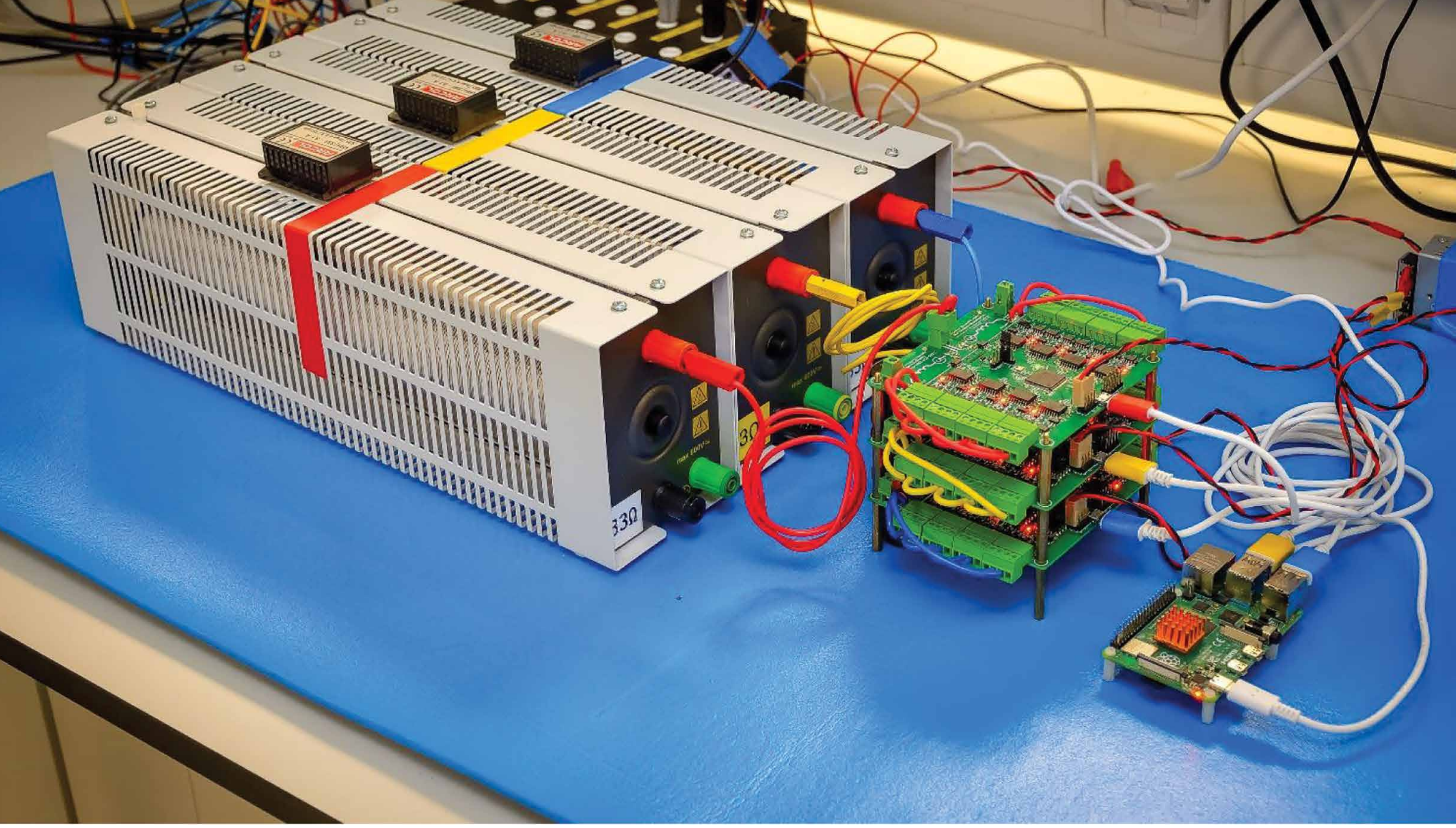


Meet the Micro-MMC

by Chuantong Hao, Junwei Cao, Peizhou Xia, Stephen J. Finney,
and Michael M. C. Merlin

The micro-modular multilevel converter (µMMC) concept proposes a benchtop-scale, low-voltage, open-source, and affordable hardware prototype of a modular multilevel converter (MMC) intended for research and teaching applications. The µMMC (µ originates from its rating being approximately one millionth of usual transmission-scale MMCs) aims to provide a solution to break the barrier from theory to practice, thanks to its all-integrated eight full-bridge (FB) submodules (SM) in a 10×10 cm printed circuit board (PCB) with a local microcontroller able to communicate with an external master controller. The electronics is rated for a 30 V dc bus voltage as typically found in traditional lab power supplies, providing both convenience and safety. This structure allows a lot of flexibility in terms of testing converter topology and control architectures. This article details the setup process of the µMMC into a 3-phase inverter to demonstrate its versatility and potential as a teaching and research tool.

