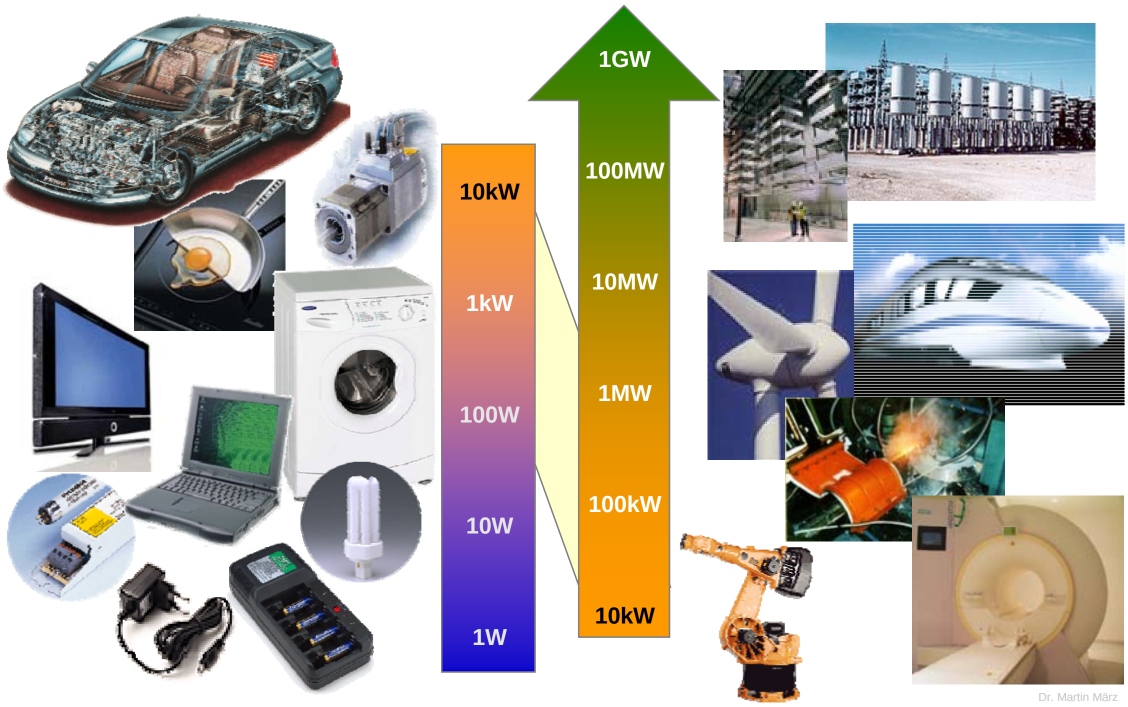
EUROPEAN POWER ELECTRONICS AND DRIVES

Position Paper

on

Energy Efficiency – the Role of Power Electronics



March 2007

ECPE European Center for Power Electronics, Nuremberg

EPE European Power Electronics and Drives Association, Brussels

Position Paper

Energy Efficiency – the Role of Power Electronics

1. Introduction and Background

Energy saving, improved energy efficiency and environmental protection are ubiquitous topics in society, in Europe and globally. Despite many efforts to save energy, demand for electricity is expected to grow and much faster in comparison with other energy sources over the next three decades. Today 40% of all energy consumption is in electrical energy, but this will grow to 60% by 2040. On the other side, the share of electrical energy which will be controlled by power electronics e.g. in variable speed drives will increase from 40% in 2000 to 80% in 2015.

Power electronics is the key technology to control the flow of electrical energy from the source to the load precisely according the requirements of the load. It is responsible for the reliability and stability of the whole power supply infrastructure in Europe from the sources, the energy transmission and distribution up to the huge variety of applications in industry, transportation systems and the home & office appliances.
But in spite of the tremendous importance of power electronics, there is a lack of awareness for the role of power electronics in the modern industrial society, even in the well informed general public.

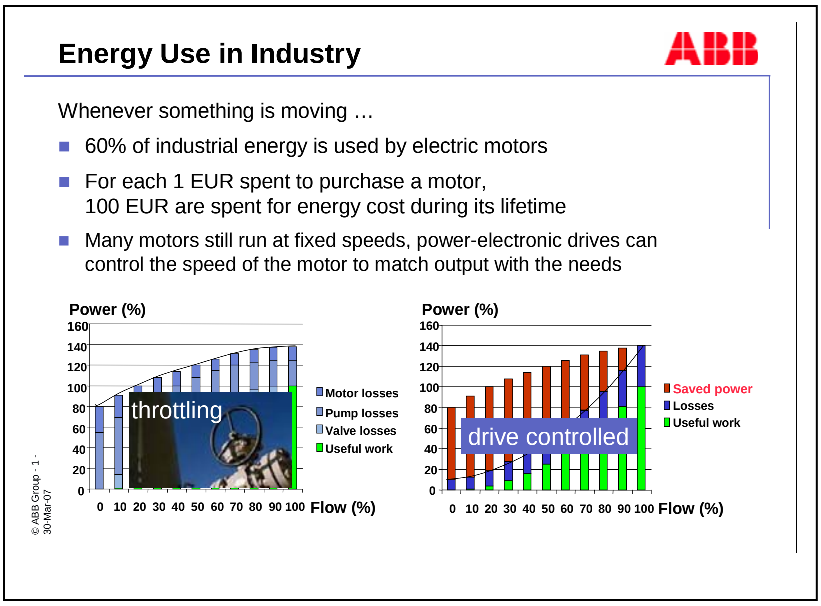
However, power electronics industry and the related research environment today are faced with several problems such as:

1. The impact of power electronics technology to provide a reliable and precisely controlled power source in all areas of life is not known in public.
2. The energy saving, which is possible in the very short-term by using power electronics technologies available today, in a wide range of applications is not utilized.
3. The tremendous potential to save energy in a sustainable way by developing new technologies on the whole power supply chain including the consumer units is not understood.
4. Furthermore, it is clear that power electronics does not have the appeal in the public and politics eye compared to e.g. microelectronics and nanotechnology, with a negative impact on attracting students and the allocation of research funding.

