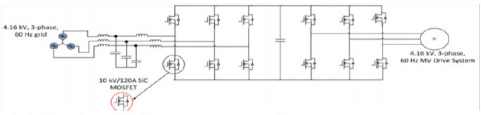

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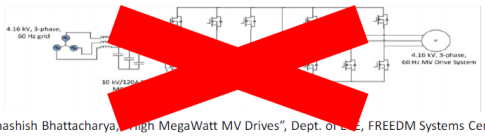
...Multi-level Converters...

- Can we use an active gate driver and slowdown the switching?
- Yes, but it does not make sense!!
- We Must split the dc bus voltage into segments and apply segment by segment on the load
  - Multi-level switching not 2-level switching



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...Multi-level Converters...

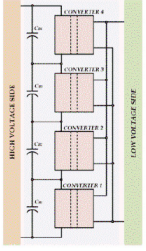
- **(Series) Multi-Level Conversion is only way to use full benefit of WBG devices in MV/HV Applications**

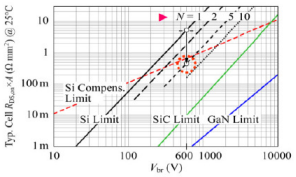
... New (OLD) Topologies... Multi-Cell & Multi-Level

-ISOP, IPOS,….-

...Multi-Cell & Multi-Level Converters...

- High Voltage Side-Series connected converters
- Low Voltage Side-Parallel connected converters

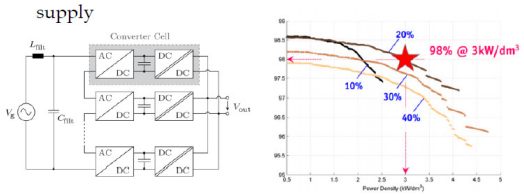




This is only way to go beyond the limit of Si devices

...Multi-Cell & Multi-Level Converters...

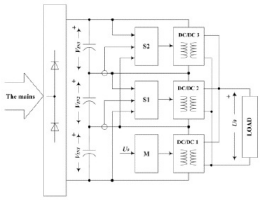
- ISOP based Ultra efficient and compact Telecom power supply

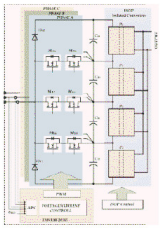


- **M. Kasper, J. W. Kolar and G. Deboy**, "98.5% / 1.5kW/dm³ Multi-Cell Telecom Rectifier Module (230VAC/48VDC) –Breaking the Pareto Limit of Conventional Converter Approaches" ECPE Workshop "Advanced Multi-cell / Multi-level Power Converters", 1-2 July, 2014, Toulouse, France

...Multi-Cell & Multi-Level Converters...

- Low Cost Aux. power supply
- 5-Level ISOP Rectifier



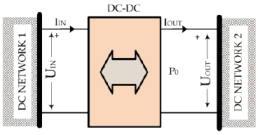


- **P. J. Grbović**, "Input Serial Output Parallel (ISOP) Connected High Voltage Power Supplies Based on Simple Master/Slave Control Technique", *IEEE Trans. Power Electronics*, Vol. 24, No. 2, pp. 316-328, February 2009.

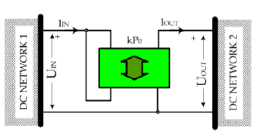
P. J. Grbović, F. Crescimbini, A. Lidozzi and L. Solero, "5-Level Unidirectional T-Rectifier and ISOP output Isolated dc-dc Converter," ECCE 2015

... New (OLD) Topologies...
Partial Power Rated Converters
-Process a Fraction of Power-

...Partial Power Rated Converters...

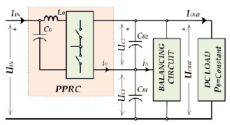


Full Power Rated Converter
- The converter is handling total power
- Size, Cost, Efficiency

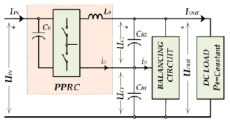


Partial Power Rated Converter
- The converter is handling just a fraction of total power
- Size, Cost, Efficiency

...Partial Power Rated Converters...