Digital Object Identifier 10.1109/MPEL.2023.3329613
Date of publication: 26 December 2023

2329-9207/23©2023IEEE

Introduction

The modular multilevel converter (MMC) has cemented itself as a pivotal converter topology within the power electronics community spanning many applications from its inception domain in high voltage direct current (HVDC) transmission systems, and recently expanding into motor control, modern static compensators (e.g., STATCOMs), and many more [1]. Using stacks of submodules (SMs)—as illustrated in Figure 1—any voltage waveforms can be synthesized by switching the charged capacitors inside the SMs in the conduction path. An interesting feature of MMC-style converters lies in their ability to withstand high dc bus voltage magnitudes, while using relatively lower-rated voltage devices, and still offering low-distortion waveforms, high power efficiency. Their modularity can also be leveraged to improve the overall converter reliability using spare SMs. Such attractive performances and wide-ranging applications make the MMC an essential study topic for both power electronics engineers and researchers.

In industrial projects, MMCs are often characterized by their large footprint; making them often easy to spot on satellite imagery. Building an industrial-scale MMC remains impractical for research and education purposes due to the high cost and time requirement associated with such a scale. Building a reduced-scale MMC (e.g., 10 kVA) has become a widely accepted option—especially in university laboratories [2]—as a way to confirm experimentally specific research objectives, but this remains a cost- and labor-intensive activity; often requiring years of researchers' time and efforts with a substantial learning curve as shared in the literature [3].

Even a reduced-scale MMC could contain dozens of SMs in total, which means the control system should handle the interaction of large amounts of sensors, communication units, and controlled actuators. Alternatively, a distributed control structure consisting of multi layers controllers has been proven to be effective in many projects developed by industry and academia [4]. It often consists of an upper-level controller which uses output voltage and power references to compute the voltage that the SM stacks should generate, which are then picked up by the lower-level controllers, which arrange the SM balancing and gate signals for the power semiconductor devices. A detailed summary of the distributed control system of MMC can be found in [5].

This article presents a turnkey, economical, and integrated concept for MMC research and teaching, nicknamed micro-MMC (µMMC). From the perspective of the power circuit, the µMMC can be seen as a single leg of the classic 3-phase MMC, as shown in the shaded area in Figure 1. The 10×10 cm PCB contains eight interconnectable full-bridge (FB) SMs, a microcontroller (MCU), two current sensors, communication interfaces, and two pre-insertion resistors. The dc bus operating voltage is designed for up to 30V, the same as the typical output of traditional laboratory power supplies. The whole µMMC concept is available as an open-source project on a GitHub repository [6], allowing users to directly download the open-sourced design files and order from popular PCB manufacturers, allowing users to get a µMMC in a matter of weeks at a cost of about 50 GBP (or 60 USD). Both serial peripheral interface (SPI) and universal serial bus (USB) communication interfaces are implemented, making it possible for the µMMC to either operate as a standalone equipment or interacts as part of a wider power converter system.

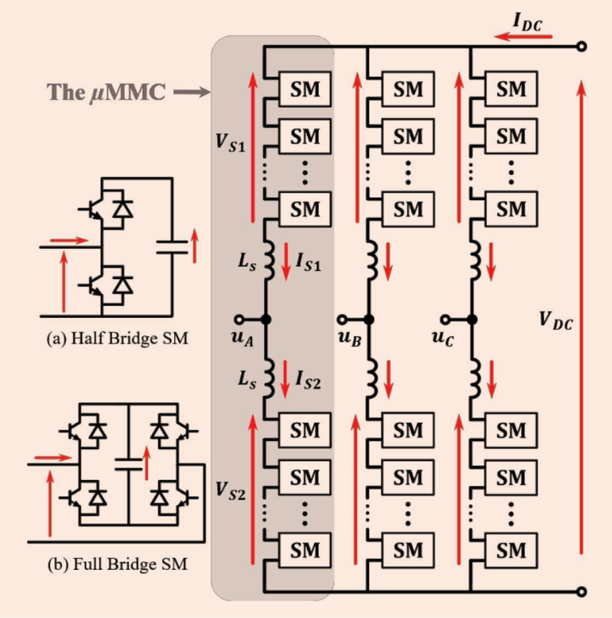


FIG 1 Three-phase MMC and SMs.

