Modular Multilevel Converter Based Reconfigurable Ac Load Emulator

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***Abstract*—Numerous testing of power electronics converters with various load types/conditions shall always be conducted before finalizing the design parameters, wherefore load emulator, also known as active power electronics load or dc/ac electronic load, is superior to passive load and real load in terms of testing flexibility and cost especially in high voltage, high power applications. This paper proposes a concept that by paralleled operation of modular multilevel converters, a versatile testing platform for dc-ac/ac-dc voltage source converters, so called Reconfigurable Ac Load Emulator, can cover extremely wide range of operation voltage and frequency while effectively emulating different types/conditions of load. The emulator enables faster, more efficient and flexible testing of power electronics converters. Both simulation and experiments prove the feasibility.**

Keywords—Modular Multilevel Converter, Reconfigurable, Power Electronics Testing, Ac Load Emulation

I. Introduction

The recently emerging applications such as electrified transportation, clean energy development and smart utility grid have led to growing interests in power electronics converters with higher power, voltage and/or fundamental frequency. Developing such power conversion systems at kilovolts (kV), megawatt (MW) level and/or kilohertz (kHz) fundamental frequency requires much more time, cost and effort. One of the reasons is the lack of suitable loads with flexible and wide voltage/frequency range at MW level. Typical loads for the testing of power electronics converters, including passives (resistors, inductors and/or capacitors) and dynamometers, do not represent the real load characteristics or are costly and generally unavailable at kV/MW/kHz level. On the other hand, the electronic loads can accurately emulate various types of load and some allow users to program load current profile without using complicated real load, however, the commercially available products usually do not exceed tens of kilowatts, hundreds of hertz and several kilovolts.

The alternative way is to use another high-power converter to serve as the load, in which case the second converter becomes an electronic load or so-called a load emulator. Fig. 1 shows the typical system configuration [1-8]. The output of the Equipment Under Test (EUT) provides the input voltage to the load emulator while the load emulator behaves as a rectifier and regulates its input current to a desired shape, which is the load current seen by the EUT. To reduce energy loss, another regenerative inverter is usually connected with the load emulator in the back to back style and feeds the power to the grid. There have been a number of research papers discussing the implementation and control strategies for this configuration. Many types of load emulation ranging from power factor control to motor start-up were successfully tested [5-8]. However, this configuration does not have flexibility and scalability in testing different EUTs with varying voltage/current/frequency ratings. For example, to test medium/high voltage EUTs, the circuit topology of the load emulator needs to change from the commonly used H-bridge to other multilevel candidates [5]. The whole system may have to be re-designed for a new EUT to be tested. Besides, the grid-connected regenerative inverter significantly increases the design effort and the control complexity.

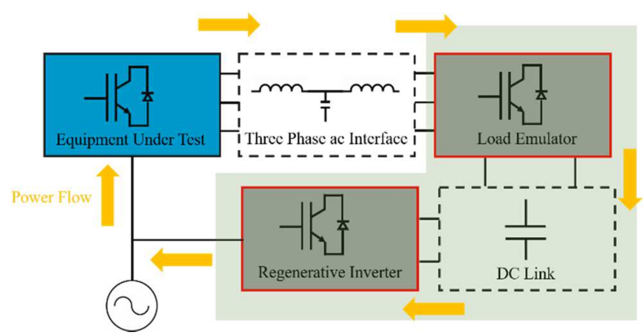

Fig. 1. The typical system configuration of converter-based ac load emulator with regeneration.

This paper proposes a new concept for ac load emulation. The circuit topology of the load emulator is derived from Modular Multilevel Converters (MMCs) and through changing the internal connections, the submodules (SMs) are then connected in series and/or in parallel. The load emulator can be reconfigured to meet requirements from hundreds of volts to tens of kilovolts dc and fundamental frequency requirements from 60 Hz to several kilohertz, all at MW level. In the meantime, the load emulator shares both ac and dc bus with the EUTs, eliminating the regenerative inverter while keeping accurate load emulation and the low system energy consumption. Section II gives detailed descriptions of the system configuration, the load emulator topology and the control architecture. Section III presents some case studies based on simulation and Section IV shows a laboratory down-scale prototype and the full scale system. Section V concludes this paper.

