Medium-Voltage DC Grids for Future Distribution Systems

China International Conference on Electricity Distribution 2014

23.09.2014

Dr.-Ing. Hanno Stagge
Presentation Outline

- "Energiewende" (Energy Transition) needs flexible grids
  - Introduction
  - Future Energy Scenario for Europe
  - Voltage levels
  - Technical problem of AC to achieve flexible grids

- Overview DC conversion technology

- Summary and Conclusions
  - Key innovations
  - Standardization required (FEN consortium Aachen)
Considering the German Federal Government CO₂ targets and nuclear fission policies, several studies come to the conclusion that the only viable options for 2030 and 2050 are:

- 2030  ➔ 100% of all electrical energy should come from renewables
- 2050  ➔ 90% of all primary energy should come from renewables

This implies increased use of electrical energy (as already suggested in earlier EU-DGTREN studies, to reduce CO₂) to minimize fossil fuel consumption by increased efficiency and increased automation (smarts)
All scientists and engineers agree: aside from fusion, there is no “silver bullet” solution. Hence, many local solutions will co-exist that are adopted to local geographical, meteorological and economical conditions, policies and regulations → flexibility at all levels is needed

Challenges of large scale use of renewables for electrical grids:

≡ On the one hand many small decentralized units connected to distribution and low voltage grid (micro- and mini-CHP, Wind, PV, solar, “prosumers”)

≡ On the other hand many large-scale wind farms, PV farms and solar power stations, that have to transmit the energy over long distances

≡ Power generation of wind and solar (PV) is volatile, which requires medium and long-term energy storage
2000 – Before Market Liberalization (EU29)
Large centralized power plants, little coupling between grids
2010 – Ten Years after Market Liberalization
Fast growing market of decentralized generation

ELECTRICITY GRID

- Wind Offshore: 3 GW, 7 TWh
- Wind Onshore: 82 GW, 143 TWh
- Photovoltaic: 25 GW, 23 TWh
- HV Transmission: 515 GW, 2900 TWh
- MV Distribution: 25 GW, 110 TWh
- Central Power Station: 41 + 185 GW, 520 TWh
- Hydro Power
- Biomass & Waste Power: 0.6 GW, 5 TWh
- Geothermal Energy: 45 GW, 245 TWh
- Mini CHP ~ 10 MW

HEAT GRID

- Gas Storage

GAS GRID

Min. 280 GW, max. 560 GW
Capacity 850 GWp
+/− 3967 TWh

2010 electricity mix
EU27 + Norway + Switzerland

PGS Power Generation and Storage Systems
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Concept for a CO₂ Neutral Electrical Energy Supply System
Technically Possible - Scenario for EU-27 + 2 (linear extrapolation)
Interesting observation: transmission system may need minimal upgrade to DC. ETG Task Force claims that DC can be integrated at lower cost in existing infrastructure.
Interesting observation: medium voltage distribution grid will need upgrades as it becomes an exchange platform between local producers and prosumers.
Interesting observation: Low-voltage distribution in factories, buildings and homes needs to exchange energy flexibly to MV grids to provide D$^2$SM and storage functionality.
What is the fundamental technical problem? (and can it be solved?)
Electrical AC grids have intrinsically little energy storage, have no fast response capability and have little automation and, worst of all, the topology does not fit...
Main Technical Problems of Classical AC Grids
Transmission is interconnected, but MV and LV AC grids are radial
Main Technical Problems of Classical AC Grids
Radial AC grids offer simple coordination
Main Technical Problems of Classical AC Grids
Radial AC grids offer high reliability but are grossly underutilized
Main Technical Problems of Classical AC Grids
Prosumers must exchange energy via transmission grid
Future Flexible MV grids should be interconnected
Exchange between prosumers possible
Future Flexible MV grids should be interconnected
Higher redundancy with high utilization of distribution grid possible
This will require DC technology, because it is more efficient, more reliable, more flexible and a lot cheaper to link grids and prosumers.
Medium-Voltage DC Grids
Electronic Transformer – “Edison’s missing Link”

- Power of 5 – 20 MW per unit, scalable to a power of several GW
- Highly efficient (up to 99,2 %)
- Medium-frequency transformer (500-2000 Hz)
  ≡ Transformer reduction of weight by factor 10

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Developed 5 kVA DC/DC converter test system for control implementation