Hardware Structure Design

A. Overall Layout

The overall layout of the µMMC is illustrated in Figure 2, where the black solid lines represent the internal electrical connection within the PCB, while the red dashed lines demonstrate the user-defined connections. The primary circuit, located at the top of the PCB, includes (i) two inductors to be used as arm inductors, (ii) two

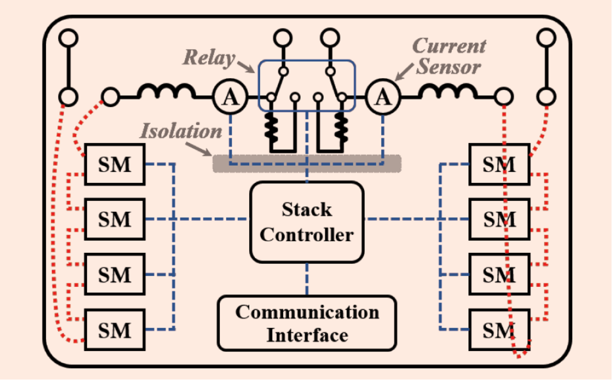


FIG 2 Overall layout of the µMMC.

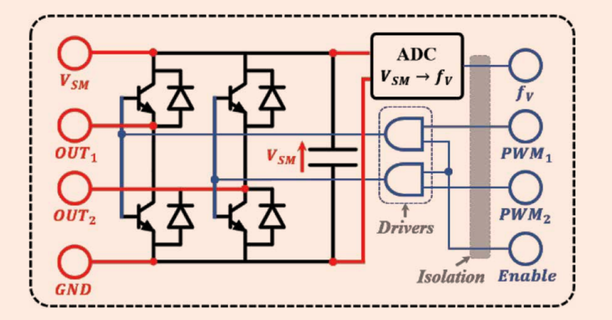


FIG 3 Submodule design in the μMMC.

hall effect current sensors, (iii) the output power connectors, and (iv) a double-pole double-throw (DPDT) relay to bypass the pre-insertion resistors used in self-starting procedures.

The layout of signal tracks, represented by the blue dashed lines in Figure 2, is distributed around the embedded STM32 MCU, which serves as the stack controller—as discussed in section "*Multilayer Control System, point A*—and manages the interface between the μMMC board and the central controller. This MCU uses its ADC peripherals to read the output from the current sensors, its GPIOs to control the relay, its timers to generate PWM signals to the SMs as well as interpreting the frequency modulated voltage measurement from the SMs. The communication to the potential master control is achieved either through USB or SPI.

B. Submodule

The SMs in the μMMC are of FB types but access to the positive and negative terminals of the SMs also allows half-bridge (HB) or other topologies to be used, as shown in Figure 3. For example, the SM will operate as an HB-SM when one of the *OUT* ports and *GND* are connected to the primary circuit. The power capacitor can either be soldered onto the PCB or be connected externally via V_{SM}, and *GND*, making it is flexibility to change the capacitance as required for different applications.

The switching states of the SM are controlled by an enable signal and two PWM signals from the stack controller. A local SM microcontroller (e.g., ATtiny) is present in the SM to measure the capacitor voltage and convert the voltage into a digital signal, denoted as f_V, of which the frequency is proportional to the SM voltage. This allows digital signals to be transmitted through a digital isolator to the stack controller. Besides, the local SM microcontroller is also used to light a local LED (omitted in Figure 3) to provide visual cue about the state of the SM, e.g., the measured voltage is within a safe range.

C. Cost of Hardware

As of July 2022, the total cost of a μMMC is estimated at 62.79 GBP when ordering a single unit, while a bulk order (e.g., 1000 units) can further reduce this value to around 50 GBP. The itemized cost is listed in Table 1. The detailed PCB design files and bill of materials (BOM) are provided on the GitHub repository [6].

Table 1. Cost of BOM (as of July 2022).

