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Preface to the Special Issue on "Simulation Technologies and Computational Design"
シミュレーション技術とコンピュータデザイン特集に寄せて

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The development of power electronics converters is driven by demands for higher efficiency, lower functional volume and lower costs. However, due to continuous progress over the past decades, power density and efficiency barriers will be reached in near future. Furthermore, high peak-to-average load ratios, extreme operating temperatures or reliability specifications have to be considered more and more frequently in the course of converter designs. Such multi-objective requirements can no longer be fulfilled with classical design methods, but only on the basis of a holistic view with a high degree of detail. Therefore, apart from the basic converter functions considered so far, special emphasis must be placed on the high frequency characteristics of magnetic components, EMC (electromagnetic compatibility) filtering, interconnection techniques, thermal management of active and passive components, and thermo-mechanical properties of power semiconductor packages. Due to the high complexity of a simultaneous consideration of all such aspects, the best possible trade-off between different requirements can only be found by means of digital simulation and a final multi-objective optimization. In this way, apart from the clarification of technical details also a comprehensive comparison of competing concepts can be carried out and hardware prototyping can be transferred to the end of the development process. This allows to significantly cut development costs and time-to-market.

The challenge of a comprehensive description of power electronics converters consists in the acquisition and combination of models of functional elements of different kinds, and in the coverage of extremely wide time, length and frequency ranges. For example, switching events must be represented in the ns range, whereas for the analysis of mission profiles hours must be covered. Here, a conventional approach via coupling of discipline-specific FEM (finite element method)-based simulation tools would lead to extreme computation times and a huge amount of data, and therefore certainly is not a feasible path. Thus new methods must be found that creatively exploit the heterogeneous structure and different physical dimensions and time constants of the functional elements of power electronics converters in order to arrive at reduced-order models that can be handled by the computer.

As an example, the geometry of a power semiconductor module may be analyzed with FEM-simulations and translated into a reduced-order thermal equivalent circuit that is limited to a few temperatures of intermediate layers. This equivalent circuit may be integrated in a natural way into a circuit simulation of the converter structure. In a similar way, starting from an electromagnetic FEM or PEEC (partial element equivalent circuit) analysis the internal power module layout may be represented in a simplified equivalent network and the behavior of the power semiconductors could be approximated by behavioral circuit models. Finally, also the electromagnetic interface to the environment could be represented in the same manner. In this way, e.g. the losses of the power semiconductors could be simulated for the actual circuit layout and directly coupled with the thermal model. Subsequently, the resulting profiles of the intermediate layer temperatures could be integrated into a lifetime analysis employing physics-based thermo-mechanical models parameterized via cycling tests.

In general, a representation based on equivalent circuits allows a simple coupling of models of different disciplines within a subsystem, but also a direct connection of various subsystem models to an entire converter. The research at the Power Electronics Systems Laboratory of ETH Zurich has focused now for over 5 years on the automated generation of reduced-order subsystem models and their connection to overall converter models. Here, important areas are thermo-electric modeling, the extraction of equivalent models of interconnection systems and EMC filter stages, including couplings between filter elements by means of PEEC, and the physics-based modeling of the lifetime of metal-metal interfaces on the basis of accumulated deformation energy, which leads to excellent agreement with experimental cycling tests. The design platform arising in this way is complemented by design tools for EMC filters and high frequency magnetics with ad-

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vanced thermal management, as well as analytical descriptions of advanced cooling systems. In parallel, an optimization platform is being developed that allows a simultaneous optimization of all converter subsystems, where also the physical dimensions of individual components appear as variables. The effectiveness of this research is well illustrated in the realization of power electronics converters with extreme power densities or efficiencies, such as a non-isolated automotive DC-DC converter with a power density of 30 kW/dm^3, an isolated DC-DC converter with a power density of 10 kW/dm^3 and a single-phase PFC (power factor correction) system with an efficiency of over 99%.

In future, multi-disciplinary simulation tools will gain enormously in importance and will be expanded to virtual prototyping platforms. A converter design can then be translated largely automatically into a reduced-order model and a complete picture of the loading of components at selected operating points or mission profiles can be obtained. Here, one could also imagine the integration of component data basis and cost models, or the iterative optimization of component values or operating parameters via higher level optimization routines. In the analysis of the subsequently realized hardware, multi-disciplinary simulation could advantageously serve for augmenting the display space, i.e. the simulation model could be adapted via calibration routines to the measurement results, so that non-accessible physical values such as internal temperatures or electromagnetic fields could be determined and displayed via parallel simulation. A further application could be the analysis of the sensitivity of system performance indices in respect of component characteristics, which would enable the derivation of roadmaps for an effective further development of component technologies. Finally, the transition from virtual prototyping to virtual manufacturing would be possible, where questions of e.g. manufacturability and logistics could be considered in an early stage of the design.

In summary, the design process of power electronics systems, which is currently based to a large extent upon human knowledge and experience, will be extended into a new dimension. Virtual design platforms will integrate know-how from various disciplines and become an important strategic factor. Here, special challenges arise in the training of engineers in the utilization of multi-disciplinary tools, and in ensuring the coordinated extension and reliable availability of the simulation programs. However, such simulation systems always will only model and optimize existing concepts; the creation of fundamentally new concepts, creativity, will remain the inherent task of the human being, the engineer.

■和文抄録（社内にて作成）

電力変換装置の効率や電力密度は過去数十年で大きく進歩し，近い将来には限界に達するであろう。磁気部品の高周波特性，EMIフィルタ，温度管理，半導体パッケージの熱膨張など，多くの専門分野を極めた装置全体の最適設計技術がいっそう必要となる。もはや従来の古典的な方法での設計は困難になると思われる。これを実現する手段としてデジタルシミュレーションが有望である。しかし，有限要素法を用いた従来の方法では計算時間やデータ量が増大するため，新たな手法を用いた連成シミュレーションが必要である。これにより，開発コストと時間の節約が図れる。

電気，熱および電磁気などの各要素を等価回路に置き換えて結合することで，システム全体をモデル化することが容易になる。スイス連邦工科大学（ETH Zurich）のパワーエレクトロニックシステムズ研究室（PES）では5年以上にわたって低次元モデルを自動生成し，システム全体へ発展させたシミュレーションの研究を行っている。熱－電気のモデル化，各システム間やEMIフィルタにおける等価モデルの抽出，ヒートサイクルエネルギーによる寿命の物理的なモデル化などを重要な研究対象としている。30 kW/ℓ の自動車用DC-DCコンバータ，10 kW/ℓ の絶縁型DC-DCコンバータおよび効率99%以上の単相PFCを実現し，この研究の有効性を実証している。将来的には，仮想的に試作機を製作するまでに発展させる。

従来は経験やノウハウに依存していた設計は次の段階に進み，仮想設計プラットフォームは多岐にわたる専門分野のノウハウを取り入れ，重要な戦略要素となる。しかし，シミュレーションツールでモデル化や最適化はできても，新しいコンセプトの創造は人の役割として今後も重要である。