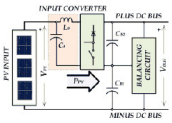


Boost Type

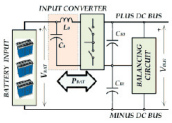


Buck Type

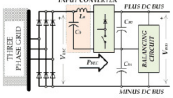
...Partial Power Rated Converters...



PV Boost & MPPT Optimizer

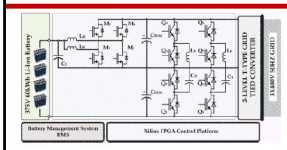


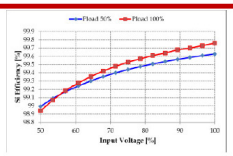
Energy Storage Interface



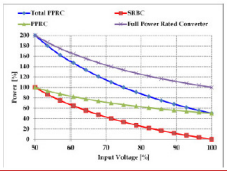
PFC

...Partial Power Rated Converters...





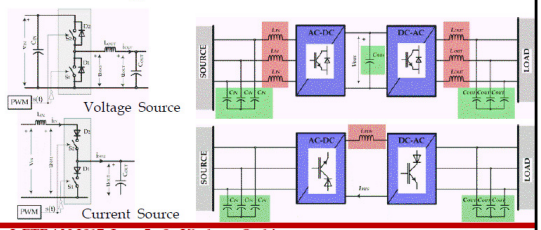
- **P. J. Grbović and J. A. Cobos**, "Partial Power Rated DC/DC Converters: A Way to Go Beyond the Limits"
  - 99.5% Efficiency
  - 50kW/dm³
  - 25kW/kg
  - Si Only (no WBG)!!



...Topologies...
Current Source Converters
-Switch the current instead of voltage-

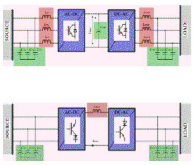
...Current Source Converters ...

- Theory of Duality
  - Voltage-Current, Inductor-Capacitor, Node-loop, Series-parallel
- PWM Voltage Source & Current Source Converter



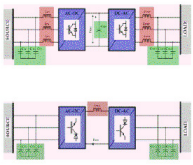
...Current Source Converters ...

- PWM Voltage Source Converter
  - 1 dc bus capacitor
  - 6 big filter Inductors
  - 6 Filter capacitors
- PWM Current Source Converter
  - 1 dc bus Inductor
  - 6 big filter Capacitors
- It looks very similar, is there any difference?



...Current Source Converters ...

- PWM Voltage Source Converter
  - 1 dc bus capacitor
  - 6 big filter Inductors
  - 6 Filter capacitors
- PWM Current Source Converter
  - 1 dc bus Inductor
  - 6 big filter Capacitors
- It looks very similar, is there any difference?
- Yes, specific energy of an inductor and a capacitor is very different
- Film Capacitors W_C=40-80 [J/kg]
- Medium frequency Inductors W_L=0.2-1 [J/kg]



...Current Source Converters ...

- It seems a power converter of the Future is PWM Current Source
  - But, is it as easy as it looks like?

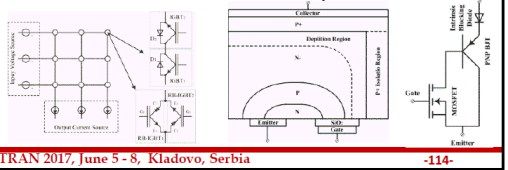
...Current Source Converters ...

- It seems a power converter of the Future is PWM Current Source
  - But, is it as easy as it looks like?
- Existing power semiconductor devices are perfectly matching to PWM Voltage Source Converters requirement
  - Current bi-directional switch
- PWM Current Source Converter requires different switch
  - Voltage Bi-directional Switch, but high frequency
- This should be focus for future research in the Arena of Power Semiconductors

...Current Source Converters ...

Reverse Blocking IGBT

- An IGBT is naturally reverse blocking device, but....
- Not required in most of applications
  - Minimized to optimize the switching performances
  - Typically 10-50V
- Matrix and current source converters requires full RB capability
- Additional p+ layer provides full RB capability
  - An "intrinsic" blocking diode
- Better conduction performances, but worst switching (turn-off)
  - Preferred solution in low frequency range <10kHz
- The same dynamic modal as an ordinary IGBT



...Digital Signal Controllers ...