	Single unit price	Bulk (1000 pieces) unit price
Electronics Components	£58.56	£47.43
PCB Manufacturing	£1.22	£0.69
SMT Service	£3.01	£1.96
Total Price per μMMC board	£62.79	£50.08

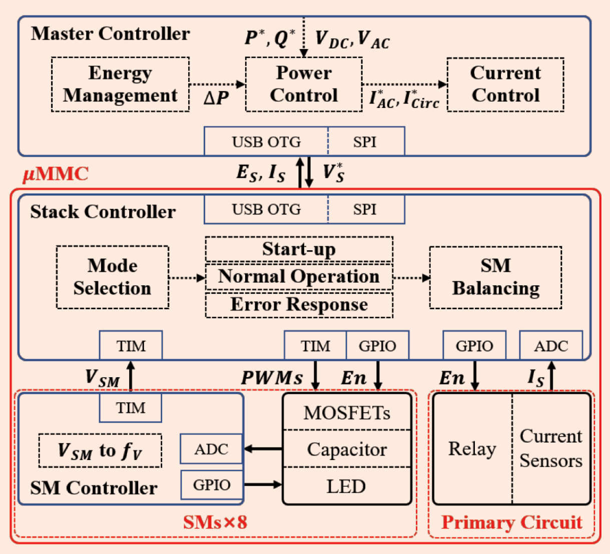


FIG 4 Control framework and peripherals.

Multilayer Control System

The stack controller MCU in the μMMC can be programmed with either the high- or low-level part of an MMC controller depending on the complexity of the experiment. Higher computational workload can be offloaded to an external central controller using the provided communication interfaces. This section introduces the control system of a typical HVDC converter operating in three-phase inverter mode and its implementation based on three μMMC boards and one separate master controller, as illustrated in Figure 4.

A. Control Algorithm

The master controller is in charge of the energy management, power control, and current control, while the stack controllers translate the voltage commands from the master into switching signals to their respective SMs. The objective of energy management in the master controller is to ensure that energy stored in each stack converges to its nominal value, by altering the different power references. The power control calculates the ac, dc, and circulating current references. Based on the variables represented in Figure 1, the dynamics of Phase A can be described by a set of voltage loops as written in Eq. (1). The current controller then computes the stack voltage commands (V_{S1} and V_{S2}) using these current references, the stack current measurements (I_{S1} and I_{S2}), the ac and dc voltages (u_A and V_{DC}).

$$\begin{cases} u_A + L\frac{d(I_{S1}-I_{S2})}{dt} + L_S\frac{dI_{S1}}{dt} + V_{S1} - \frac{1}{2}V_{DC} = 0 \\ u_A + L\frac{d(I_{S1}-I_{S2})}{dt} - L_S\frac{dI_{S2}}{dt} + V_{S2} + \frac{1}{2}V_{DC} = 0 \end{cases} \tag{1}$$

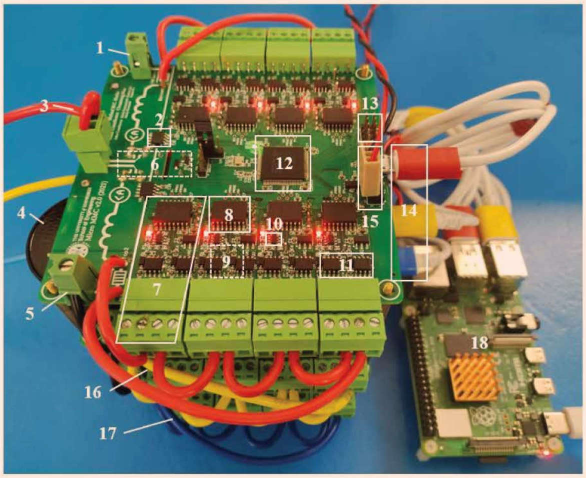
The stack controller cycles between three modes of operation. First, upon powering up, the stack controller will operate in start-up mode, where the pre-insertion resistors are switched in and the SMs are alternatively switched in till the capacitors have reached their pre-charged voltage threshold. Then, the stack controller moves to normal operation, where it receives the stack voltage commands from the master controller and sends its own stack energy levels and current measurements back to the master controller. These stack voltage commands are translated by the stack controller into PWM signals for each SM based on individual SM charge state command current direction to ensure correct voltage balancing between SMs. The third mode of operation kicks in in case of error detection, e.g., when a SM voltage or current cross safety threshold. In this mode, the stack resistors are switched in to limit current magnitudes and all SMs are blocked to protect the components from being damaged.