Power Electronics is a cross functional technology covering the extreme high Giga Watt (GW) power e.g. in energy transmission lines down to the very low milli Watt (mW) power needed to operate a mobile phone.

This position paper highlights the contribution of power electronics to reduce energy consumption, and the technologies which will be needed to develop to elevate Europe in the future to a leading position in terms of

- saving electrical energy,
- ensuring a reliable power supply infrastructure,
- employment through a competitive power electronics industry.



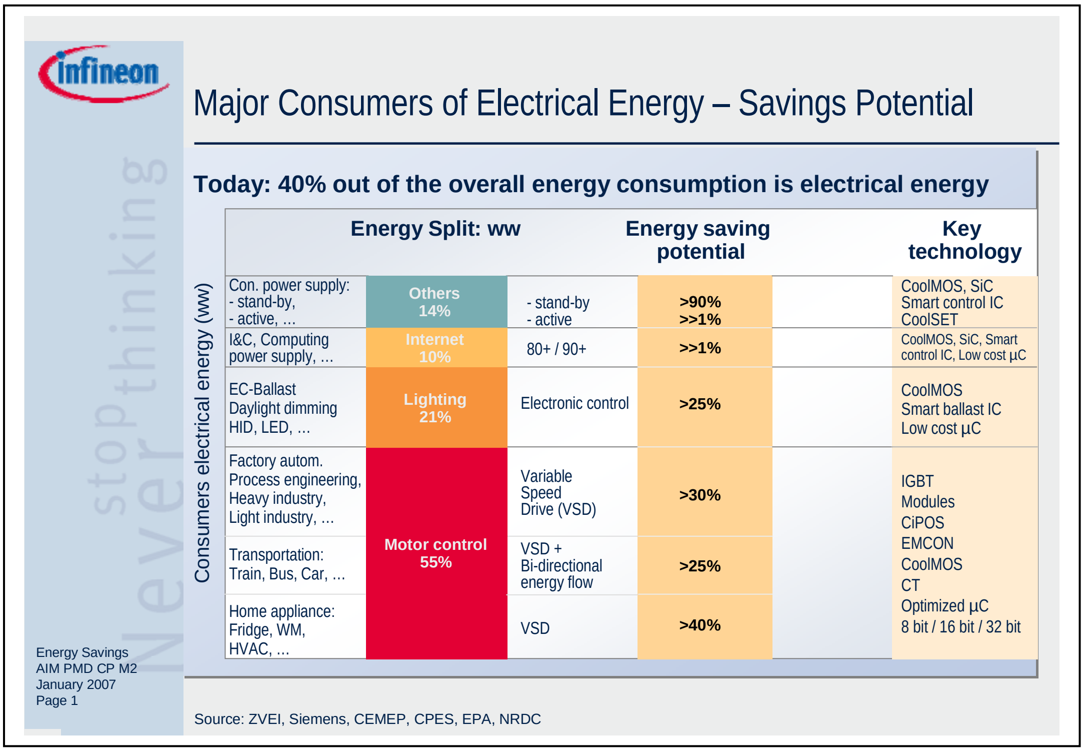
2. Situation and Challenges

Power electronics is “the” enabling technology to efficiently use, distribute and generate electrical energy. Many market segments such as domestic and office appliances, heating, ventilation and air conditioning, digital consumer, communication, factory automation and drives, traction, automotive and renewable energy, can potentially benefit from the application of power electronics technology. Advanced power electronics could for example realise savings of more than 50% in energy losses in converting from mains or battery voltages to that used in electronic equipment.

Some examples which highlight potential savings:

- New concepts for power supplies can improve overall efficiency of 2-4% by reducing low power and standby consumption or a reduction in losses of 14 to 30%. Digital control techniques can further reduce energy consumption.
- Motor drives use 50-60% of all electrical energy consumed in the developed world. By using power electronics controlled motor drives a potential reduction in energy consumption of 20-30% is achievable.
- In home appliances electronic thermostats for refrigerators and freezers can yield 23% energy saving, and an additional 20% can be saved by using power electronics to control compressor motors (with 3-phase PMDC motors).
- In general lighting power electronics can improve the efficiency of fluorescent and HID ballasts by minimum 20%. Advanced power electronics for dimming together with light and occupancy sensing can save on average an additional 30%.
- The connection of renewable energy sources to power grids is not possible without power electronics: photovoltaic power electronic converters optimise the efficiency of PV solar panels, inverters are necessary for wind generators etc.
- In automotive applications electric and hybrid drive trains are only possible with efficient and intelligent power electronics. X-by-wire concepts operated by power electronics will generate saving potential of more than 20%.

All the above examples show how power electronics is key for using electrical energy efficiently and reducing overall energy consumption.



3. Actions required

Europe should make use of the potential of power electronics in improving energy efficiency and saving electrical energy and, at the same time, strengthen the position of European power electronics industry in the world market to compete with increasing competition from the new economic giants China, India and Korea.