...Digital Controllers...

- Digital Signal Controllers dedicated for Power Conversion Applications
  - TI Delfino TMS 28335, 28337…
    - Up 18 PWM, 16 ADC (80ns)…150-300MHz..15-25$...

Do we need something better?

...Digital Controllers...

- Digital Signal Controllers dedicated for Power Electronics Apps.
  - TI Delfino TMS 28335, 28337…
    - Up 18 PWM, 16 ADC (80ns)…150-300MHz..15-25$...

Do we need something better?

Yes, we do!!

- 3-phase 3-level 3-cell Inverter:
  - →36 PWM
  - →13 ADC
- Smart Grid Battery Converter and Interface:
  - → 48 PWM
  - →20ADC

...Digital Controllers...

- Digital Signal Controllers dedicated for Power Electronics Apps.
  - TI Delfino TMS 28335, 28337…
    - Up 18 PWM, 16 ADC (80ns)…150-300MHz..15-25$...

Do we need something better?

Yes, we do!!

- Control Frequency >100 to 200kHz → Interrupt Period <5 to 10 μs

...Digital Controllers...

We would need a customized DSC/FPGA/ASIC with:

A. up to 48 PWM channels,
B. up 16 to 32 ADC
   - <50ns acquisition time
C. Control frequency up to 1MHz
D. Simple UART Communication

NI System on Module (SOM

...High Level Control…

...High Level Control...

- Not many things to be done on the converter level control
  A. Very Fast current control and Active Damping (Multi-Cell/Level Converters)
     - L_0<0.2% f_0 >10-15kHz
  B. Multi-converter & Grid Interaction Control, and
  C. Virtual Inertia Control for Grid connected. Converters
     - **This is not Only Control issue, this is Energy Storage and the System Design**
  D. Extremely fast voltage control for CPU power supply
     A. Load disturbance >600A/μs

...High Level Control...

- High Level Control Issues
  A. On-line monitoring,
  B. End of Life prediction
     - Electrolytic capacitors,
     - Electrochemical batteries
     - Power semiconductors
  C. Self tuning and Plug & Play feature

...At the end of the day, is it correct what we are doing?...

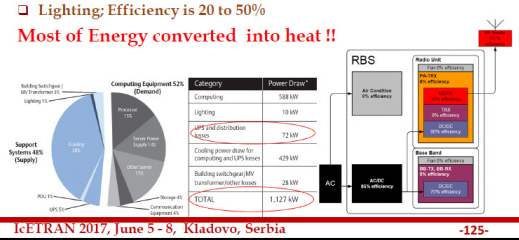
..?????..

- Loss-free power conversion system does not exist!
  - Energy wasting, and need for a bulky heat sink!
- **Data Center ; What is Efficiency ???**
- **Radio Base Stations; What is ???**
- **Lighting; What is Efficiency ???**

..?????..

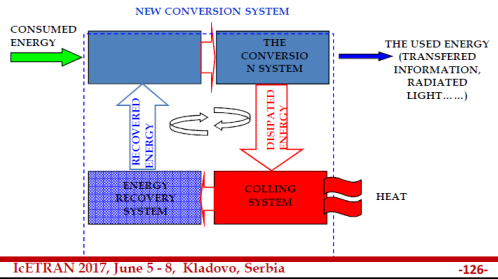
- Loss-free power conversion system does not exist!
  - Energy wasting, and need for a bulky heat sink!
- Data Center; Efficiency is 0%
- Radio Base Stations; Efficiency is 2 to 10%
- Lighting; Efficiency is 20 to 50%

Most of Energy converted into heat !!



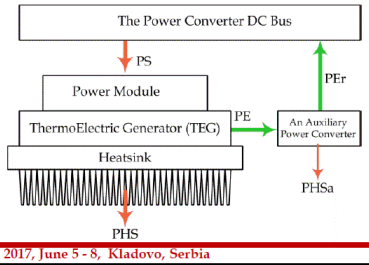
..?????..

- We need to recover the energy from the heat…



..?????..

- Use Thermo-Electric Generator & Power Converter to converter a part of heat into electric energy and re-use it in the system



Thank You Very Much for Your Time

Any question at any time, be free to contact me

petar.grbovic@gmail.com
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