B. Concrete Implementation

The SM voltages in MMC are inherently floating in relation to the MCUs and thus require a specific system to pass on the information back to the stack controller. The solution implemented in the µMMC—as illustrated in the left bottom of Figure 4—uses a local, small MCU (here an ATtiny) to generate a square wave whose frequency is linearly proportional to the input voltage.

The generated square waves are decoded by the stack controller using its timer modules operating in input capture mode. Whenever a specific signal edge occurs on the input capture channel pin, the current value of the TIM counter is saved in the input capture register (CCR). The time period of the input signal is calculated by the difference between the CCR values of two adjacent rising or falling edges and the clock frequency of the TIM module. Together with the linear frequency/voltage function obtained from the SM controller, the SM voltages can be derived by the stack controller.

The communication between the µMMC and the external master controller is achieved by either USB or SPI interfaces. The USB provides the most convenient serial interface having the characteristics of simplicity and flexibility (plug-and-play), bidirectionality, increasing speeds, and low cost. SPI is a synchronous communication scheme with a separate clock wire, apart from the signal wires and chip select wire, so it can work up to faster speed than what universal asynchronous receiver-transmitter (UART) and inter-integrated circuit (I^{2}C) can provide. The µMMC operates in USB device mode or SPI slave mode, so technically multiple µMMCs can be controlled by a single master controller to demonstrate a more sophisticated power electronics system.



1: DC+ Connector
2: Current Sensor
3: AC Output Connector
4: Arm Inductor
5: DC- Connector
6: DPDT Relay(Bottom)
7: Sub-Module
8: Digital Isolator
9: SM Capacitor(Bottom)
10: SM Controller
11: Half Bridge Modules
12: Stack Controller
13: Debugger Connector
14: Micro-USB Ports
15: SPI/Power Connector
16: Phase B
17: Phase C
18: Master Controller

FIG 5 Experiment setup of a three-phase MMC.

After creating the Simulink model, users can simulate the model and download the completed algorithm for standalone execution on the development boards. MATALB/Simulink also offers a useful capability to tune parameters live from the Simulink model while the algorithm runs on the hardware. Both the communication interfaces on the master controller, and the control algorithms can be configured through graphical interfaces, greatly shortening the process from theory to practice.

Case Study

The experimental setup for the three-phase µMMC described in section "Multilayer Control System" is pictured in Figure 10 with all key components listed in Figure 5. Each µMMC board operates as one phase of the MMC labelled with red, yellow, and blue wires and USB cables representing Phase A, Phase B, and Phase C, respectively. The MMC converts 16V dc voltage from the power supply to 7V 3-phase ac voltage output on three 20Ω resistors set up as a star-configured load. The Raspberry Pi communicates with the µMMCs through USB interfaces.

Table 2. Parameters of the experiment setup.

Nominal ac Line Voltage (Peak)	7 V	Load Resistance	20 Ω	Nominal SM Voltage	4
Number of SMs (per stack)	4 V	Nominal dc Voltage	16 V	Designed Maximum Power	90 W
Master Controller Frequency	1 kHz	ac Frequency	50 Hz	PWM Frequency	10 kHz

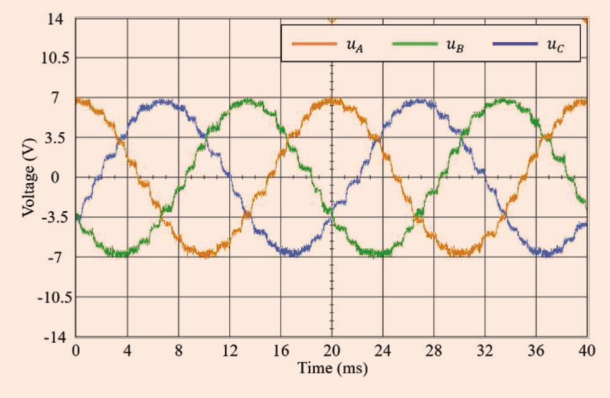


FIG 6 Three-phase ac output voltage.