- **Power electronics should be recognised in Europe as a key and enabling technology important for future growth and prosperity of Europe's industrial society, as China already does.**
- **The enormous energy saving potential of state-of-the-art power electronics in the various applications should be exploited by proactively promoting the benefits which can be realised and/or regulation.**
- **The further potential to improve energy efficiency by developing advanced intelligent power electronics should be realised by a focussed research activity in Europe.**
- **Power electronics research should be supported by being specifically included in relevant EC Research Programmes in the field of energy, information and communication technologies, transport and materials & new production technologies.**
- **Due to the cross functional nature of power electronics, joint calls should be made in key topic areas between the appropriate Thematic Areas of the 7th Framework Programme e.g. ICT and energy or transport and energy.**
- **In accompanying measures, power electronics networking of academia and industry in Europe should be supported with focus on joint research, education & training, European conferences and standardisation.**

Therefore, Europe has to invest in these areas with focussed R&D effort e.g. in:

- Next generation of semiconductors, advanced device concepts and high temperature (wide band gap) power semiconductor materials (SiC, GaN, diamond)
- New concepts for pure Si and/or SiC system design
- Semiconductor elements allowing higher voltage and power
- Advanced materials (isolation, thermal conductivity, passives, sensors) for system integration and harsh environment, incl. nanostructure materials and filled polymers
- New interconnection technologies for ultra-high power density systems and high temperature electronics
- Advanced thermal management; high temperature magnetics, capacitors, sensors, control ICs
- Advanced EMI filtering and high level of passive integration
- System cost reduction by standardisation of mass producible power electronics building blocks
- Functional system integration (reduce losses, costs, weight and size, optimise cooling)
- Topologies for further standby power reduction
- Digital power conversion and smart power management
- In lighting smart and simple dimming concepts; smart control of street lighting; high efficient light sources (LED/OLED) and their power electronic drivers
- Higher level of integration e.g. for more compact energy saving lamps
- Integrated mechatronics e.g. for fridge compressors, air conditioners and pumps
- Low cost direct drives e.g. for washing machines
- New topologies for PV solar converters, more efficient PV solar cells
- Load management by power electronics in distributed energy generation networks
- Zero-defect design and improved system reliability incl. fault-tolerant systems
- Multi-domain/level modelling and simulation; stress analysis and build-in reliability

4. Conclusion

Power electronics has more that 40 years history in Europe and has set many milestones in industry. Power semiconductor devices and smart control ICs have been the key technology driver for the last two decades. In the next two decades, however, packaging and interconnection technologies, high power density system integration together with advancements in Si devices and system reliability will dominate the power electronics development.
With the top experts in industry and universities in Europe, the excellent education of students and the outstanding research infrastructure there is a good basis to compete in the future. Furthermore, there is a real chance to keep electronics production in Europe, and even get back production to Europe, where it has been already lost, with the highly sophisticated assembly lines for high temperature power electronics or ultra-high power density mechatronic systems e.g. in transportation, information and communication, medical and industrial applications.

In the ´Action Plan for Energy Efficiency´ [1], the European Commission has underlined the importance of this topic for Europe. In the next step, the potential must be realised by establishing a European R&D Platform for power electronics supported by the European Commission.

ECPE European Centre for Power Electronics will support this process by a European initiative of academia and industry to jointly develop power electronics research and technology roadmaps. Eight working groups for key applications and systems using power electronics have been formed with experts from industry as well as from university and research institutes. The vision is that these medium to long term research roadmaps (up to 2020) will become a guideline for power electronics research in Europe and help industry to prepare for upcoming technology challenges.

[1] ´Action Plan for Energy Efficiency: Realising the Potential´, European Commission, Brussels, 19.10.2006

[2] ECPE study ´Power Electronics Potentials and Political Framework to Improve Energy Efficiency´, Nuremberg, March 2007

This Position Paper is based on the results of the **“EUROPEAN WORKSHOP on Energy Efficiency – the Role of Power Electronics”** held on 7 February 2007 in Brussels which has been organised by ECPE European Center for Power Electronics in cooperation with EPE Association.

Objectives:

- show the energy saving potential of power electronics in key applications e.g. for motor control, lighting and power supplies
- demonstrate the importance of power electronics in saving electrical energy as a key and enabling technology
- inform on planned topics in FP7 referring to power electronics, especially in energy efficiency
- show R&D needs in power electronics to improve energy efficiency: examples and visions
- prepare research proposals: R & D needs and research directions

This position paper summarises the results and key statements from the European Workshop on ´Energy Efficiency – the Role of Power Electronics´ held on 7 February 2007 in Brussels with 125 participants from 20 European countries. The presentations from the workshop are available for download on the ECPE web site under http://ecpe.org/power_electronic/power_electronic_e.php.

Leading European power electronics experts from academia and industry have contributed to the workshop and the subsequent position paper:

- **P. Barbosa, ABB**
- **R. Bassett, Areva T&D**
- **F. Blaabjerg, Aalborg University**
- **J.A. Cobos, Technical University of Madrid**
- **A. Consoli, University of Catania**
- **R. De Doncker, RWTH Aachen**
- **B. Eschermann, ABB**
- **G. Griepentrog, Siemens**
- **M. Hendrix, Philips Lighting**
- **U. Kirchenberger, STMicroelectronics**
- **J.W. Kolar, ETH Zurich**
- **L. Lorenz, Infineon Technologies**
- **Ph. Mawby, University of Warwick**
- **M. Mermet-Guyennet, ALSTOM Transport**
- **M. Schlenk, Infineon Technologies**
- **T. Undeland, NTNU Trondheim**

coordinated by:

