This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TPEL.2018.2859902, IEEE Transactions on Power Electronics

Modular Multilevel Series/Parallel Converter with Switched-Inductor Energy Transfer Between Modules

Ricardo Lizana, *Member, IEEE*, Sebastian Rivera, *Member, IEEE*, Zhongxi Li, *Student Member, IEEE*, Jenny Luo, Angel V. Peterchev, *Senior Member, IEEE*, Stefan M. Goetz, *Member, IEEE*,

***Abstract*—This paper presents a modular multilevel series/parallel converter (MMSPC) with inter-module switched-inductor power transfer. The switched-inductor voltage conversion feature allows controllable and efficient transfer of energy between modules with nonnegligible voltage difference, providing both step-down and step-up functionalities. Thus, this converter can accurately control and rapidly adjust the voltage of each module to generate an ac output voltage waveform with a controllable number of levels, increasing the quality of the output. Moreover, the intrinsic dc–dc conversion feature can generate a dc controllable output voltage and enable new applications. In this text, we specifically demonstrate how the flexibility of obtaining both ac and dc output with the same setup renders the topology promising for battery energy storage systems (BESS) and dc microgrid applications. Experimental results validates the topology and concept of an MMSPC with intrinsic switched-inductor conversion.**

***Index Terms*—DC-AC power conversion, DC-DC power conversion, Energy storage, Modular Multilevel Converter, Power converter.**

I. Introduction

OVER the last years, multilevel converters have gained wide acceptance for high-power, medium- and high-voltage applications, in both industry and academia. When compared to traditional two-level voltage-source converters, these converters offer significant advantages, such as a superior harmonic performance, improved efficiency levels, lower common-mode voltages, smaller filter requirements, and reduced switching frequencies while featuring the use of standard semiconductor technology for high-power applications in the medium- to high-voltage range [1]–[3].

Within this category of converters, the multicell ones stand out in terms of modularity and flexibility. If the number of modules that comprise the power converter increases, the harmonic content in the generated output voltage/current waveforms of these converters decreases [4]. Within the multicell family, the modular multilevel converter (MMC) offers the additional advantages on top of aforementioned ones: transformerless operation, a common dc bus, and a completely modular and flexible structure. These features allow the implementation of the MMC in various applications, *e.g.*, medium-voltage motor drives, high-voltage direct current (HVDC) transmission systems, and active filters [5].

For every MMC application, the control scheme has to meet several control objectives simultaneously, such as balancing the capacitor voltages among the modules and reducing the circulating current, besides the generation of the required input/output characteristics. In order to achieve these objectives, different control strategies are reported in the literature, including methods in classical open- or closed-loop fashion and predictive control [6].

Recently, the development of more capable module configurations as well as extensions of the conventional MMC have received increased attention, aiming at complying with new operational requirements (e.g., dc-side fault-current blocking, smaller capacitor voltage ripple or further reducing the losses to name a few [7]). Among these new circuits, the modular multilevel series/parallel converter (MMSPC) appears as a promising configuration. The MMSPC is a generalization of the traditional MMC topology as it allows not only the series interconnection of the modules, but also their parallelization. In other words, the modulation scheme as an additional degree of freedom, and it can alternate series or parallel connection of cells in order to accomplish the control objectives. This feature can use modules, which would otherwise be bypassed when not actively needed in a converter arm, to take over current from parallel modules. This is also beneficial as it reduces the total parasitic inductance and resistance as well as aids in the balance of capacitors [7]. Such degrees of freedom render the MMSPC compelling for a wide range of applications [8]–[10].

The work presented in [10] describes the implementation of an energy storage system that incorporates batteries in the modules of the MMSPC, while still providing a flexible and high-quality output. Switched-capacitor alternation between series and parallel connection of modules smooths the charge/discharge dynamics and enables simple sensorless cell voltage balancing. However, the sensorless balancing operation relies on local circulating current between the paralleled

Manuscript received March 2, 2018; revised June 4, 2018; accepted July 10, 2018. This work was supported by the projects FONDECYT Iniciacion under grant no. 11160227, AC3E (CONICYT/Basal/ FB0008), SERC Chile (CONICYT/ FONDAP/15110019), the National Science Foundation No. 1608929, the North Carolina Biotechnology Center No. 2016-CFG-8004, and by a seed grant from the Duke University Energy Initiative.