II. SYSTEM DESCRIPTIONS

Fig. 2 shows the overall system configuration. Compared to the system structure described in Section I [1-8], the load emulator and the EUT are connected at both dc and ac sides. This enables the testing not only for inverter mode EUTs but also for rectifier mode EUTs. In the latter scenario, the load emulator is to provide a stable three phase ac voltage to the EUT instead of regulating its ac current. Another advantage of this configuration is the regenerative inverter is no more needed to feed the power back to the utility grid while the dc power supply behaves as an energy buffer between the grid and the system. The grid only compensates for the switching/conduction loss and passive components loss in the system. Since the power rating of the dc power supply is small even for testing MW level EUTs, it is generally available on the market.

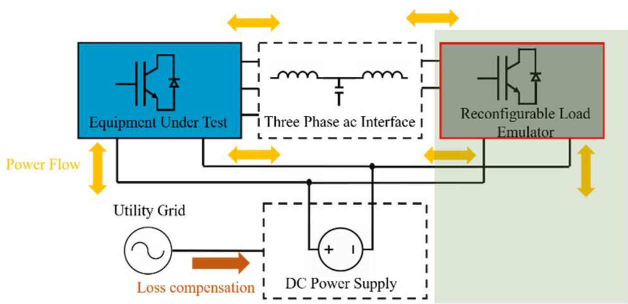

Fig. 2. The system configuration of proposed ac load emulator.

A. *Reconfigurable Topology of the Load Emulator*

As aforementioned, a versatile testing platform must be used for EUTs in wide ranges of voltage/current ratings. A fixed circuit topology can hardly meet this requirement. Fig. 3 shows the proposed reconfigurable topology of the ac load emulator, where only phase A is shown but phase B and phase C are identical. This topology is based on the MMC invented by Dr. Rainer Marquardt in 2003 [9]. Compared to a typical MMC, each arm in Fig. 3 consists of more than one string of submodules, which are usually half-bridge type as shown in Fig. 4, and these strings are connected in parallel. Therefore, there are in total y (series connected submodule number in one string) times x (parallel connected string number) submodules in each arm. By re-connecting the submodules, for example, connect all xy submodules in series for high voltage applications and connect all xy submodules in parallel for high current applications, the load emulator can cover extremely wide ranges voltage/current ratings. Redundant submodules, if not used in some cases, can help to improve the fault tolerance capability of the system. In addition, the multilevel feature of MMC enables smaller passive components and improves the fundamental frequency capability with limited switching frequency.

B. *Design Philosophy of the Submodules*

The design of the submodule includes sizing the capacitor, selecting the switching device and cooling method, as well as the design of control circuits, bus-bars and the mechanical structure. Since the purpose of this paper is to introduce the new concept of the reconfigurable ac load emulator, only the key parameters that relate to the application are discussed, which are the switching device rating and submodule capacitance. Besides, because the load emulator is to serve as load for targeted 1-MW EUTs (part of) listed in Table I where the dc voltage ratings range from 1 kV to 25 kV, the series and parallel numbers in each case also need to be carefully determined.

Table I: Specifications of targeted EUTs

V_{dc} / V	V_{ac} / V	AC Frequency / Hz	Power Rating / MW
1,000	480	400-3000	1
4,507	2,300	60-200	1
9,014	4,190	60	1
13,522	6,900	60	1
25,000	13,800	60	1

The criteria of selecting the submodule capacitance and the switching device rating are as follows:

1) Submodule voltage utilization is 0.5-0.6 of device voltage rating;

2) The peak ripple of submodule voltage is lower than $(1+\varepsilon)$ of nominal voltage, $\varepsilon \leq 0.2$;

3) Normalized dc voltage modulation factor

$$b = \frac{V_{dc}/2}{NV_{sm}}, 0.35 \leq b \leq 0.45,$$

The procedures or equations to calculate the submodule capacitor ripple can be found in papers on the design of MMC [14], which are not repeated here. Considering the availability and cost of the capacitor and switching device, the submodule design results are obtained by sweeping possible combinations of devices, capacitors, series number and parallel number. The results are shown in Table II for the EUTs listed in Table I.

