特集に寄せて

# Power Electronics
# – A Key Enabling Technology for Modern Society

# パワーエレクトロニクス
# ―― 現代社会の鍵となる実現技術 ――

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Ever since the invention of the first power semiconductor devices(1), the development of robust power semiconductor devices has spurred the development of power electronic energy converters worldwide(2), (3). Electrical power converters are essential to link sources of electrical power to loads and to enable a controlled power flow between them, thereby improving system performance while saving energy. Obviously, power electronic converters are only implemented in systems when their investment costs and operating expenses are sufficiently compensated by the benefits they provide to the end-users. Consequently, in industrial applications and consumer products, power electronic systems have to be very efficient (today typically between 90-99%), highly reliable (long life), safe to use, and above all should be produced at low cost.

Today, one can say that power electronics has reached that point of maturity where its deployment in industrial processes and drives is becoming standard. Moreover, the cost of power electronic semiconductor devices has decreased substantially over the past decades, while the cost of conductor materials (copper, aluminum) and magnetic materials (Si-steel, ferrites, permanent magnets) have increased substantially and keep on increasing. Hence, more and more engineers are reconverting or redesigning their products under the motto "more silicon and less copper" to obtain lower cost products, essentially saving materials. As a consequence, it is almost impossible today to imagine a world without power electronics and the future will bring even more applications in which power electronics is required. Hence, the need for skilled engineers and power electronics designers is great and job opportunities are plentiful. However, it is interesting to note that the field of power electronics is not well known to most people and young students. This is why I call power electronics, the "quiet revolution", clearly not so visible as the revolutions made by microelectronics and the information and communication technologies (ICT). In my opinion, the lack of engineers is now limiting the future near term growth of the power electronic field. It is of utmost importance that industry, research institutions and educators recognize the importance of this field to overcome this problem.

Power electronics systems have become lighter, i.e reached higher power densities (kg/dm$^3$) and saved materials by operating at higher frequencies. It is well-known fact that, for a given power rating, electromagnetic devices such as transformers, actuators and electrical machines become smaller when operating at higher frequencies(4). Examples are power supplies for the electronic and ICT devices we all use today. About 35 years ago a power supply using linear regulators and 50/60 Hz transformers would reach an efficiency of less than 50% and weigh approximately 75 kg per kW. Today, a standard computer power supply (operating at 150 kHz) has an efficiency above 90% and would weigh less than 5 kg per kW. Modern power transistors (IGBT, MOSFETs) made this possible. Frequencies will increase by using for example new generation IGBTs, super-junction based devices that can operate at elevated temperatures and using new wide bandgap materials, such as SiC diodes, GaN HEMTs, etc. Several studies have reported on power supplies that weigh about 500 gram per kW, while delivering efficiencies above 95%. Note that next to specific weights, power densities improved substantially as well reaching in some applications 25 kW/dm$^3$ (5).

As the world is becoming aware of climate change caused by increased use of fossil fuels, it is important to save energy in industrial and commercial processes. This can be achieved by automation, for example by



increased use of variable speed drives in factories, in heating ventilation and air-conditioning units, such as heat pumps. Variable speed drives enable enormous energy savings, especially under partial load conditions. Actually, the first power electronic converter applications, which offered short pay-back times were compressor, blower and pump systems. The fact that our primary energy sources, that are known to us, will become more expensive, has motivated most developing nations who depend heavily on import of primary energy, such as Japan and Europe, to employ even more power electronic systems, for example in renewable power sources (wind turbines, photovoltaic converters), decentralized power generation (fuel cells) and storage systems (batteries). In 2010, it can be estimated that the installed capacity of converters for wind turbines alone exceeded more than 30 GW, while production of PV converters reached more than 15 GW. To support the development of decentralized power systems further, so-called smart grids will be needed. It is often said that ICT technology will enable such smart grids. However, reality is that ICT alone cannot achieve this. Without power electronics, i.e. an actuator, grids cannot be made "smart" or flexible to realize greater stability and improve transmission efficiency. One can anticipate that more DC technology and DC cables will be used in transport and distribution of electrical energy, simply because it will be cheaper, more acceptable and more efficient. In DC systems power electronic DC-to-DC converters will become the "electronic transformer" to link different voltage levels together[(6), (7)]. I believe, that if Edison had had such a power electronics device available 125 years ago, we would not have had an AC grid today! At RWTH Aachen University we have started an international consortium on DC medium- and high-voltage power electronic systems to accelerate innovation in this area.

In addition, concern for quality of life in cities has increased tremendously the interest in hybrid and full electric vehicles. In Germany, the government is supporting massively the development of full electric vehicles (EVs). The target is to have 1 Million EVs on the road by 2020. Power semiconductors will be needed for battery chargers, dc-to-dc converters, protection systems and inverters for high-performance drives. It is clear that the automotive market will be the next mass market opportunity for development of power semiconductors, packaging technology, EMI design, as well as control and communication integration to reduce cost and improve thermal cycle life.

Semiconductor device manufacturers, have responded to the increased global need of power electronics not only by increasing production capacities but also by integrating more functionality in the power devices and packages. Reverse blocking IGBTs, reverse conducting IGBTs and IGCTs, intelligent power modules are just few examples of new products that make design of power electronic converters easier. No doubt, this development will continue at a high pace as power electronics becomes cheaper, more applications open up. Power electronic converter manufacturers are now experimenting with these new devices and materials to identify solutions for new market opportunities. The market opportunities are plenty and the markets are enormous. What is assuring is that the market drivers are guaranteed, because power electronic system designers are in the forefront to reduce our carbon footprint and our impact on the environment by saving materials and energy. No doubt, power electronics will be the key enabling technology for the next decades to accomplish these ambitious goals.