R. Lizana is with the Department of Environment and Energy, Universidad Catolica de la Santisima Concepcion, Concepcion, Chile, e-mail: ricardolizana@ucsc.cl

S. Rivera is with the Department of Electronic Engineering, Universidad Tecnica Federico Santa Maria, Valparaiso and the Faculty of Engineering and Applied Sciences, Universidad de los Andes, Santiago, Chile, e-mail: s.rivera.i@ieee.org

Z. Li, J. Luo, A. V. Peterchev and S. M. Goetz are with Duke University, Durham, NC, USA, e-mail: zhongxi.li@duke.edu, jenny.luo@duke.edu, angel.peterchev@duke.edu, stefan.goetz@duke.edu

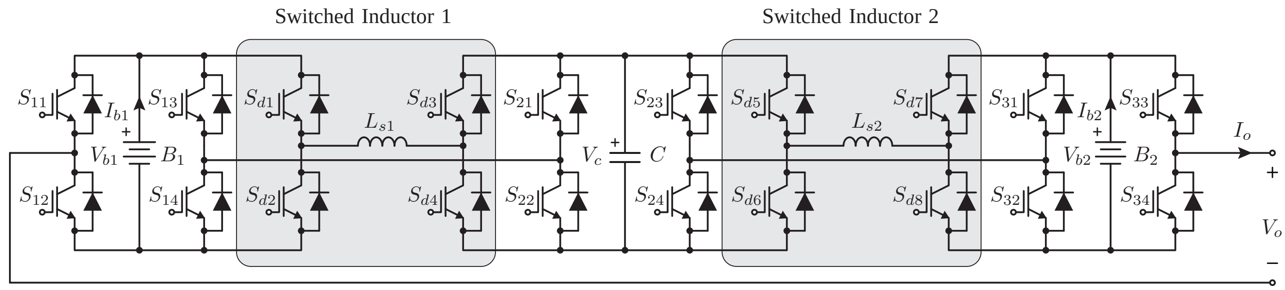

Figure 1. Proposed power circuit for the MMSPC with switched-inductor energy transfer.

modules, which produces additional conduction losses. To substantially reduce the losses, it is desirable to ensure a short interval between leveling the modules by the parallel connection [7]. Moreover, the idea of the parallel connection between the modules is based on the concept that all the modules of the converter have similar voltage levels, *i.e.*, they are fairly balanced. This principle of operation is similar to the traditional MMC [11], [12], in terms of redundancy and modularity.

However, the previously established constraints limit the extension of the modulation strategy. Typically, modulation at high frequencies based on triangular carrier signals or model-predictive control strategies are used to ensure frequent parallelization [13], [14]. Both modulation strategies are established and well-known, but they have the disadvantage of high switching losses compared to fundamental frequency modulation schemes. In addition, the parallelization has to be performed between modules with similar voltage levels, complicating the implementation of asymmetrical configurations of the MMSPC. This latter feature is advantageous as it allows to increase the available voltage levels in the output voltage while using the same number of modules or keeping a reduced device count.

Considering the previous statements, this paper proposes a novel configuration of the MMSPC, which features the use of asymmetrical dc sources. The key motivations are: first, to significantly reduce the conduction losses by limiting and controlling, via the bidirectional dc–dc stages, any circulating surge currents due to parallelization of modules with significant voltage differences; second, a reduction of the number of power cells required to reach a certain number of voltage levels or output voltage. Then, aiming to energy storage applications, the converter permits to replace some storage elements with capacitors in order to increase the cost-competitiveness of the structure, while keeping the voltage of the battery modules relatively low. Another benefit of the proposed structure when compared to the traditional MMC is the generation of both ac and dc outputs, while substantially attenuating the second-order oscillation in the battery modules, which otherwise severely damages and reduces their lifespan [15].

These features are achieved through the incorporation of inductors into some module interconnections in order to operate them as bidirectional dc–dc stages. Thereby, the converter is able to:

- Transfer energy between the modules efficiently even for nonnegligible voltage differences and enable asymmetrical module configurations.
- Enable the energy transfer between modules efficiently and with controllable impedance, assigning the energy balancing approach to the intrinsic switched-inductor conversion. As a result, the system can use low-frequency modulation strategies—*e.g.*, selective harmonic elimination, staircase, or nearest level modulation—for the output in order to reduce the switching losses of the system.
- The proposed configuration can generate both ac and dc outputs, extending the application of the MMSPC to BESS or bipolar dc microgrids. As it will be shown in later sections, the proposed converter offers a seamless transition for the output polarity. This feature, in addition to the four-quadrant capability of the circuit are attractive for applications in high-quality dc distribution systems.
- The proposed topology allows to use batteries and capacitors as energy storage units in the system. With this hybrid configuration on the storage elements, it is possible to achieve higher voltage levels with the control of the capacitor voltages without the needs of increase the number of battery units, allowing in this way to reduce the cost of the system.

The following will present the general concept of transferring energy between modules widely independent of the module voltage conditions and of adjusting their voltages dynamically, *e.g.*, to improve the output quality. In this paper, a flexible re-configurable battery system is presented. It consists of battery modules that are complemented with capacitor modules. The capacitor modules will demonstrate the flexibility of power transfer and the extended output voltage range well above that achievable with the batteries alone.

The remainder of this paper is organized as follows. In Section II, the proposed topology description is presented, Section III presents the operational principle. Simulation studies and experimental results are included in Sections IV and V. Section VI draws the conclusion of the work.

II. Topology Description

The proposed power circuit is shown in Fig. 1 for three cascaded modules. Each of the modules located at both terminals of the topology incorporate six semiconductors and a battery, whereas the module located in the centre of the topology is