- **T. Harder, ECPE European Center for Power Electronics**

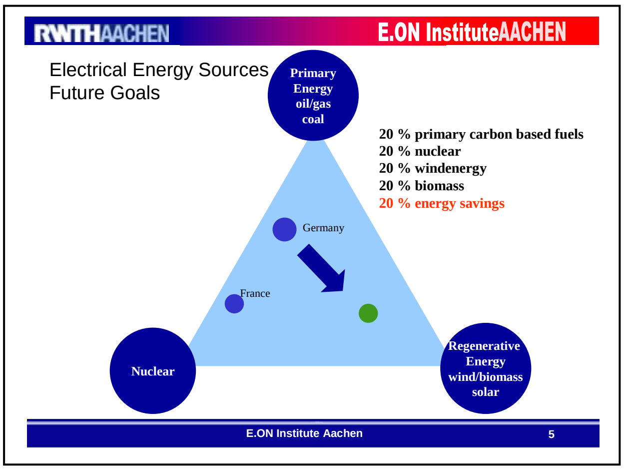
Annex

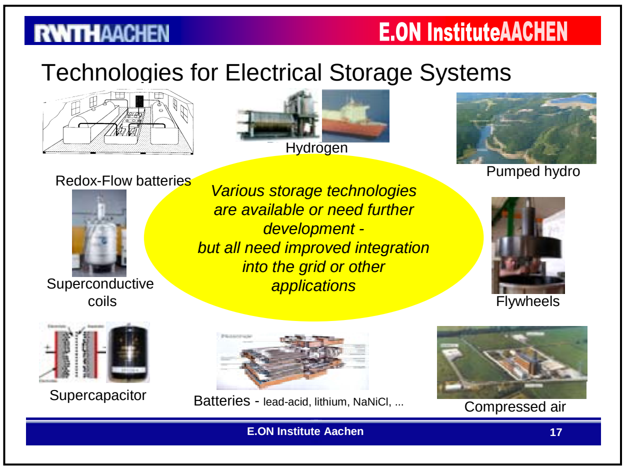
Energy Saving Potential, Trends, R&D Needs
and Future Research Directions in
Main Power Electronics Applications:

- **Power Generation & Distribution and Energy Storage**
- **Transport and Mobility**
- **Industrial Drives**
- **Information and Communication Technologies**
- **Home Appliances**
- **Lighting**

Application: Power Generation & Distribution and Energy Storage

Chairman: Prof. Dr. R. De Doncker (RWTH Aachen)



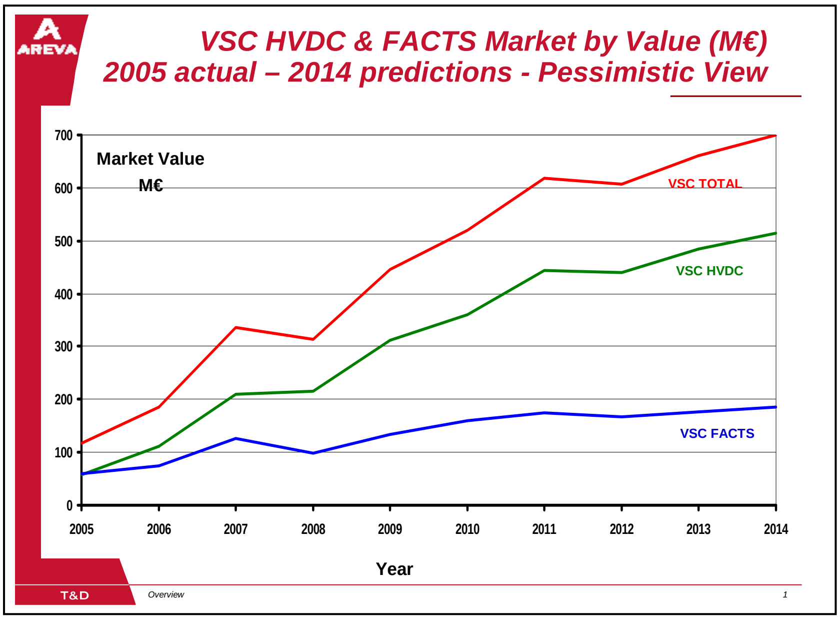


Key statements:

High voltage (DC/HVDC) transmission, static VAR compensators, dynamic voltage restorers (DVRs) and medium voltage static transfer switches (MVSTS) are existing applications of power electronics in distribution and transmission systems to improve power quality and reduce transmission losses. More and more, power electronics is being used on the generation side to convert electrical power, often from DC to 50 Hz fixed frequency AC. For example, power electronic converters are standard in wind turbines, photovoltaic systems, fuel cells and high speed generators. Power electronics is also indispensable to link future storage systems to the power grid. It is anticipated that in the future all electrical energy will flow at least once through silicon. Power electronics not only makes the power systems more flexible and stable, but allows significant energy savings in partial loads (maximum power point tracking) and major investment cost savings as new and lighter power sources can be realized. To “break through” in the field of power generation, distribution and storage systems, power electronics research should focus on:

- increase reliability
  - simpler control
  - better packaging
  - power electronic building blocks (PEBB)
- lower cost
  - optimised cooling
  - improved packaging
  - lower losses
  - smaller weight and size
- more integration
  - higher temperatures
  - integrated cooling
  - less weight
- interface with utility communication systems (standard protocol and platform required)

Key statement from Dr. R. Bassett (AREVA T & D)



Power Electronics in Electricity Transmission and Distribution (T&D) Applications

High Voltage Direct Current (HVDC) and Flexible AC Transmission Systems (FACTS) based on Power Electronics form important components in Europe's national and international grids. For future applications there is a drive to encompass higher voltages and power ratings whilst reducing overall system cost and size.

Analysis of the potential evolutionary development of silicon-based power electronics in HVDC and FACTS [1,2] indicates performance and cost limitations that will prevent effective implementation of the "New Unified European Electricity Grid" [3]. Similarly, the cost of silicon-based power electronic systems will limit the penetration of small distributed generators (DG) in Europe's Electricity Supply Grid that are envisaged in EC publication "*New ERA for electricity in Europe*" [3]. In comparison, high voltage silicon carbide (SiC) based technology, with SiC device ratings between 10 and 15 kV have the potential of offering the performance advances and system cost reductions required to allow effective implementation of a European Grid and to enable deep penetration of DG. These SiC devices would be exploited as part of a new class of Voltage Source Converters (VSC) that would be dramatically more reliable and energy efficient than those currently in silicon. Such devices will provide substantial reductions in the size of the entire HVDC and FACT systems allowing, for example affordable increase in capacity of transmission lines into cities.

