Model-Based Development of DC-DC Converters with Wide Operation Range and High Dynamics

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to my wife Jingyan and our daughter Vicky with all love

to my mother Dongling Liu and my father Zuozeng Cao

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Zhiyu Cao
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Abstract

For the development of photovoltaic (PV) inverters, electrical drives and E-mobiles high-performance DC power supplies are required for emulating batteries, fuel cells, solar arrays, etc.. For such energy source simulators the specifications are extreme allowing a wide operation range and high dynamics besides the basic requirements in terms of efficiency, harmonic distortion and power factor. Especially in order to develop and test PV inverters with maximum power point tracking (MPPT) the output characteristics of solar arrays are to be emulated with high dynamical performance.

Current solutions of DC power supplies often base on the phase-shifted full bridge (PSFB) topology, since it is well supported by application notes, integrated circuits and a multitude of publications. Due to the high turn-off current and circulating current during freewheeling, it is difficult to operate the PSFB with higher switching frequency without increasing the converter losses. This implies using state-of-the-art silicon semiconductor devices does not enable reduction of the output filter for enhancing the dynamical performance of the PSFB.

The primary objective of this work is to select a most suitable topology for a DC power supply, develop and optimize it to facilitate a wide operation range and high dynamics. Therefore a model-based development procedure is set up. Quantitative study of the current solution indicates three potential solutions: Using of multi-level topologies, interleaved multi-phase topologies and resonant converters. Model-based quantitative comparison of all potential topologies yields the series-parallel resonant converter with LC output filter (SPRC-LC) as the most qualified solution.

The requirement of an extreme wide operation range can be served best by using an optimized modulation (OM) strategy, which combines a control of switching frequency and duty ratio. A model-based development and optimization of the SPRC-LC under OM is performed in this contribution and includes:

- Steady-state modeling and converter design of the SPRC-LC under OM
- Implementation of a fully digital OM control unit
- Modeling of converter dynamics under OM and control design

The second objective of this work is to build a development environment to enable a long-term utilization of research results achieved in this work, which consists of two parts: The

first part is a computer-aided analysis (CAA) and design (CAD) software package for design and optimization of phase-shifted PWM converters and resonant converters; the second part is a real-time simulator, which enables testing the total control unit of the SPRC-LC in software-in-the-loop (SiL) or hardware-in-the-loop (HiL) mode without need to build the physical power converters. The development environment should on the long-term facilitate a considerable reduction of cost, time to market and required design expertise for future developments.

Zusammenfassung

Für die Entwicklung von Solarwechselrichtern, elektrischen Antrieben und Elektromobilen sind hochwertige DC-Quellen für die Emulation von Batterien, Brennstoffzellen, Photovoltaik-Modulen (PV), usw. eingesetzt. Neben grundlegenden Anforderungen in Bezug auf Effizienz, Klirrfaktor und Leistungsfaktor, müssen solche Quellen einen extrem großen Arbeitsbereich unterstützen und hohe Dynamik aufweisen. Vor allem in Hinblick auf die Entwicklung und Test des PV-Wechselrichters mit Maximum Power Point Tracking (MPPT) muss die Ausgangskennlinie des PV-Arrays mit hoher Dynamik emuliert werden.

Aktuelle Standardlösungen stützen sich meistens auf die phasengesteuerte Vollbrücke (PSFB), denn sie ist durch Anwendungshinweise, integrierte Schaltungen und eine Vielzahl von Publikationen gut unterstützt. Aufgrund des hohen Abschaltstroms und des Kreisstroms während der Freilaufphase ist es schwierig, ohne Verlusterhöhung die PSFB mit höherer Schaltfrequenz zu betreiben. Dies impliziert, dass unter Einsatz üblicher Silizium-Halbleiter die Dynamik der PSFB nicht durch Reduktion des Ausgangsfilters verbessert werden kann.

Das primäre Ziel dieser Arbeit ist es, eine am besten geeignete Topologie für o.g. DC-Quellen auszuwählen, sie zu entwickeln und optimieren. Daher wird ein modellbasiertes Entwicklungsverfahren genutzt. Eine quantitative Untersuchung der aktuellen PSFB zeigt drei mögliche Lösungen: Die Verwendung von Multi-Level-, Mehrphasen-Topologien und Resonanzkonvertern. Aus dem Vergleich dieser Topologien resultiert der Serien-Parallel-Resonanzkonverter mit LC-Ausgangsfilter (SPRC-LC) als die qualifizierteste Lösung.

Die Forderung an einen extrem großen Arbeitsbereich wird am besten mittels optimierter Modulation (OM) erreicht, die eine Steuerung der Schaltfrequenz und des Tastverhältnisses kombiniert. Eine modellbasierte Entwicklung und Optimierung des SPRC-LCs gesteuert mittels OM wird in diesem Beitrag ausgeführt, und enthält:

- Modellbildung des stationären Verhaltens und Konverter-Entwurf
- Implementierung der volldigitaler OM Steuereinheit
- Modellbildung des dynamischen Verhaltens und Regelungsentwurf

Zweites Ziel dieser Arbeit ist eine Entwicklungsumgebung zu entwickeln, um eine langfristige Nutzung der Forschungsergebnisse zu sichern. Die Entwicklungsumgebung besteht aus zwei Teilen: Der erste Teil umfasst eine computergestützte Analyse (CAA) und den Entwurf

(CAD) der phasengesteuerten PWM Konverter und Resonanzkonverter; der zweite Teil besteht aus einem Echtzeit-Simulator, der die Prüfung der Gesamtsteuereinheit des SPRC-LCs in Software-in-the-Loop (SiL) oder Hardware-in-the-Loop (HiL) Modus ermöglicht. Die Entwicklungsumgebung soll langfristig eine erhebliche Reduzierung der Kosten, Time-to-Market und erforderlichen Designkompetenz für zukünftige Entwicklungen ermöglichen.

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