Modified IGCT stack CAD layout for soft-switching operation

Transformer litz winding during assembly

Dc-dc converter operating range for highest efficiency. Diagram showing transformer currents

Characterization of high-power IGCT series connection

Measured three-phase transformer excitation

Developed 5 kVA DC/DC converter test system for control implementation

PhD Thesis Dr. R. Lenke, 2012
Limited power of single converter
Parallel / series connection
- Reduced size of capacitor with proper control
Similar modules could be manufactured for various applications
Combination of storage systems with existing HVDC concepts is possible
Device Selection for DAB

- 4.5 kV device
- × 5.5 or 6.0 kV device
- + 6.5 kV device

$E_{off}$ in mJ/A vs $V_{on}$ in V

$FoM$ in V·mJ/A
Medium-Frequency Transformer

- Predominant core losses at medium frequency
  - Very thin lamination to suppress eddy currents
  - Amorphous iron and silicon steel are evaluated

- Measurements at medium-frequency for both materials were carried out
  - Amorphous iron provides very low hysteresis losses but production is difficult and costs are higher
  - Higher power density using silicon steel due to increased saturation flux density and increased thermal conductivity but slightly higher no-load losses

  - Trade-off between cost and efficiency but efficiencies are very similar
  - Core cost may determine choice

PhD Thesis Dr. R. Lenke, 2012
Efficiency Measurements and Calculation

- Calculation based on synthetic tests:
  - Measured losses of semiconductor switches
  - Measured transformer losses (300 kVA)
- \( P = 7 \text{ MW}, \ V_{DC} = 5 \text{ kV} \pm 10 \% \)
- Efficiency up to 99.2 \%
- Ultimately air-cooled devices are an option

*PhD Thesis Dr. R. Lenke, 2012*
Multi-terminal HVDC (Overlay Grid) with Standard AC Collector Fields and AC Grid – high conversion losses

Conversion losses for off-shore ca. 11%
Multi-terminal HVDC with MVDC Collector Field and DC Grids – higher efficiency

Conversion losses for off-shore ca. 5%
Summary and Conclusions

- The “Energiewende” will move us towards:
  - More electrical systems
  - More decentralized energy production
  - Greater diversity in energy sources (energy scavenging)
  - More smarts
- Distribution System Design will determine success of Energiewende
- Power electronics will remain the most important key enabling technology that allows flexible and efficient energy conversion to control the (smart) electrical grid
- Increased use of power electronics makes DC grids a viable alternative, as DC cables can be integrated in existing infrastructure and are perceived to be acceptable by society
Future – 100% Renewable Electrical Energy Supply
Technically Possible Scenario requires PEL

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Future – 100% Renewable Electrical Energy Supply
Technically Possible Scenario requires PEL and ICT and PEL

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Future – 100% Renewable Electrical Energy Supply
Technically Possible – Key Innovations

- Medium Voltage DC
- Smart Homes
- Emobility
- ICT Centers
- Thermal
Summary and Conclusions

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Needs experience and standardization – FEN Consortium
Overview Forschungscampus Future Electrical Networks

- To achieve a higher generation of electricity from renewable power sources, the electrical grids have to
  - be able to operate with higher flexibility,
  - transport and distribute energy with increased efficiency

- DC technology shows a high potential to achieve these goals

- The Forschungscampus Future Electrical Networks (FEN) will facilitate fundamental innovations from joint pre-competitive research together with industry partners
  - Components
  - Services
  - Standards and guidelines

- The German Ministry of Education and Research (BMBF) will support research at RWTH Aachen University with 30 M€ for 15 years
Research Activities

- Lighthouse-project MVDC Research Grid
  - Multiple test benches of RWTH Aachen University will be connected with a medium-voltage DC grid
  - The grid will be used for research and to develop standards

- 15 professorships of RWTH Aachen University will work together in multiple layers on different research topics
  - Materials and components
  - Technical realization
  - Planning
Lighthouse Project
Research Grid on University Campus

- 4 MW CWD
  Test bench for wind energy converters

- 0.1 MW EHome
  Research project smart home, connection to medium-voltage

- 1 MW IME
  Heavy Drive Train Center

- 5 MW PGS
  Test bench for power electronics and electrical drives
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Vision LV prosumers
Electric vehicles and “Smart Homes” – AC

New build smart home will require more cooling power than heating (HVAC)

Requires expensive battery charger with PFC and EMI filters
The smart home with DC will be smarter!

