Requirements of Cell Capacitor for High Power-Density Design in Modular Multilevel Converter with H-bridge Cell

Toshiki Nakanishi*, Jun-ichi Itoh*

[1] Nagaoka University of Technology, Japan

This paper presents a volume evaluation of capacitors for high power-density design in a step-down rectifier employing a modular multilevel converter (MMC) in a power system interconnected to a 6.6 kV AC power grid. This paper focuses on minimizing the capacitor volume by considering rated ripple current and the number of cells as evaluation factors. In this design, commercial electrolytic capacitors are utilized as cell capacitors instead of customized capacitors. Additionally, the conditions for high power density in the MMC are clarified based on the volume evaluations of the electrolytic capacitor.

Keywords Modular Multilevel Converter, High Power Density Design, Volume of Electrolytic Capacitor, Ripple Current

1. Introduction

Recently, step-down rectifiers employing a modular multilevel converter (MMC) to avoid utilization of a bulky transformer in a DC micro-grid has been proposed [1]. The conventional power system connected to a utility grid of 6.6 kV has an isolated transformer. However, the volume of the isolated transformer is large because the isolated transformer operates in commercial frequency. Hence, a step-down rectifier with an H-bridge cell type MMC is suitable for DC micro-grid in terms of volume reduction.

In many AC-DC converters employing MMC, the design methods for achieving high power-density have been considered by setting specific design criteria [2]. However, the design criteria focusing on the utilization of the electrolytic capacitors in the H-bridge cell type MMC have not yet been reported in detail, even though electrolytic capacitors possess a high voltage rating of several hundred volts and a high capacitance per capacitor volume.

This paper discusses the design criteria with the aim of obtaining high power density in the MMC which is based on the volume evaluation of the electrolytic capacitors. The original contribution of this paper is to clarify the number of cells and to select the rated ripple current associated with the smallest possible overall volume. Finally, the conditions in order to obtain high power density and the requirements of the electrolytic capacitors are clarified.

2. Configuration of proposed system

Fig. 1 shows the configuration of an H-bridge cell type MMC. In practice, multiple cascaded cells are used because the effect of harmonic distortion reduction is increased by increasing cell numbers. The MMC is also able to reduce the voltage rating of the devices on each cell due to the cascade cell connections, and so lower voltage switching devices can be utilized with the MMC. The MMC converts a medium AC voltage to a DC voltage of several hundred volts. Finally, the DC output voltage of 400 V is obtained by the isolated DC-DC converter.

3. Operation of step-down rectifier using MMC

Fig. 2 shows the waveforms for the input phase voltage, the input current and the DC output voltage in the miniature model. The waveforms for the input phase voltage and the input current confirm that a unity power factor is obtained. The total harmonic distortion (THD) of the input current is 3.2%. It can also be seen that the DC output voltage waveform in the lower side of Fig. 2 indicates that the step-down rectifier converted the input voltage of 200 V into a constant output DC voltage of 75 V. Therefore, the MMC achieves step-down rectification.

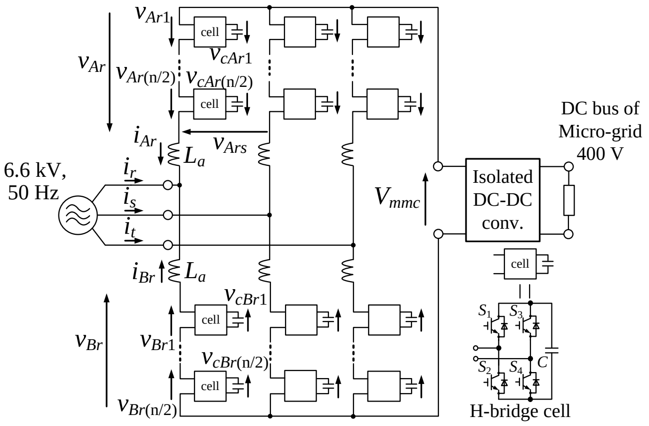

Fig. 1. Circuit configuration of step-down rectifier incorporating MMC.