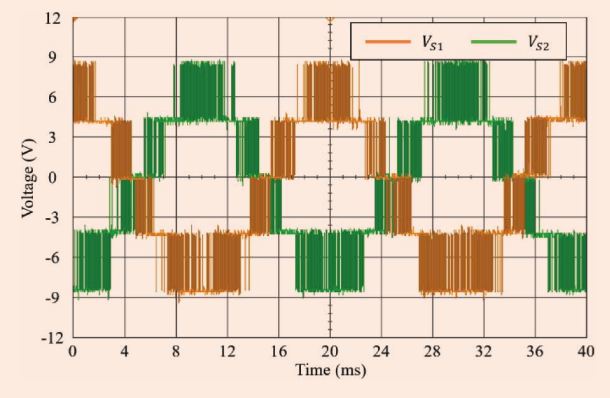


FIG 7 Stack voltages of phase A.

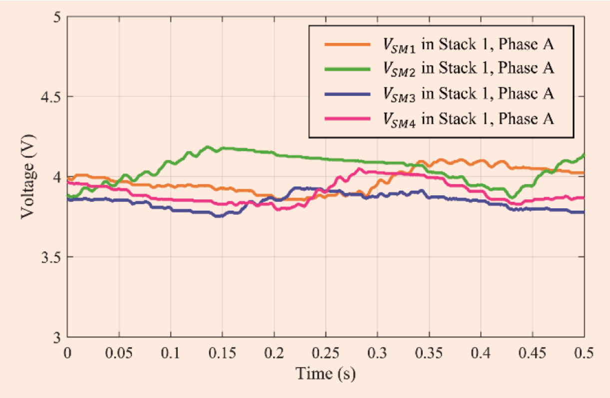


FIG 8 SM voltages in a single stack.

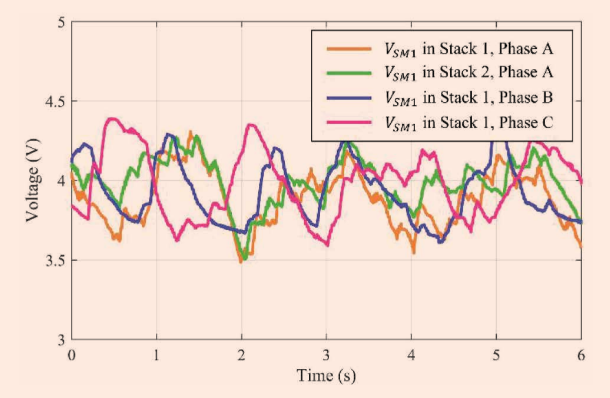


FIG 9 SM voltages in four different stacks.

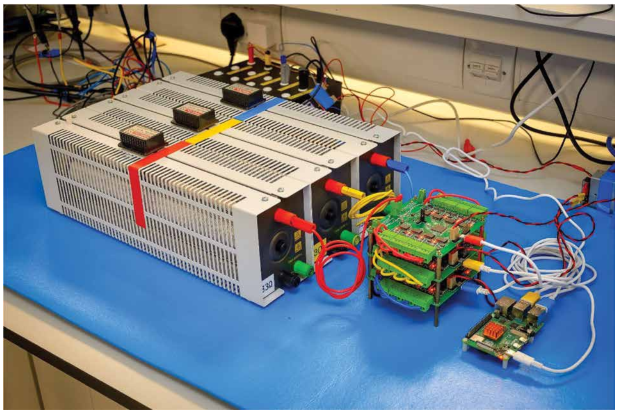


FIG 10 µMMC experiment of a three-phase MMC with a resistive load.

Energy management and voltage and current closed-loop control models are built in MATLAB/Simulink and employed to the Raspberry Pi. The control objective is to track the sine wave output voltage references set at a frequency of 50Hz and an amplitude of 7V peak, while maintaining the voltage balancing of all SMs. The system parameters are summarized in Table 2.

Two cycles of the three-phase ac output voltages are shown in Figure 6. The master controller updates the voltage references every millisecond, which can be seen on the voltage outputs. Figure 7 presents the stack voltages of Phase A. Both the upper stack voltage and the lower stack voltage are typical staircases and complementary in phase angle, showing that the stack controller and the semiconductors in the µMMCs operate in sync.

The capacitor voltages of four SMs in the upper stack of Phase A are shown in Figure 8, while Figure 9 presents four SM voltages in four different stacks over a longer timescale. The capacitor voltages of SMs in one stack and capacitor voltages of SMs in different stacks are all dynamically balanced, representing energy stored in all SM capacitors are balanced. Figure 8 illustrates the effectiveness of the SM balancing algorithm implemented in the stack controller, while Figure 9 illustrates the effectiveness of the energy balancing algorithm implemented in the master controller, and the effectiveness of the communication between the master and three slaves.