New build smart home will require more cooling power than heating (HVAC)
New build smart home will require more cooling power than heating (HVAC)
Retrofit AC cables
DC doubles power capacity of standard building wire

- Installation cable voltage rating
  - 300Vac : Phase – Ground
  - 500Vac : Phase – Phase

- Cable power transmission capacity
  - ① Three-Phase Cable :
    - $U_{N,ac} = 230$Vac , $I_N = 16$Arms , $\lambda = 0.95$
    - $P_N = 3 \times U_{N,ac} \times I_N \times \lambda = 10,488$ W
  - ② DC Cable
    - Single Pole Cable : $U_{dc} = \sqrt{2} \times U_{N,ac} = 325$ Vdc , $P_N = U_{dc} \times 2 \times I_N = 10,400$ W
    - Double Pole Cable : $U_{dc} = 2 \times \sqrt{2} \times U_{N,ac} = 650$ Vdc , $P_N = U_{dc} \times 2 \times I_N = 20,800$ W
Material savings in transmission
Increased power transmission with DC

- Same mast (DC improves life)
- Same safe operating area
- The transmission capacity could be increased by a factor of 3.5 (with redesign)
- The transmission capacity would have been increased by a factor of 2.0 by just converting to DC (without redesign)
GERMANY has a problem. The decision to close down power stations risks leaving the country with insufficient supplies of electricity. Power will have to be brought in from elsewhere. One alternative is to make better use of existing lines. In theory, the simplest way of doing so would be to run direct current through them, instead of the existing alternating current. AC suffers transmission losses around 6%. With newer technology the transmission of high-voltage DC would reduce those losses and thus provide more capacity, but it is technically awkward. An experiment by Amprion and TransnetBW suggests it could be easier than engineers had feared... The only things that need be changed are the insulators. Doing that will be much easier than building a whole, new line.
Material savings in transmission
HT-Superconductor at 10 kV cheaper than 110 kV GiL in Essen
Germany's energy transformation

Energiewende
German plans to cut carbon emissions with renewable energy are ambitious, but they are also risky

Jul 28th 2012 | BERLIN AND NIEBÜLL | from the print edition

The rest of the world watches with wonder, annoyance — and anticipatory Schadenfreude ... To many the Energiewende is a lunatic gamble with the country’s manufacturing prowess. But if it pays off Germany will have created yet another world-beating industry, say the gamblers. Alone among rich countries Germany has “the means and will to achieve a staggering transformation of the energy Infrastructure” ...

Much could go wrong. Wholesale electricity prices will be 70% higher by 2025, predicts the Karlsruhe Institute of Technology. Germany must build or upgrade 8,300 km (5,157 miles) of transmission lines (not including connections to offshore wind farms). Intermittent wind and sun power creates a need for backup generators, while playing havoc with business models that justify investing in them.
„...the grid reconversion remains the achilles heel of the Energiewende“

Three-Phase Dual Active Bridge Converter, Waveforms

- $U_T$
- $2U_{in}/3$
- $-2U_{in}/3$
- $I_t$
- $I_{s1}$
- $I_{prim}$

phase 1 primary secondary

$I_{mag}$ neglected

$N_1/N_2 = 1$

$U_{in} > U_{out}$
DAB Soft-Switching Range

\[ \frac{U_{\text{DC, out}}}{U_{\text{DC, in}}} \]

- Primary bridge hard-switched
- Secondary bridge hard-switched
- Both bridges soft-switched

\[ \frac{P}{P_N} \]
DAB Zero-Voltage Switching

Upper switches conduct current

Upper snubber capacitors charge, lower snubber capacitors discharge

Lower diodes conduct current, Lower switches turn-on at zero voltage

Lower switches take over current without turn-on losses

Snubbered turn-off upper switches

Lower capacitor voltage reaches zero

Current reversal initiated externally
Soft-Switching Operation of DAB

- Snubbered turn-off with capacitors greatly reduces switching losses
  - Reduced stress on insulation with smaller $dv/dt$
  - Voltage balancing ensured in high-voltage converters
- Low-saturation and fast-switching IGCT and IGBT devices evaluated
  - Up to 80% reduced switching losses @ 1 kHz
  - Fast-switching IGCT offers lowest losses