The international market for high voltage SiC technology based systems is expected to grow to become much larger than the pessimistic view given in the table which does not rely on a deep penetration of DG. Europe's strength in HVDC and FACTS positions it to rapidly achieve global leadership in SiC-based technology thus allowing it to timely provide the technology required to implement the future electricity grid. As a consequence, funding of a European programme needs to be made a high priority. This programme would pull together Europe's distributed expertise and manufacturing base to effectively compete against US and Japan based competitors [4]. Such a project would protect existing jobs in the European power electronics and power industries, whilst providing affordable and reliable electricity and societal to European Citizens.

The required European-level programme of work would have synergies to that required for SiC electronics for the automotive industry. However, there are unique requirements, e.g. low-cost, thick epitaxial growth techniques, new high-voltage insulation and new circuit designs.

Overall, the application of SiC in VSC HVDC will power electronics to “come of age” and become the new standard for power transmission.

References

[1] SiC Devices offer improved reliability for T&D applications, R Bassett and J Ballad, 18th International Conference on Electricity Distribution (C I R E D) Proceedings, Alpha Session 1 - Network Components, Turin, 6-9 June 2005

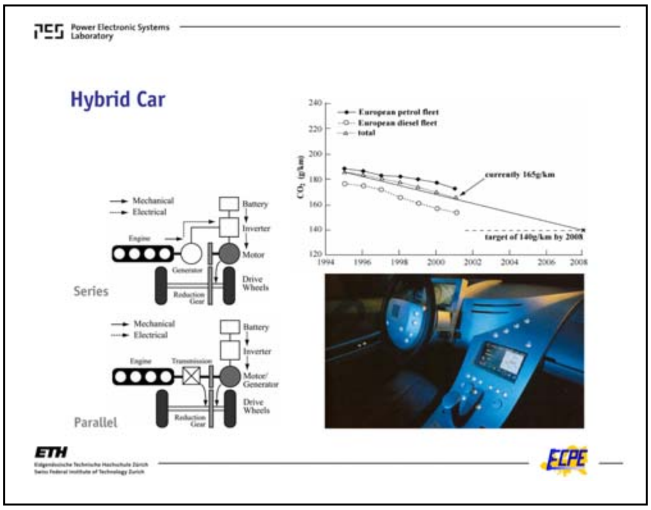
[2] Future T&D Technology, C Oates and R Bassett, EPE-PEMC 2006 Conference Proceedings, Portoroz, Slovenia, 30 August to 1 September 2006, Page 2144

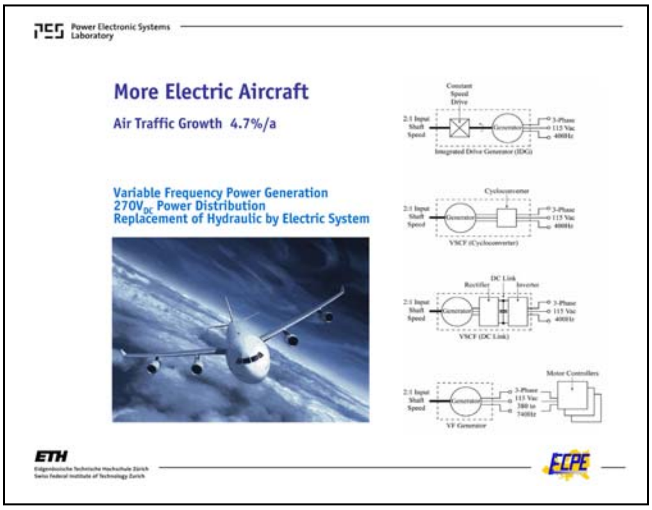
[3] EUR 20901 - New ERA for electricity in Europe, European Commission Directorate-General for Research, Office for Official Publications of the European Communities, Luxembourg, ISBN 92-894-6262-0.

[4] FP 6 Project no. 15821, Project title Wide Bandgap Semiconductor Roadmap (Widgap) SPECIFIC SUPPORT ACTION Thematic Priority: 2 INFORMATION SOCIETY TECHNOLOGIES

Application: Transport and Mobility

Chairman: Prof. Dr. J.W. Kolar (ETH Zurich)





Key statements:

Power Electronics is a key enabler for realizing energy efficient vehicles with hybrid powertrains. Due to recuperation of kinetic energy, operation of the internal combustion engine (ICE) with maximum efficiency, and ICE shut down at idle hybrid cars show a significantly improved fuel economy for standard city based drive cycles. However, the automotive environment challenges the power electronics controllers with extreme temperatures and requirements for low weight/low volume and "zero defect" over 15 years lifetime. Furthermore, cost reduction by factor of 4 until 2020 is a predicted as prerequisite for allowing wide spread of hybrid technology.

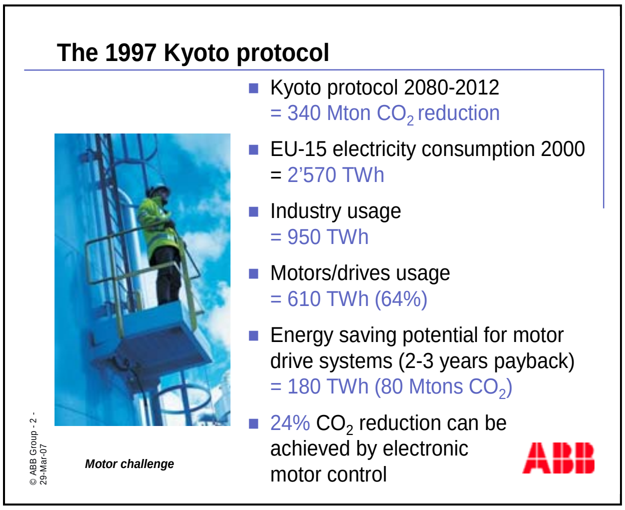
To meet these challenges research in power electronics has to focus on

