Modular Multilevel Converter for Wind Power Generation System connected to Micro-grid

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Abstract— **This paper discusses a AC-DC converter which is constructed by a Modular Multilevel Converter (MMC) for a wind power generation system connected to Micro-grid. The proposed system which is constructed the MMC with an H-bridge cell achieves to convert from a generator voltage of 3.3 kV into DC bus voltage of 340 V. Moreover, as a fundamental evaluation, the experimental result by miniature model of 700 W confirms that the proposed system achieves the step-down operation from input voltage of 200 V into DC voltage of 65 V. Finally, the proposed system maintains the capacitor voltage of each cell to the voltage command. Furthermore, the maximum voltage error between the voltage command of the cell capacitor and the measured voltage is 10% or less.**

Keywords-Modular Multilevel Converter;H-bridge cell; Micro-grid; wind power generation system; high power rectifier

I. INTRODUCTION

Recently, a micro-grid and a DC power grid are actively researched as a next generation power supply. Advantages of the micro-grid are summarized as follows [1]-[4]; (i) the system achieves high efficiency operation because of the reduction of conversion losses in inverters between dc output sources and loads. (ii) it is not necessary to consider synchronization with utility grid and reactive power. (iii) when a blackout or voltage sag occurs in the utility grid, it does not affect the dc bus voltage of the micro-grid directly because of the stored energy of the dc capacitor and the voltage control of AC-DC converter. (iv) the micro-grid is suitable to connect a battery energy storage system and a renewable energy source such as a photovoltaic generation system and a fuel cell because the output voltage of many renewable energy sources is DC voltage. From advantages of the above, the micro-grid has been applied to the power grid in isolated islands as a stand-alone power system [5]-[6].

Moreover, a wind power generation is also applied to the power grid in isolated islands as one of the power source. Presently, many power grids in isolated islands are constructed by a diesel generation system. However, this system is very costly because the generation costs in the isolated island involve a high transportation cost to carry fuels for diesel generators [5]. Thus, applications of renewable energy sources such as a wind power generation are actively researched and developed in order to reduce the fuel cost. Moreover, locations of offshore and the isolated island are suitable for a wind power generation with high power capacity because wind is much stronger and much constant compared with wind conditions of onshore [8]-[10]. Therefore, the wind power generation is applied as one of power sources for the micro-grid in isolated islands.

Presently, a conventional wind power generation system is constructed by a transformer and a bidirectional converter in order to connect to an AC grid [11]-[13]. Besides, a wind power generation system connected to the micro-grid has a feature which the rated voltage of the wind power generator with high power capacity is higher than DC bus voltage of 340V in the micro-grid [1], [8]. Therefore, it is necessary for a power system to convert from generator voltage into DC bus voltage when power is supplied from the wind power generator into the micro-grid. Additionally, the system has to boost from DC bus voltage into generator voltage because starting torque is required while the wind power generator starts up. Thus, the bidirectional AC-DC converter operates as a rectifier when the system generates power. In contrast, the bidirectional AC-DC converter operates as an inverter when the generator starts up. However, a size of the transformer is bulky because the transformer operates in low frequency because the generator operation frequency is low. In addition, the reasons which the transformer is bulky include that a high transformer ratio is required to convert from generator voltage into DC bus voltage.

As one of solutions, employing a Modular Multilevel Converter (MMC) to the wind power generation system connected to the micro-grid is an effective method. Advantages of the MMC are as follows; (i) the circuit configuration is simple because of cascade connection of cells. (ii) the MMC reduces the harmonic distortions because the MMC output the multilevel waveform (iii) low voltage devices are applied to each cell because the output voltage of the cell is low by increasing a number of cells. Thus, the system achieves the high response operation. From the advantages of the above, the MMC has been actively researched as a next generation high power converter without the bulky transformer [14]-[16]. Therefore, the wind power generation system achieves the size reduction by applying the MMC into the system.

However, in the general AC-DC converter using the MMC which consists of chopper cells, it is difficult to achieve the step-down rectified operation because chopper cells cannot output negative voltage. Moreover, many control methods of the MMC have been reported. Fundamental configurations of control system for the MMC are constructed from a current control system and a capacitor voltage control system. However, most of conventional systems are complex and it is difficult to understand these control principle instinctively.

Especially, the capacitor voltage control is constructed from many components. For example, a main control system in order to control average value of all capacitor voltage is applied. In addition, many balancing control systems are applied as sub control system [16]. Therefore, it is also difficult to design control parameters in each controller.