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*PhD Thesis Dr. R. Lenke, 2012*
Hybrid Switches for High-Voltage DC

- Challenge: no natural zero crossing in dc systems
- Combination of semiconductors with mechanical switches: hybrid circuit

Source: Cigre, Bologna 2011
Tendencies

- Prices of metals continue increasing (Copper, Si-Steel)
- Prices of silicon keeps going down (Inverters from 500 €/kVA down to 25 €/kVA over past 25 years, down to 5 €/kVA by 2020) due to increase production volumes, new generations of power semiconductors and higher switching frequencies and voltage levels

Milestone: in 2013 breakeven was reached between inverter and 50 Hz transformer cost approx. 20 €/kVA
Material usage in power transformers
Frequency matters!

Weight distribution of copper and Si-steel in machines and transformers:
Copper: 25 – 30 %
Iron lamination: 70 – 75 %
Specific weight Fe: 8 g/cm³
Specific weight Cu: 9 g/cm³

50 Hz Transformer: 2.5 kg/kVA

1,000 Hz Transformer: 0.25 kg/kVA
AC grids are based on transformer technology

- Designed for top-down energy transmission
- Constant voltage and constant frequency
- Flexible AC grids (FACTS) will require major investments in infrastructure and power electronic energy conversion and storage systems

In 2000, EU29 had 685GW installed capacity, i.e. 13.7 Mton on Cu and Si-Steel in generators and transformers, i.e. 109.6 B€ (at price of 8 €/kg)

20,000 ton/GW
Renewables will require 17.8 Mton Cu & Fe at cost of 142 B€
Renewables will require 9.1 Mton Cu & Fe at cost of 73 B€
In conclusion - AC versus DC
Cost for active power only (no FACTS), efficiency at rated power

<table>
<thead>
<tr>
<th></th>
<th>AC classic</th>
<th>AC CO(_2) neutral</th>
<th>DC CO(_2) neutral</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency of converters</td>
<td>94%</td>
<td>89%</td>
<td>95%</td>
</tr>
<tr>
<td>Weight Transformers</td>
<td>13,7</td>
<td>17,8</td>
<td>9,1</td>
</tr>
<tr>
<td>Cu/Si-Fe (Mio. ton)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Cost Transformers</td>
<td>110</td>
<td>142</td>
<td>73</td>
</tr>
<tr>
<td>(B(\varepsilon) @8(\varepsilon)/kg)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost PEL Converters</td>
<td>-</td>
<td>36 + FACTS 9 + FACTS</td>
<td>60 15</td>
</tr>
<tr>
<td>(B(\varepsilon) @20 (\varepsilon)/kVA)</td>
<td>(B(\varepsilon) @ 5 (\varepsilon)/kVA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum (B(\varepsilon))</td>
<td>110</td>
<td>178 + FACTS 151 + FACTS</td>
<td>133 88</td>
</tr>
<tr>
<td>Sum (B(\varepsilon))</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Grid transmission capacity</td>
<td>100 %</td>
<td>100 %</td>
<td>&gt; 200%</td>
</tr>
</tbody>
</table>

All numbers are estimates anno 2014, hybrid AC/DC solutions were not considered
R. De Doncker, “Power electronics – the key enabling technology for flexible DC Distribution Grids”,
IPEC-IEEE ECCE 2014, Hiroshima, Japan, May 2014,
ICT - Concept

- Commutation of full anode current at turn-off
- Pre-charge value of gate voltage influences
  - Commutation
  - Power consumption

→ $L_\sigma$ and $R_\sigma$ as low as possible:
  → High number of MOSFETs and capacitors in parallel

Allowed stray inductance at $I_L = 4 \text{ kA}, t_s = 0.8 \text{ \mu s}$

Source: ABB
ICT - Concept

- Integration of key components into the press-pack

Classical IGCT:

ICT:

- Requirements for components of the turn-off unit
  - Low volume
  - High pulse current capability
  - High temperature capability
  - High cycle reliability
ICT – Turn-Off Unit

- Assembly below the gate spring contact
- Cooling with press-pack case
- Use of MLCC and Direct-FETs
- Electrical data
  - $300 \text{ A per submodule}$
  - $1 \text{ kHz switching frequency}$
  - $350 \mu\text{F capacitance}$
ICT - Realization