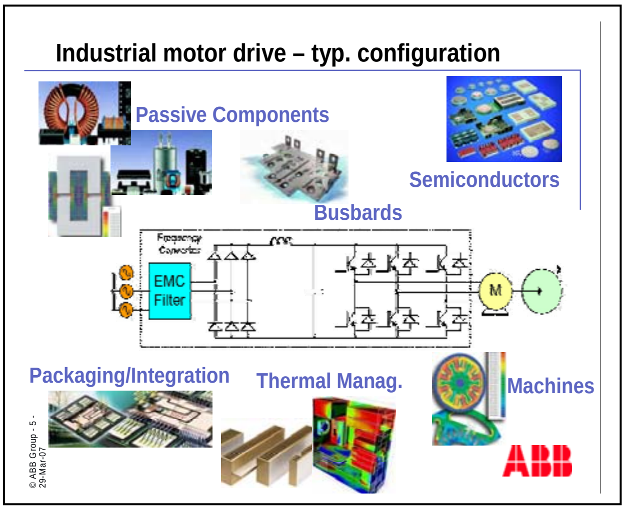
- Functional integration / modularization of various converters systems
- Advanced thermal management
- Homogeneous (space/time) power conversion / multi-cell converters
- High speed machines
- Advanced EMI filtering
- High temperature magnetics/capacitors/sensors/control ICs
- Application of wide band gap power semiconductors
- Fault tolerant converter/motor systems
- Stress analysis/reliability prediction
- Multi-domain/scale/level modelling and simulation

Similar research requirements exist for more electric aircraft where hydraulic actuators are supported or replaced by power electronics controlled electromechanical actuation. Reduction of aircraft weight / fuel economy, easier maintainability and aircraft design flexibility are main advantages/drivers in this area.

Application: Industrial Drives

Chairman: Dr. P. Barbosa (ABB)





<u>Key statements:</u>

1. Potential for energy savings

The Kyoto protocol establishes that by 2012 Europe must reduce 8% (340 Mton) CO_2 emission compared to the levels of 1990. In 2000, the total EU-15 electricity consumption was 2'570 TWh [1]. Out of this, industry use accounted for 950 TWh. Industrial motors and drive systems alone consumed the bulk electricity, that is, 610 TWh or 64% of the total industrial consumption. The study concluded that 180 TWh is the potential to save energy using variable speed drives (VSDs), which accounts for 80 Mtons of CO_2 reduction.
As a result, industrial VSDs can accomplish alone 24% of the required CO_2 reduction per the Kyoto protocol. If we consider the EU-25 member states, the potential to save energy increases to 200 TWh or 100 Mtons of CO_2 reduction. It is amazing to notice that in terms of power plant requirements, the energy that can be saved is equivalent to 45 GW of installed generation capability, that is, 130 fossil fuel 350 MW power plants or enough energy to supply a whole country the size of Spain. The conclusion is that savings justify by themselves a massive investment on industrial VSDs.

2. Industrial drives - Workshop summary statement

The matter of fact is that today's VSD technologies are fully capable to provide the savings described above. So, what is motivating us to doing more research in this area? Indeed, to improve the performance and widen the acceptance of VSDs we have to make them:

- More reliable
- Lower cost
- More efficient
- More compact
- Easier to manufacture and easier to use

To accomplish results in the issues listed above we will need to develop technology in the following multidisciplinary areas:

Passive Components

Passive components have not shown a fast development track record in the last 30 years. For this reason, size, operating temperature and frequency are barriers which are easily reached by state-of-the-art components. There is a great need to develop new/better materials for capacitors, inductors, transformers and filters. As a result, higher energy density materials, such as nano-magnetics and nano-dielectrics are required to achieve compactness, higher operating temperature, and higher frequencies.

Semiconductor devices

Power semiconductors have developed much faster than passive components in the last 30 years. The invention of the insulated gate bipolar transistor (IGBT) and the integrated gate commutated thyristor (IGCT) have been responsible for major breakthrough in industrial VSDs. Both devices are made of Silicon (Si), while the main trend in the development is to reduce operating losses and increase SOA. Clearly, further loss reduction is needed for high voltage IGBTs (> 1700 V). In addition, operating at higher temperatures is extremely beneficial to slashing cost related to thermal management. To make it possible to improve the performance of power semiconductor devices further development of Si IGBTs, super-junction devices and new wide-band gap components based on silicon carbide (SiC) or gallium nitride (GaN) are necessary.

Packaging and integration technologies

Packaging of power semiconductor devices relies on wire bond interconnections. These wires are limited in thermal cycles (reliability) and are responsible for losses in the power semiconductor modules. We face pressing needs to improve the chip interconnection technology to eliminate the wire bonds and also bring up the possibility for double-sided cooling. The challenge is to come up with something better, more reliable and lower cost to replace wire bonds. In addition, developing wide-band gap materials would not make much sense if high temperature packaging technologies were not developed in parallel.
Aiming at facilitating manufacturing and therefore reducing costs, integration technologies for passive components such as electromagnetic interference (EMI) filters must be addressed in the light of compact design, reliability of the technology, and use of advanced materials.

Thermal management

Most industrial VSDs are seriously limited by thermal management. State-of-the-art cost-effective cooling technologies are extremely limited in performance. New ideas based on new thermal materials must be addressed from the component to the system level. Besides the need to cool power semiconductor devices, passive components such as inductors, capacitors, and filters are not easily cooled by today’s thermal management solutions. Cost-effective ideas ought to be proposed to reduce thermal stress on various components.

Modelling

Simulation results are as good as their models. Better modelling of semiconductor, thermal management, magnetic materials, filters, inductors, capacitors, etc are definitely required to improve simulation results and therefore reduce time to market of new products. The need for coupled electro-thermal simulation is growing faster with the requirements to get further optimization of designs that are constantly under cost pressure.

Design for reliability

Besides improving reliability at all levels: power semiconductor modules, passive components (capacitors, inductors, filters, etc…), printed circuit boards (PCBs), and interconnections, we should seek ways to design our VSDs for a specified reliability. The design for reliability requires then deep knowledge of the physics of failure modes to reproduce more accurate models for reliability analysis.