Table II: Specifications of targeted applications

Case #	Vdc / V	Series # y	Parallel # x	Cap & Nor. Voltage
1	1,000	2	22	2 mF, 500 V
2	4,507	8	4	2 mF, 563 V
3	9,014	16	2	2 mF, 563 V
4	13,522	22	2	2 mF, 614 V
5	25,000	44	1	2 mF, 568 V

In addition, the proposed topology differs from a typical MMC not only in the paralleled strings, but also the arm inductors. Usually, there are 6 bulky arm inductors equipped with a typical MMC. They are not suitable for this topology because once the application scenario changes and the submodules are reconfigured, the required arm inductance will change accordingly. Therefore, a small inductor is installed within each submodule instead of using a big inductor within each arm. The distributed arm inductance changes automatically with submodule reconfiguration. The design results indicate 80 uH inductor with 70 A RMS current rating and 3 kV insulation capability to be installed in each submodule to meet requirements from all the cases.

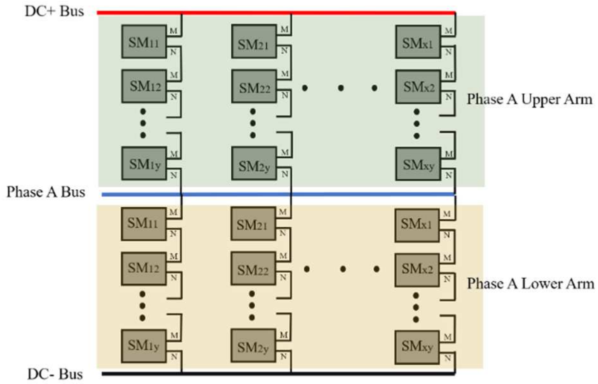

Fig. 3. The circuit topology of the reconfigurable ac load emulator.

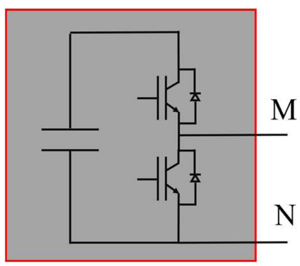

Fig. 4. Half-bridge based submodule topology (output inductor not shown).

C. Control Architecture

There have been several papers discussing the control architecture to achieve programmable load current emulation [4, 6, 10]. These are basically all output ac current control strategy. In addition to the load emulation, MMC requires a cascaded control structure for multiples control objects such as submodule capacitor voltage balancing, arm voltage balancing and circulating current control [11]. Combing the knowledge, as well as current sharing strategies for paralleled legs which are essential for the proposed topology, Fig. 5 shows the simplified control architecture of the system.

Note that with different configurations of submodules, the modulation and control strategy are different as well. For example, for case #1 in Table I, carrier phase shift modulation is selected and when the fundamental frequency is at kHz level, circulating current control is no more necessary. For case #2, nearest level modulation combined with PWM switching is selected. For case #5, since the series connected number of submodules is high and there are no paralleled strings, nearest level modulation scheme is selected and current sharing controller is eliminated. Since the purpose of this paper is to introduce the new concept of Ac load emulator for high-power, high voltage applications, the details of the controller design are not presented here.

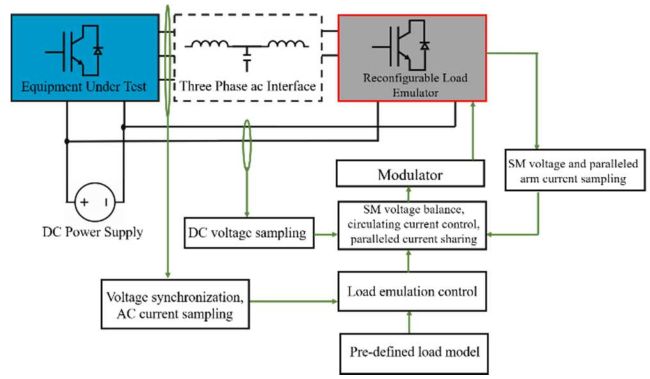

Fig. 5. Simplified control architecture of the MMC based reconfigurable ac load emulator.