Conclusion

This article introduces the hardware design of the µMMC, which integrates eight full-bridge SMs in a 10×10cm PCB with an embedded MCU and communication interfaces to interact with an external master controller. The cost for a single µMMC board with components could be around 60USD with all hardware and source codes freely available and open-source. The control framework and implementation process for a three-phase, low-voltage MMC are presented in detail for users to experiment on their own. The use of high abstraction programming tools makes it possible to shorten the development process from simulation to hardware realization to only a few hours. The experiment setup and results of a three-phase inverter mode MMC verify the effectiveness, scalability, and convenience of the proposed µMMC concept.

In conclusion, the µMMC is at its core an open-source and affordable project, providing a timely platform to both educate and do further research on MMC, which is becoming an established technology, both for transmission and drive applications. On the educational side, educators can teach about MMC topology and control, showcasing the high-quality waveforms and scalability of MMC. On the research side, the µMMC concept can cheaply and quickly be adapted to new research themes from the study of new modular topologies to the provision of new grid services.

About the Authors

Chuantong Hao (haochuantong@poweroak.net) received the bachelor's and master's degrees in control engineering from Tsinghua University, Beijing, China, in 2016 and 2019, respectively, and the Ph.D. degree in power electronics from the University of Edinburgh, Edinburgh, U.K., in 2023. He is currently a Senior Engineer with POWEROAK, Shenzhen, China. His research interests include the design, control, and application of power electronics converters.

Junwei Cao (jcao@tsinghua.edu.cn) received the bachelor's and master's degrees in control theories and engineering from Tsinghua University, Beijing, China, in 1996 and 1998 respectively, and the Ph.D. degree in computer science from the University of Warwick, Coventry, U.K., in 2001. He is currently a Professor with the Beijing National Research Center for Information Science and Technology, Tsinghua University, Beijing, China. His research interests include distributed computing technologies and energy/power applications.

Peizhou Xia (p.xia@sms.ed.ac.uk) received the B.E. degree in electrical engineering from the Department of Electrical and Electronic Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China, in 2018, and the M.Sc. degree in electrical power engineering from the University of Edinburgh, Edinburgh, U.K., in 2019, where he is currently pursuing the Ph.D. degree. His current research interests include bidirectional dc–dc converters, power electronics, and renewable power conversion systems.

Stephen J. Finney (stephen.finney@ed.ac.uk) received the M.Eng. degree in electrical and electronic engineering from the Loughborough University of Technology, Loughborough, U.K., in 1988, and the Ph.D. degree from Heriot-Watt University, Edinburgh, U.K., in 1994. He joined the University of Edinburgh as a Professor of power electronics in 2017. He is currently a Professor with the University of Edinburgh. His current research interests include power electronics for high-power applications and the management of distributed energy resources.

Michael M. C. Merlin (michael.merlin@ed.ac.uk) received the Electrical Engineering degree from ENSEA, France, in 2008, and the M.Sc. degree in control systems, and the Ph.D. degree in electrical engineering from the Imperial College London, U.K., in 2008 and 2013, respectively. In 2017, he became a Lecturer with the University of Edinburgh, Edinburgh, U.K. He is currently a Senior Lecturer with the University of Edinburgh. His main research interests include design, optimization, and control of power converters, more specifically of the modular types which use stacks of submodules to achieve high power efficiency, and waveform quality.

References

[1] R. Marquardt, "Modular multilevel converters: State of the art and future progress," *IEEE Power Electron. Mag.*, vol. 5, no. 4, pp. 24–31, Dec. 2018.

[2] Y. Zhou et al., "A prototype of modular multilevel converters," *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3267–3278, Jul. 2014.

[3] T. Heath et al., "Cascaded- and modular-multilevel converter laboratory test system options: A review," *IEEE Access*, vol. 9, pp. 44718–44737, 2021.

[4] S. Lu et al., "An improved phase-shifted carrier modulation scheme for a hybrid modular multilevel converter," *IEEE Trans. Power Electron.*, vol. 32, no. 1, pp. 81–97, Jan. 2017.

[5] R. Wachal et al., *Guide for the Development of Models for HVDC Converters in a HVDC Grid*. Paris, France: CIGRE Working Group, Dec. 2014.

[6] C. Hao and M. Merlin. *Schematic, PCB, and Code for Micro-MMC*. Accessed: Sep. 2022. [Online]. Available: https://github.com/mmcmerlin/Micro-MMC