More efficient electric machines

Further improving the efficiency of the entire process is highly important to increase energy savings. In Europe alone, every 1% increase in efficiency saves about 400 MW of installed electricity generation capability. Improving the efficiency of machines through better design and even new concepts can be significant to achieve more energy efficient processes.

Educating skilful people

It is worthless making a strategy to develop all these technologies if we lacked skilful people to do the work. For that matter, it is highly important that ECPE helps to develop with the competence centres an integrated education program able to address the multidisciplinary needs of the technologies described above. It would be highly appreciated to have integrated educational programs in which students would move from one campus to the next to absorb the best education needed to realize our technology needs now and in the future.

Synergies

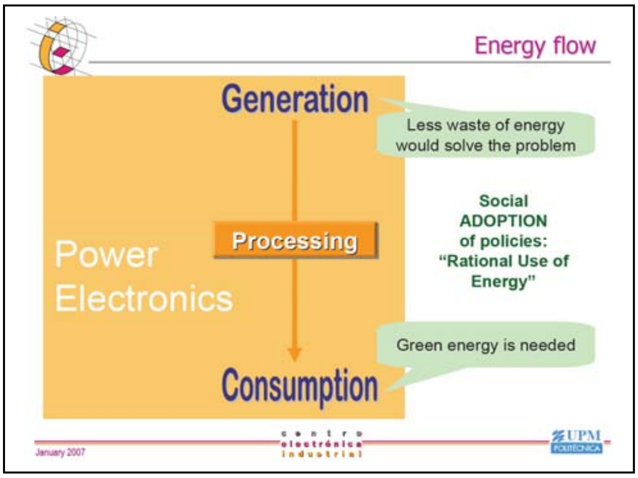
All applications and presentations discussed in the workshop have strong synergies in terms of technology needs. Similarities should be capitalized to better coordinate the efforts.

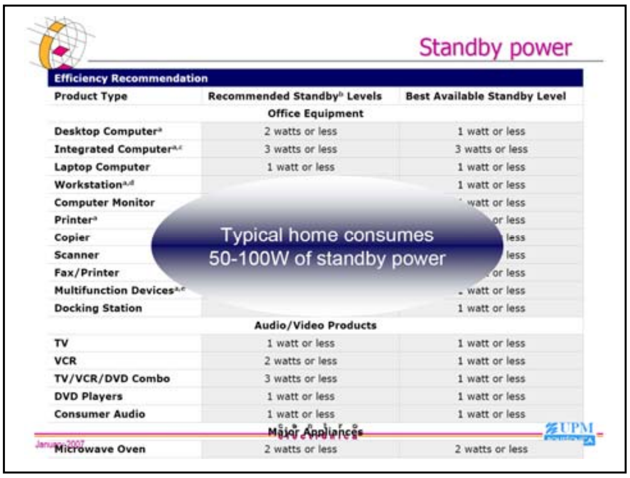
3. References

[1] De Keulenaer, H, et al, “Energy Efficient Motor Driven Systems can save Europe 200 billion kWh of electricity consumption and 100 million tonne of greenhouse gas emissions a year,” Motor Challenge Programme, 2004

Application: Information and Communication Technologies

Chairman: Prof. Dr. J.A. Cobos (Technical University of Madrid)



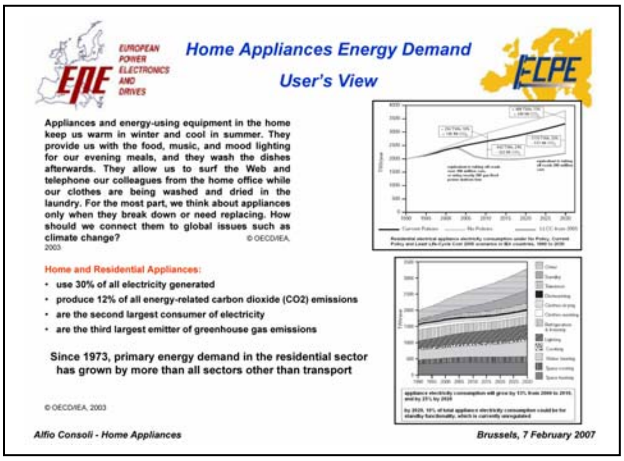


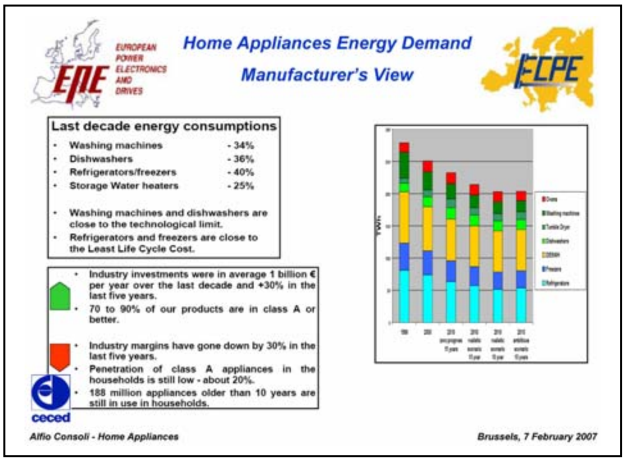
Key statements:

- Drivers for energy efficiency are, mainly: environmental concern, regulations, performance and cost. Enthusiasm from power electronics engineers is not enough, it should be consistent with the real drivers.
- Energy improvements at load level have very strong impact, since they affect the whole energy path (from well to wheel) (multiplying factor).
- In microprocessors, the figure of merit is no longer "performance/€", but "performance/Watt".
- Cost of energy in servers is comparable to cost of data hardware.
- Load consumption may be dramatically reduced by an appropriate supply strategy (microprocessors with variable supply voltage, dynamic voltage scaling, voltage partitioning; RF transmitters with modulated supply voltage in EER techniques, etc).
- Therefore, power electronics helps not only at the energy conversion level (reducing conversion losses), but it ALSO helps to reduce energy consumption at load level.
- Breakthrough technologies open new opportunities, either if these technologies affect the energy conversion or if they affect the loads.
- Standby power:
  - A microwave oven consumes more energy running the digital clock than heating the food.
  - Standby functionality is needed, and increasing with more sophisticated devices.
  - Standby power may be limited only by regulations: Though global numbers are a major concern, for end users it is just peanuts.