III. CASE STUDY BY SIMULATION

A simulation model is built in MATLAB/Simulink. The simulation results of 2 typical cases in Table I are presented. They represent the applications that require the highest number of parallel connected strings and the highest number of series connected submodules.

A. Case Study 1: 1 MW high speed ac drive

Application #1 in Table I is the target EUT in this case. The 1-MW EUT operates at 1000 V dc and its output frequency is 60-3000 Hz. Assumed EUT topology is a 3-level ANPC inverter using space vector modulation [12]. The load emulation is to control the EUT's output power factor to be 1.

The keys in this case are to regulate the high fundamental frequency ac current and keep equally distributed current in paralleled strings. The EUT's switching frequency is 60 kHz and submodule switching frequency is set at 20 kHz. Fig. 6 shows the regulated three phase output current of the EUT at 3000 Hz. The output power factor of EUT is controlled at 1, which means the EUT outputs 1 MW real power and the total power consumption of the entire system including both the power loss of the EUT and the load emulator, is around 65 kW. Fig. 7 shows the equal current sharing between 22 paralleled strings. Although the realistic situation is not the same as that the paralleled strings are nearly identical in the simulation, this proves the effectiveness of the current sharing strategy for 22 paralleled MMCs.

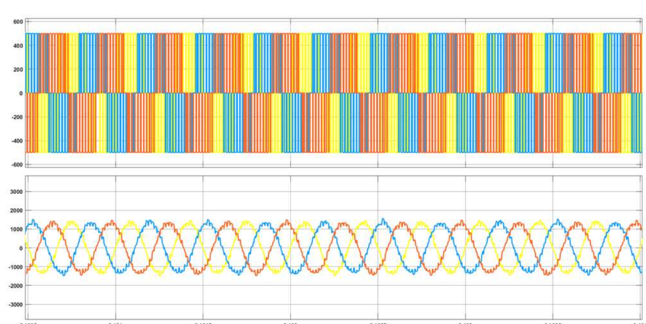

Fig. 6. EUT output voltage and controlled current.

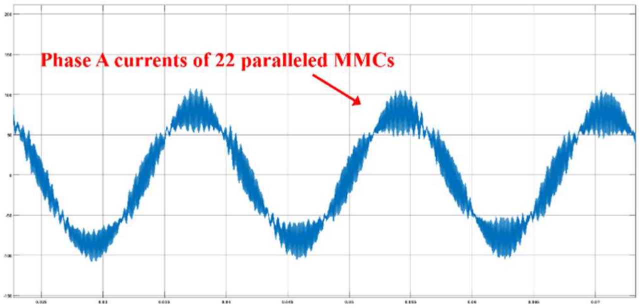

Fig. 7. Current sharing in paralleled MMCs, phase A.

B. *Case Study 2: 1 MW medium voltage inverter*

Application #5 in Table I is the target EUT in this case. The 1-MW EUT operates at 25 kV dc and its output frequency is 60 Hz. Assumed EUT topology is a MMC with 4 SM per arm using carrier phase shift modulation [13]. The load emulation is to control the EUT's output current to the specified amplitude.

The key in this case is to regulate the current and keep the balanced voltages of series connected submodules. The nearest level modulation and the sorting algorithms with 10 kHz executing frequency [15] are applied. Fig.8 shows the regulated EUT output current. The load current is controlled to step from 60 A to 30 A peak and the smooth transition is achieved. Fig. 9 shows the submodule voltage balancing results.

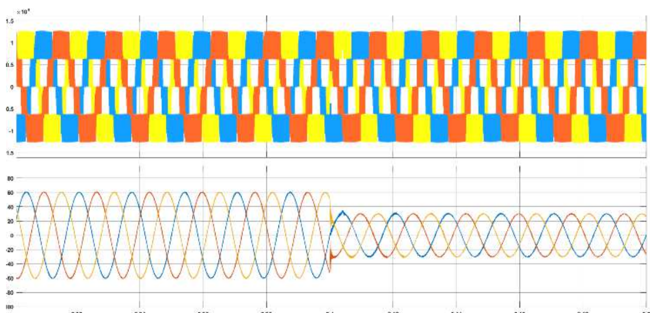

Fig. 8. EUT output voltage and controlled current.