- Idea: Use of a GCT with gate ring on the outside
- Turn-off units
  - Easy connection
  - Ring under the outside of the GCT
- Very short commutation path
- No influence on the heat transfer from the GCT wafer
No GCT available with outside gate ring
- Construction in modified package
- Contacts to middle part of standard wafer
  - Rated current ca. 1050 A
ICT – Prototype
ICT – Turn-Off Measurements

- Test conditions
  - DC-link voltage: 2.8 kV
  - Device temperature: 25°C
- Current turn-off capability depending on negative gate voltage
  - 1080 A with -10 V
  - 1260 A with -15 V
Conclusions: ICT

- Smaller semiconductor device
- Higher SOA
- Reliability
  - No electrolytic capacitors
  - Lower ambient temperature at GDU
  - Lower part count for driver including turn-off unit
- Lower power consumption of driver:
  - Around 60% in turn-off unit
    → Reduction of ca. 30%
- Mechanical design
  - Higher flexibility with a standardized GDU
  - Cable connection from driver to power part
IETO - Concept

- Emitter Turn-off Thyristor (ETO)
  - With second MOSFET capacitors can be left out

Advantages:
- No turn-off capacitor unit
- Current sensing via $S_K$ possible (short-circuit detect)
- MOS turn-off unit (voltage controlled)

Disadvantages:
- Additional conduction losses due to $S_K$
- Main current path is partly outside the press-pack
- Undefined error state

Source: Emitter Turn-off (ETO) Thyristor, ETO Light Converter and Their Grid Applications; A. Huang et al.; 2009
Comparison: IGCT vs. IETO

- IGCT driver stage
  - 300 parts
  - PCB: 220 x 190 mm², 4 layers

- IETO driver stage
  - 123 parts
  - PCB: 80 x 54 mm², 2 layers
  - No electrolytic capacitors

- IETO driver stage is a lot cheaper

- GDU power loss reduced by 75%

- SOA: ca. 670 kW/cm² IETO vs. 300 kW/cm² IGCT
Dual-ICT - Concept

- Technology curve of the semiconductor
- Idea: parallel connection of conduction-optimized and switching-optimized GCT
- Monolithically integrated onto a single wafer
- With intelligent control the overall losses can be reduced
Dual-ICT: Components

- Dual-GCT silicon wafer disc
- Package
  - (Turn-on unit)
  - Turn-off unit
- GDU
  - Logic
  - (Turn-on unit)
  - Holding current GCT A and GCT B
  - Short circuit detection
  - Power supply
  - Communication
**Dual-ICT: Summary**

- Additional process steps necessary during wafer production

- High increase of ratings
  - $V_{DC}=3000 \text{ V}; \quad I_L=2200 \text{ A at } f = 800 \text{ Hz possible (vs. } 200 \text{ Hz)}$

- Reliability
  - Lower ambient temperature at the GDU
  - Lower part count, only 50% in driver stage including turn-off unit

- Lower power consumption of the driver unit

- Mechanical design
  - Higher flexibility with a standardized GDU
  - Cable connection from driver to power part
Conclusions

- Continued development of power semiconductor devices is still a driving factor to reduce overall power systems cost for medium-voltage dc-dc converters
  - Research on new materials
  - New packaging technologies
  - Improved integration of driver circuits
Dual-Active Bridge

- DC-DC converter suitable for high-power and medium-voltage applications
- Inherent soft-switching capability
- Galvanic isolation via build-in transformer
  - Operation at elevated frequency (1 kHz @ 2.2 MVA, 3.6 kV)
  - Increased power density
  - Lower core losses
Transformer Voltage and Currents

- Transformer operated with a square-shaped voltage
- Phase shift between primary and secondary voltage determines transferred power
Transformer-Core Materials

- Frequency limited by power-electronic switches (IGCTs)
- Typical switching frequencies in hard-switched applications 400 ... 600 Hz
- Target frequency for soft-switched applications 1000 Hz
  - Potential to increase the frequency further

- Suitable core materials
  - Silicon steel (0.18 mm)
  - Amorphous iron
  - (if frequency can be increased)
    - Nanocrystalline
    - Ferrites
Comparison Sinusoidal vs. Square Wave

- Epstein test bench allows arbitrary voltage profile
- Lower core loss measured at square-wave excitation
  - Less area spanned by hysteresis loop
  - Lower $dB/dt$