Application: Home Appliances

Chairman: Prof. Dr. A. Consoli (University of Catania)





<u>Key statements:</u>

1. Home appliances is a special application field where cost is the main driver. This implies different views of the related issues:

   User's View

   Home appliances:
   - use 30% of all electricity generated,
   - produce 12% of all energy-related carbon dioxide (CO_2) emissions,
   - are the second largest consumer of electricity,
   - are the third largest emitter of greenhouse gas emissions.

   Since 1973, primary energy demand in the residential sector has grown by more than all sectors other than transport.

   Manufacturer's View

   Last decade energy efficiency results:
   - Washing machines and dishwashers are close to the technological limit of efficiency.
   - Refrigerators and freezers are close to the least life cycle cost.
   - Industry investments were in average 1 billion € per year over the last decade and +30% in the last five years.
   - 70 to 90% of products are in class A or better.

2. Evolution of the appliance market is based on two related trends:
   a. New products based on ICT
   b. Networking all appliances from white to brown goods and heat ventilating/Air Conditioning Systems

3. New horizons must be defined for Home Automation that has shown weaknesses and hard acceptance from users.

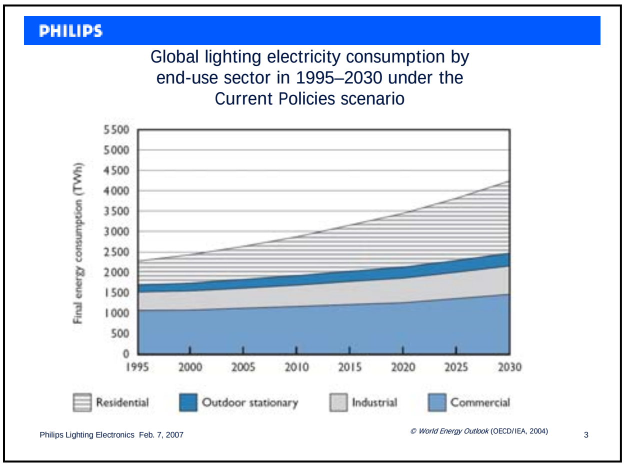
4. There is a large market of small appliances where motor efficiency is still in the order of 5-10%. Efficiency of the larger appliances ranges within 50-60%. New solutions such as Permanent Magnet motor drives must be adopted.
5. Power Electronics can help to improve efficiency at the converter stage by introducing new solutions for power components and sensing (Intelligent Power Modules, Hybrid integration, IGBT drivers, PFC, current sensing).

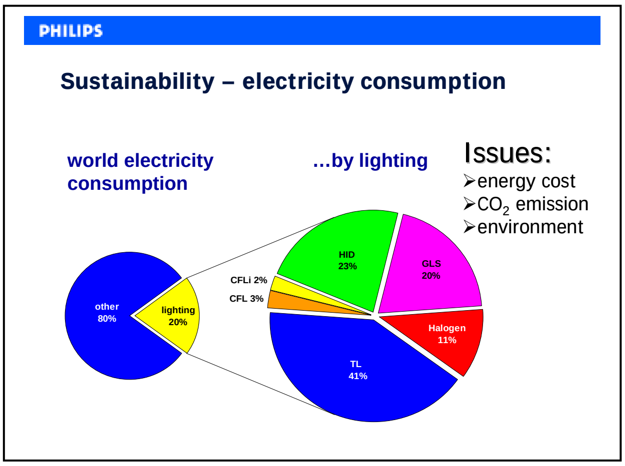
6. Power Electronics can also help at the control stage enhancing efficiency and reliability of the home appliances (Sensorless control, Field Weakening operation, Reliability of torque and power estimation, Dynamic maximization of torque/current ratio, load identification algorithms).

7. Concerted actions from Academia and Industries are needed to ensure for Europe an efficient, secure, and clean Home Energy Model

Application: Lighting

Chairman: Prof. ir. M. Hendrix (Philips Lighting)





<u>Key statements:</u>

To make lighting significantly more efficient than it is today, *several high-risk scientific research projects should be initiated in the following areas:*

1. Fast, high voltage (400-800 V) and high temperature (120 - 250ºC) switch technologies (e.g. SiC or ESBT). These switches, including their drive and protection mechanisms, should be very inexpensive.

2. A cost-breakthrough for lighting is possible when both high voltage (diodes and switches) and low voltage IC processes (controllers) can be *combined on the same die*.

3. For lighting applications cost can be saved with an order of magnitude faster microcontrollers with on-chip very high resolution (nanosecond) timers. High speed can be used to circumvent costly hardware -- fast ADC and DAC's with off-chip components. Higher processing speed and faster timers allow e.g. direct driven switches and adaptive on-line dimming algorithms for very efficient high-intensity, and thus energy-saving, discharge lamps.

4. Solutions are necessary for the soldering point temperature (i.e. reliability) problem. Without this, high-temperature (and thus smaller, cheaper and/or more reliable) chips and switches can not be used.

5. Research on high temperature (>140°C) magnetic materials, e.g. magnetic nanocomposites.

6. Research on high-temperature electrolytic capacitor replacements, e.g. high-temperature polymers.

In short: *Breakthroughs for lighting will come from technological breakthroughs in the key components used for its power electronic drivers.* Breakthroughs will lead to higher efficiency lighting solutions being introduced to the market many years sooner than would normally the case (10 years). Because the extremely cost-sensitive lighting industry does not develop its own electronic components, outside stimulation is necessary to speed up this process.