This paper discusses a wind power generation system connected to the micro-grid using the MMC which consists of H-bridge cells in order to convert from high generator voltage into DC bus voltage. Employing H-bridge cell is able to solve the voltage limit. Moreover, the system is able to operate as a high power step-down rectifier. Additionally, a proposed control system is very simple because the proposed control system is constructed from the capacitor voltage control system and the arm current control system for each arm. Thus, it is able to control each arm independently. In addition, as voltage balancing control system in order to compensate the effort among cells in the arm, the output DC voltage of the cell is varied depending on the capacitor voltage. Furthermore, it is easy to design the control parameters by applying the proposed balancing control system which is very simple. As a fundamental evaluation, this paper proposes a control method in order to achieve the step-down rectification. Moreover, from an experimental result by miniature model of 700 W, the proposed system achieves to convert from three phase voltage of 200 V into the DC voltage of 65 V.

II. Wind Power Generation System Using MMC

A. Main circuit configuration

Fig. 1(a) shows the main circuit configuration of the proposed wind power generation system using the MMC. Each leg consists of two buffer reactors L_b and H-bridge cells. Due to cascade connection of cells, the converter achieves a multi-level voltage waveform and also reduces the rated voltage of each cell. Thus, many cascaded cells are used in practical because it reduces harmonic distortion and utilize with a low voltage rating devices. On the other hand, in the MMC, the output DC voltage depends on the summation of the average value of cell output voltage.

Table 1 shows the configuration example of the MMC when the MMC is applied into the wind power generation system as the step-down converter connected to the micro-grid. The power capacity of the system is 1 MW and the generator voltage is 3.3 kV. On the other hand, the DC voltage of the micro-grid is 340 V [1] In addition, each parameter is calculated when the IGBTs which the voltage rating is 1,200V and the current rating is 2,400 A. are applied. Moreover, the capacitor voltage is calculated by (6) when the modulation factor λ is set to 0.8. Additionally, the voltage rating of the IGBT is set 30% more than the capacitor voltage. The current rating of IGBT is set 50% more than the each arm current. The numbers of capacitor are calculated when each cell has one capacitor. Finally, examples of high power IGBTs which meet the conditions of the rating voltage and rating current are shown.

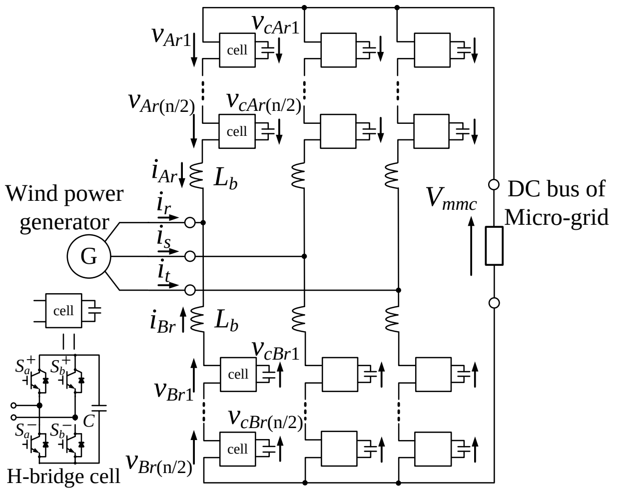

Fig. 1. Circuit configuration of the MMC for the wind power generation system connected to the micro-grid. The MMC with H-bridge cells is able to operate the step-down rectifier.

TABLE I. THE CONFIGURATION EXAMPLE OF THE WIND POWER GENERATION SYSTEM @1 MW

Voltage rating of IGBT	1,200 V
Current rating of IGBT	2,400 A
Capacitor voltage @λ = 0.8	860 V
Numbers of Cells @ leg	8
Total numbers of Cells	24
Numbers of Switching Device	96
Numbers of Capacitors	24
Examples of IGBTs	1MBI2400U4D-120 (Fuji Electric Co., Ltd.) MBN2400E17D (1,700 V, Hitachi, Ltd.) FZ2400R12HP4 E9 (Infineon) 5SNA 2400E170305 (1,700 V, ABB)

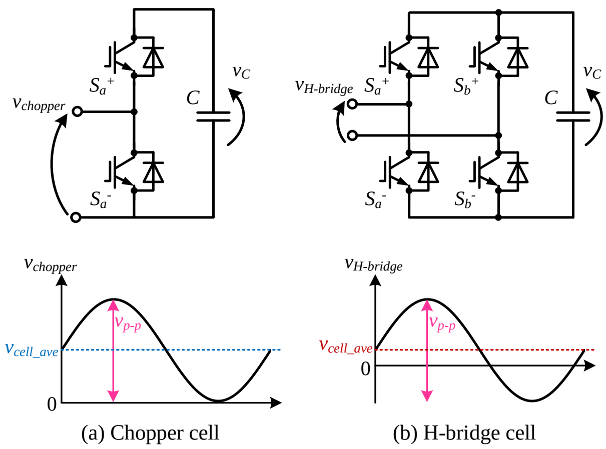

Fig. 2. Circuit configuration and output voltage of each cell. The chopper cell has the output voltage limit because the chopper cell cannot output the negative voltage. On the other hand, the H-bridge cell does not have the output voltage limit.