Fig. 3 plots the waveforms for all cell capacitor voltages that are connected to the R-phase leg. The capacitor voltage is controlled by the capacitor voltage command. As a result, the proposed step-down rectifier maintains the capacitor voltage of each H-bridge cell to the voltage command level of 130 V. In addition, the maximum voltage error between the voltage command of the cell capacitor and the measured voltage is 2.0% or less.

4. Evaluation of capacitor volume

Fig. 4 shows the relationship between the ripple current and the capacitor volume attracted from the database of commercial electrolytic capacitors. In this graph, the number of capacitors connected in parallel in one cell increases with the required ripple current values. The minimum point of each mark indicates the ripple current and the volume of the single capacitor. These data demonstrate that the overall volume of the capacitors is reduced by connecting capacitors with small rated ripple currents in parallel, compared to the use of only one capacitor with a large rated ripple current. Consequently, the parallel connection scenario is preferable.

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a) Correspondence to: Toshiki Nakanishi
E-mail: nakanishi@stn.nagaokaut.ac.jp,

Fig. 5 plots the relationship among the number of cells, the capacitor volume and the voltage rating ratio. Note that the number of series connected capacitors increases when the required voltage rating increases above the voltage rating of a single capacitor, which requires the use of a series connection of capacitors. The capacitor volume is determined by the quantity of series connected capacitors multiplied by the number of cells under the same ripple current conditions. The voltage rating ratio is defined as the ratio between the required voltage rating and the actual voltage rating when the capacitors are connected in series. As a result, the capacitor volume becomes small when the voltage rating ratio at each point is close to 1.0. Consequently, it is possible to achieve the desired volume minimization by designing a device so that the voltage rating ratio is close to 1.0.

From above results, the requirements of electrolytic capacitors in the cell are that (i) the rated ripple current per unit volume is high, and (ii) the voltage rating per unit volume is high. Additionally, the conditions to achieve further volume reduction are as follow;

(a) An equivalent series resistance of the capacitor should be small.

(b) Heat dissipation characteristic of inside heating should be high.

(c) The voltage rating is more than 500 V.

Conditions (a) and (b) are required to suppress the raise of inside heating. The volume reduction of the capacitor is achieved by decreasing the raise of inside heating. In addition, Conditions (c) is required to eliminate balancing resistances. When 1.7-kV IGBT and the capacitor with the voltage rating of 400 V are applied, three or more capacitors are necessary. Moreover, balancing resistances are required when more than three capacitors are connected in series. When the capacitor with the voltage rating of more than 500 V is employed, the balancing resistances are not required. Besides, the volume of capacitor with the voltage rating of more than 500 V should be as small as possible for the volume reduction.

Fig. 6 presents the breakdowns of the overall volume when the MMC output voltage is 1200 V and 1.7 or 1.2-kV IGBTs are used. Note that the minimum total volume of inductors and heat sink in each number of cells is chosen by Pareto front optimization. As a result, it is obvious that the capacitor volume is the largest component in the overall volume and the variation of the capacitor volume with different devices and numbers of cells is remarkably high. These results demonstrate that, as the first step of the design, it is necessary to focus on selecting the number of cells at which the capacitor volume is small based on the voltage rating ratio.

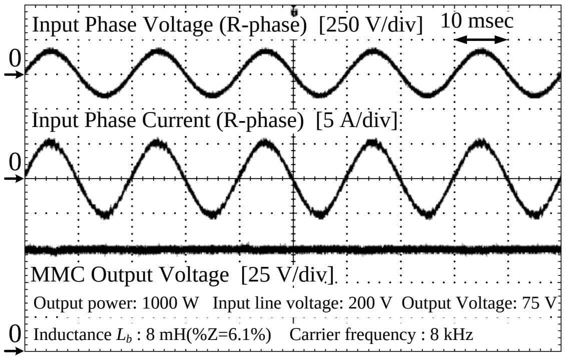

Fig. 2. Waveforms of input voltage, input current and DC output voltage.