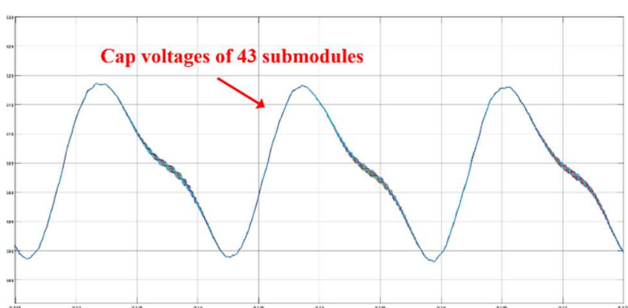

Fig. 9. Balanced SM voltage in series connected SMs.

IV. EXPERIMENTAL RESULTS

A laboratory down-scale prototype has been built to validate the concept. Fig. 10 is the hardware picture of the half-bridge submodule and the test set up. As previously discussed, the reconfigurable load emulator differs from typical MMCs because it has paralleled legs in each arm. The waveforms in Fig. 11 shows the testing result of currents of 4 paralleled legs in one arm, which are very well shared equally (overlapped).

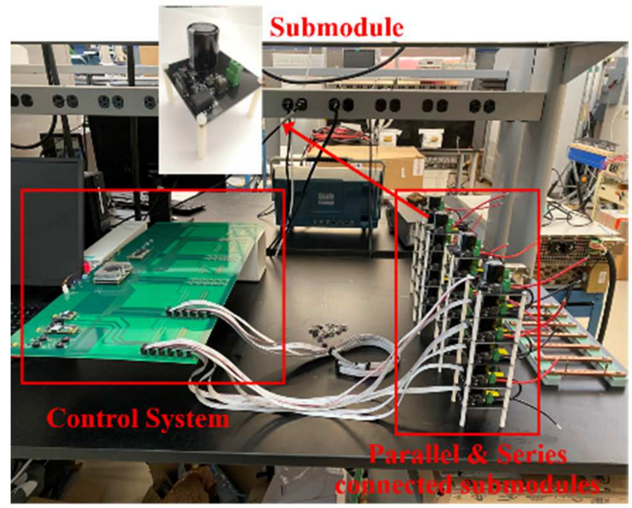

Fig. 10. Down-scale prototype with control system.

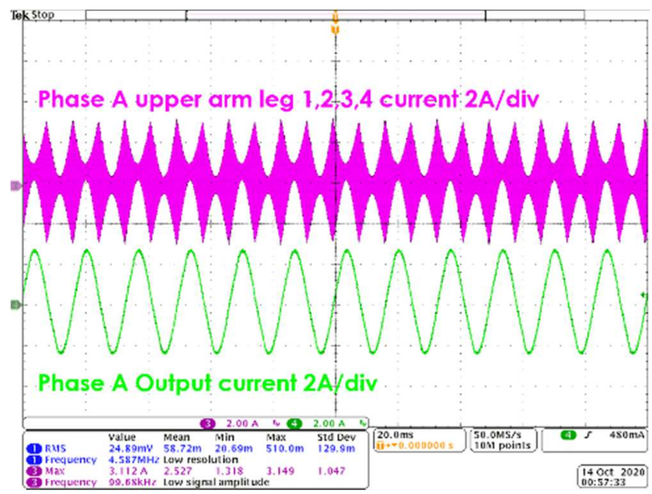

Fig. 11. Test result of paralleled operation of 4 legs.

The full-scale system construction and the control system development are still in progress by the time this paper is completed. Fig. 12 and Fig. 13 show the module and power cabinet building. Complete testing results will be provided in future publications.

Fig.12. Full-scale module with 2 submodules connected in series.

Fig.13. Full-scale power cabinet per arm.

V. CONCLUSIONS

This paper proposes a new concept to build a scalar, universal ac load emulator for testing of high power, wide frequency and voltage range voltage source converters. Based on MMC and thanks to the research progress on paralleled operation of power converters, the load emulator can be flexibly reconfigured to cover extremely wide voltage/frequency ratings of EUTs. Compared to typical testing methods, it significantly accelerates the testing process of high-power converters as well as saves tremendous amount of cost.