**References**

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■和文抄録（社内にて作成）

最初のパワー半導体が発明されて以来，パワー半導体の発展が世界的にパワーエレクトロニクス（パワエレ）技術を用いた電力変換装置の開発に拍車を掛けてきた。電力変換装置は電力源と負荷をつなぎ，それらの電力の流れを制御するために必要不可欠である。産業や消費者向け製品においては，パワエレシステムは非常に高効率（現在の効率は一般的に 90 ～ 99%）でなくてはならない。そして，信頼性が高く（長寿命），安全に使え，さらに低コストであるべきである。

現在まで，パワエレは大きな発展を遂げてきた。パワー半導体のコストは過去数十年にわたって大幅に安くなっているのに対して，導電性材料（銅，アルミニウム）や磁性材料（けい素鋼板，フェライトおよび永久磁石）のコストは大幅に上昇し，現在もなお上昇し続けている。そこで，多くの技術者達は材料の使用量を抑えてコストを下げるように，“シリコン増やせ，銅減らせ”をモットーに製品を転換または再設計している。その結果，パワエレのない世界を想像するのはほとんど不可能であり，将来はパワエレが必要とされる分野がさらに増えるであろう。そのため，スキルを持った技術者やパワエレの設計者の必要性は大きく，活躍の場は大いにある。しかしながら，注目すべき点は多くの人々や学生にパワエレ分野が良く知られていないことである。私の考えでは，技術者不足は今やパワエレ分野の近い将来の成長を制限している。産業や研究機関および教育者たちが，この問題を解決することの重要性を認識することが最も重要である。

パワエレシステムは動作周波数を高めることで，材料の消費量を抑え，軽量化が進んできた。例えば，35 年前の変圧器を使用したリニア電源と比較して，現在のコンピュータ用内部電源は，効率が 50% 未満から 90% 以上へ，出力当たりの質量は 1/15 以下に改善された。新しいワイドバンドギャップ材料を用いた SiC ダイオードや GaN-HEMT などのパワー半導体によって，高温で動作でき，動作周波数をさらに増加させることができるので，重量と電力密度は今後も大きく改善されるであろう。

化石燃料の使用量が増加していることによる環境変化が意識され，産業・商業プロセスにおいても省エネルギーが重要になっている。これは例えば，工場や空調設備において可変速ドライブを多用することで実現できる。1 次エネルギーが高価になったことで，その多くを輸入に強く依存している日本や欧州などほとんどの先進国は，再生可能エネルギー（風力発電，太陽光発電）や分散型電源システム（燃料電池）および蓄電システム（蓄電池）のようなパワエレ機器をより多く使用する方向にある。2010 年の推計では，太陽光発電用の電力変換装置の生産は 15 GW 以上になるとともに，風力発電用の電力変換装置の生産は 30 GW 以上になった。さらに分散型電源システムの開発をサポートするためには，スマートグリッドと呼ばれるものが必要になる。パワエレ無くして，アクチュエータや電力系統の安定性や効率を向上させる“スマート”“フレキシビリティ”を実現させることはできない。直流技術や直流ケーブルは安価で受け入れやすく，効率が良いことから送配電に多く使われるようになると予想されている。直流システムにおいて，パワエレ技術を用いた DC-DC コンバータは異なる電圧レベル同士をつなぐ“電子変圧器”となるであろう。われわれは RWTH アーヘン工科大学で，この分野の革新を加速するための中圧および高圧の直流パワエレシステムに関する国際的なコンソーシアムを発足させた。

さらに，都市ではハイブリッド自動車や電気自動車（EV）が非常に注目されている。ドイツでは政府が電気自動車の発展を大いに支援している。2020 年までに 100 万台の EV を普及させることを目指している。高性能な運転を実現するため，パワー半導体は蓄電池の充電装置や DC-DC コンバータ，保護システムおよびインバータに必要となる。自動車分野は，パワー半導体やパッケージ技術，EMI 設計および制御技術において，コストを低減し，さらに熱サイクル寿命を改善して発展するための大きな市場機会になることは明白である。

半導体メーカーは生産能力の向上だけではなく，パワー半導体やパッケージの中により多くの機能を集積することによって，世界的にパワエレの必要性を向上させてきた。逆阻止 IGBT（Insulated Gate Bipolar Transistor），逆導通 IGBT や IGCT（Integrated Gate-Commutated Thyristor）およびインテリジェントパワーモジュールは，パワエレ機器の設計を容易にする新しい製品のほんの数例である。この開発によりパワエレ機器は急速に低コスト化し，適用分野が拡大するであろう。パワエレ機器のメーカーは新しい市場機会における課題解決に向けて，これらの新しいデバイスと材料を用いた試みを行っている。その市場は広く，規模は莫大である。パワエレシステムの設計者は温室効果ガスを減らし，材料とエネルギーの消費量を抑えることによって環境への影響を低減するための最先端にいる。パワエレは，これらの大いなる目的を成し遂げるための今後数十年間における鍵となる実現技術であることは確かである。

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