➢ Validation using Steinmetz equations
Steinmetz Parameter Extraction

- Si-Steel samples characterized on same Epstein Test Bench
- Parameter extraction using sinusoidal excitation
  - Original Steinmetz Equation (OSE)
    \[ \alpha = 1.6155 \quad \beta = 1.7021 \quad k = 5.2 \cdot 10^{-4} \]
- Results are validated using improved Generalized Steinmetz Equation (iGSE)
The question:

Why did we use AC grids in the first place?
Because when the age of electricity started, only AC could be easily and efficiently converted for transmission and distribution.
In the beginnings there was Direct Current (DC) Distribution

- Edison’s Pearl Street installation (1882)
  - Local dc supply for incandescent lighting in lower Manhattan, New York
  - 6 constant current dynamos (invented by Werner Siemens) with 100 kW each
  - Two-wire 110 V distribution, soon replaced by three-wire 200 V system

- Disadvantages of early dc
  - Low voltage, high currents
    - High cost due to large amount of copper
    - Only limited distance between generation and load possible
  - No “dc transformer” available

Source: IEEE Power & Energy Magazine
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Source: IEEE Power & Energy Magazine
The Rise of Alternating Current (AC)

- Development of ac systems starting in the 1880s
  - Voltage transformation using “secondary generators” (Gaulard and Gibbs)
  - Development of polyphase ac motors and other ac equipment (Tesla, Westinghouse)
- The final breakthrough of ac
  - Illumination of the 1893 Chicago World’s Fair
  - Accelerating decline of dc distribution
- Long-distance ac transmission in the 1890s (Niagara project)

Source: IEEE Power & Energy Magazine
First rotating AC-DC converters

Source: US patent 373035 – G. Westinghouse
The Rise of Alternating Current (AC)

- However, AC was a compromise as it was more difficult to control voltage at user end.
- Power quality standards require precise control of voltage and frequency, this can be partially solved by VAR compensation and active power control (nowadays FACTS).
- Problem: no market interest in FACTS.

\[ V_{\text{Gen}} = j\omega L_N \cdot I + R_N \cdot I + V_{\text{Load}} \]

\[ V_{\text{Gen}} + V_{\text{Load}} = V_{\text{Load}} + V_{\text{Gen}} = \text{prosumer} \]
Where are we located?
Founded in 1870; one of the largest technical universities in Europe
130 degree courses
498 professors (46 Junior Prof.)
40,375 students (57% Engineering)
  ≡ 5,244 graduates, 7,288 new enrollments
8,185 employees
  ≡ 2,031 research associates
  ≡ 3,000 third party research associates
  ≡ 718 apprentices and interns
830 M€ Budget
E.ON Energy Research Center: Overview

- June 2006: the largest research co-operation in Europe between a private company and a university was signed.
- Five new professorships in the field of energy technology were defined across four faculties.
- Research areas: energy savings, efficiency and sustainable power sources.

**Institute Profiles**

- **ACS**: Institute for Automation of Complex Power Systems
- **EBC**: Institute for Energy Efficient Buildings and Indoor Climate
- **FCN**: Institute for Future Energy Consumer Needs and Behavior
- **GGE**: Institute for Applied Geophysics and Geothermal Energy
- **PGS**: Institute for Power Generation and Storage Systems

**Faculties**

- Electrical Engineering & Information Technology
- Mechanical Engineering
- Business and Economics
- Georesources & Materials Engineering
Institute for Power Generation and Storage Systems (PGS)

- Decentralized power generation
- Power electronic energy conversion systems for renewable power generators
- Flexible medium and small-scale power plants
- Flexible, multi-terminal electrical networks
- Linkage of electricity, heat and gas grid
- Electrochemical energy conversion and storage systems

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Research, develop and apply power electronic conversion and storage technologies (medium voltage building blocks) to significantly improve performance of generation (efficiency, life cycle cost, flexibility), storage, medium-voltage distribution and multi-terminal DC transmission systems.

This requires

- Design, fabrication and testing of high-power semiconductor switches
- Development, design and testing of medium-voltage power converters (AC-DC and DC-DC converters) and high-speed drives
- Development, design and testing of fast hybrid switches and electronic substations for DC distribution and transmission systems.
- Analysis and control automation of mini-power (MW) power plants
- Analysis, design and development of electrochemical energy conversion and storage systems (batteries and electrolyzers)
- Development of controller hardware and real-time emulators