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REFERENCES

[1] Olias Vazquez, A. Lazaro, A. Barrado, and J. Pleite. "Implementation of a loss-free programmable AC load." In IECON'98. Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society (Cat. No. 98CH36200), vol. 2, pp. 630-635, 1998.

[2] Ju-Won Baek, Myung-Hyo Ryoo, Jong Hyun Kim, and Jih-Sheng Lai. "50kVA Regenerative Active load for power test system." In 2007 European Conference on Power Electronics and Applications, pp. 1-8, 2007.

[3] Zheyu Zhang, Zou Yunping, Wu Zhenxing, and Tang Jian. "Design and research of three-phase power electronic load." In 2009 IEEE 6th International Power Electronics and Motion Control Conference, pp. 1798-1802, 2009.

[4] Bruno W. França, Leonardo F. da Silva, and Maurício Aredes. "A novel predictive controller and experimenntal analysis of a power electronic load." In XI Brazilian Power Electronics Conference, pp. 715-719, 2011.

[5] Jeong In Wha, Mikhail Slepchenkov, and Keyue Smedley. "Medium voltage multilevel AC regenerative load with One-Cycle Control." In 2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 2084-2091, 2011.

[6] Rafael Luís Klein, Angelo Fillipi de Paiva, and Marcello Mezaroba. "Emulation of nonlinear loads with energy regeneration." In XI Brazilian Power Electronics Conference, pp. 884-890, 2011.

[7] Christian Nemec, and Jörg Roth-Stielow. "Ripple current minimization of an interleaved-switched multi-phase PWM inverter for three-phase machine-emulation." In Proceedings of the 2011 14th European Conference on Power Electronics and Applications, pp. 1-8, 2011.

[8] Jing Wang, Yiwei Ma, Liu Yang, Leon M. Tolbert, and Fred Wang. "Power converter-based three-phase induction motor load emulator." In 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 3270-3274, 2013.

[9] Anton Lesnicar, and Rainer Marquardt. "An innovative modular multilevel converter topology suitable for a wide power range." In 2003 IEEE Bologna Power Tech Conference Proceedings, vol. 3, pp. 6-pp, 2003.

[10] Zhi Geng, Dazhong Gu, Tianqi Hong, Jiaxin Teng, and Dariusz Czarkowski. "Novel control architecture for programmable electronic AC load to achieve harmonic load profiles." In 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 2888-2893, 2017.

[11] Makoto Hagiwara, and Hirofumi Akagi. "Control and experiment of pulsewidth-modulated modular multilevel converters." IEEE transactions on power electronics vol. 24, no. 7, pp: 1737-1746, 2009.

[12] Fred Wang, Ruirui Chen, Handong Gui, Jiahao Niu, Leon Tolbert, Daniel Costinett, Benjamin Blalock et al. "MW-Class Cryogenically-Cooled Inverter for Electric Aircraft Applications." In AIAA Propulsion and Energy 2019 Forum, p. 4473. 2019.

[13] Shiqi Ji, Xingxuan Huang, Li Zhang, James Palmer, William Giewont, Fred Wang, and Leon M. Tolbert. "Medium voltage (13.8 kV) transformer-less grid-connected DC/AC converter design and demonstration using 10 kV SiC MOSFETs." In 2019 IEEE Energy Conversion Congress and Exposition (ECCE), pp. 1953-1959, 2019.

[14] Cong Zhao, Zhe Wang, Zixin Li, Ping Wang, and Yaohua Li. "Characteristics analysis of capacitor voltage ripples and dimensioning of full-bridge MMC with zero sequence voltage injection." IEEE Journal of Emerging and Selected Topics in Power Electronics 7, no. 3 (2018): 2106-2115.

[15] Jiahao Niu, and Fred Wang. "The Impact of Execution Frequency in Sorting Algorithm on Nearest Level Modulated Modular Multilevel Converter." In 2019 IEEE 10th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), pp. 582-588. IEEE, 2019.