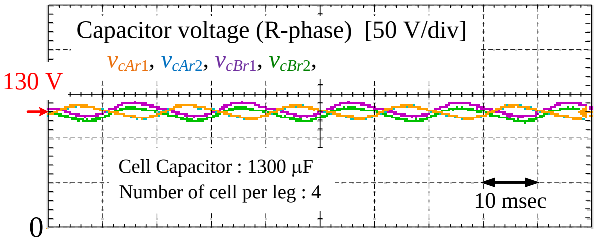

Fig. 3. Waveforms of capacitor voltage in R-phase leg.

5. Conclusion

This paper detailed the volume evaluation of electrolytic capacitors based on the rated ripple current and the number of cells. As the conditions and the requirements for the high power density, the volume minimization was achieved by selecting the number of cells so that the voltage rating ratio is close to 1.0. Besides, in the electrolytic capacitor, the low inside heating characteristic and the voltage rating of more than 500 V were desired.

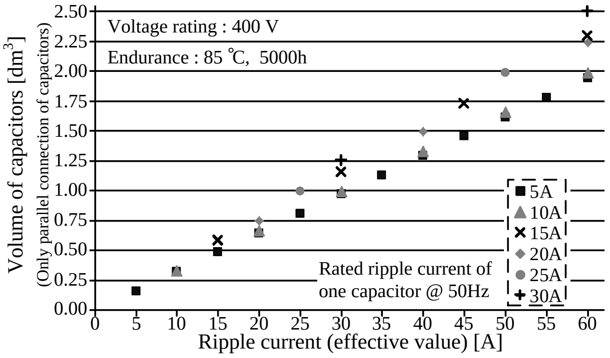

Fig. 4. Relationship between ripple current and capacitor volume.

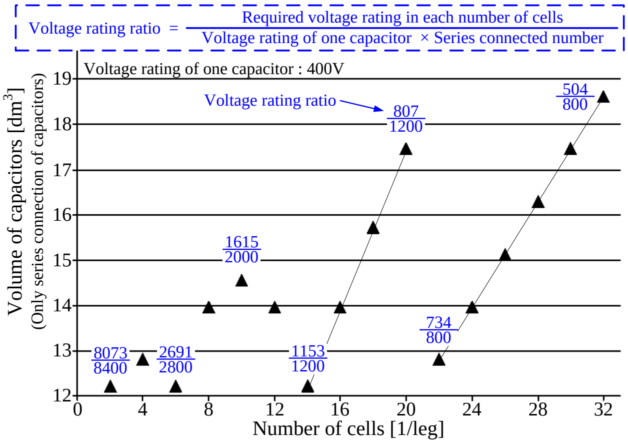

Fig. 5. Relationship between the number of cells and capacitor volume.

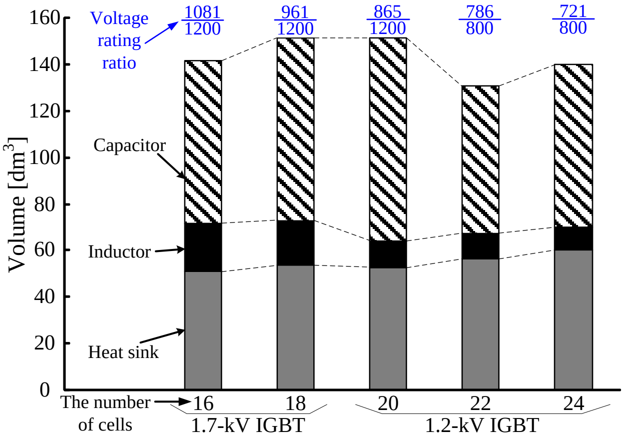

Fig. 6. Breakdown of the overall volume in 1.7 and 1.2 kV-IGBT.

References

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