B. *Relationship between cell circuit configurations and output voltage*

Fig. 2 shows relationships between cell circuit configurations and output voltage. In the AC-DC converter using the MMC, a maximum value of generator output voltage is applied to each arm of the MMC when the wind generator operates. Hence, a peak-to-peak value of the cell voltage $v_{p\text{-}p}$ is given by (1) from generator output voltage and the number of cells per leg

$$v_{p-p} = 2\sqrt{\frac{2}{3}}\frac{E}{n}. \tag{1}$$

where E is an effective value of the output line to line voltage in the wind generator, n is the number of cells at each leg.

In addition, the output DC voltage of the AC-DC converter using the MMC V_{mmc} equals a summation of cell output average voltage at one leg. Hence, V_{mmc} is given by (2).

$$V_{mmc} = n v_{cell\_ave}. \tag{2}$$

where v_{cell_ave} is an average value of the cell output voltage.

Fig. 2(a) shows the relationships between the chopper cell and its output voltage. In the case of applying the chopper cell, a lower limit of cell output average voltage is uniquely determined from the peak-to-peak value of the cell voltage $v_{p\text{-}p}$ and the number of cells at each leg n because the chopper cell cannot output negative voltage. Therefore, in the chopper cell, the lower limit of output average voltage is given by (3)

$$v_{cell\_ave} = \frac{1}{2} v_{p-p}. \tag{3}$$

From (1), (2) and (3), the lower limit of the output DC voltage V_{mmc} equals a maximum voltage of the wind generator phase voltage. From the principle of the above, the MMC with chopper cells cannot achieve the step-down rectified operation.

Fig. 2(b) shows the relationships between the H-bridge cell and its output voltage. In the case of the H-bridge cell, there is no limit of cell output average voltage because it is possible for H-bridge cell to output negative voltage. Hence, it is possible for H-bridge cell to control lower voltage than that of (3). Therefore, the MMC with H-bridge cells achieves the step-down rectified operation.

III. CONTROL STRATEGY

Fig. 3 shows the control block diagram of the proposed step-down converter. One of the features in the proposed system is to control each arm as shown in Fig. 1. The control block diagram is separated to the capacitor voltage control block and the input current control block. Moreover, the capacitor voltage control block consists of a voltage averaging control system and a voltage balancing control system. At first,

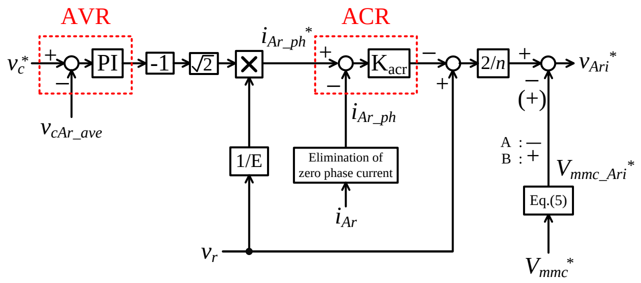

Fig. 3. Control block diagram for step-down rectified operation of MMC. The proposed control system is applied to each arm of the MMC in order to control each arm. Moreover, the ACR controls only the AC component of the arm current. i is the index of the cell number.

the voltage averaging control system corrects the error between the capacitor voltage command and the average value of capacitor voltage in the arm. Additionally, the voltage balancing control system corrects the error among the capacitor voltage in the arm.

A. *Voltage Averaging Control System*

The voltage averaging control system is applied in order to control the average value of all capacitor voltage in the arm. Therefore, the average value of all capacitor voltage has to be calculated in each arm. Each average value of the capacitor voltage is given by (4).

$$v_{cmk\_ave} = \frac{2}{n}\sum_{x=1}^{n/2} v_{cmkx}, \quad m = \text{A, B} \quad k = \text{r, s, t} \tag{4}$$

where v_{cmk_ave} is the average value of the capacitor voltage. m shows the index which is the upper side A or the lower side B. k is the index of each phase. Moreover, m and k are matched in both side of the equation.

The error between the capacitor voltage command and the average value of capacitor voltage in the arm is corrected by a PI controller. Moreover, the output value of the PI controller is given as the arm current command. In the proposed control system, the command of a positive phase current is generated depending on the fluctuation of the average value of all capacitor voltage. Thus, the command of a positive phase current is multiplied by the sinusoidal wave in order to synchronize with the input phase voltage.

Moreover, the cell output the DC voltage in order to achieve the rectification. Therefore, the capacitor voltage includes the voltage ripple which the cycle same as the input voltage one. The control system may become instability due to the voltage ripple. Thus, in order to keep the stability of the control system, the response angular frequency of the PI controller would be designed into low or a filter in order to damp the frequency component of the input voltage cycle should be applied.

B. *Arm Current Control System*

Each arm current includes the DC component and the AC component. The DC component of the arm current flows in order to supply the DC power into a load. Moreover, the DC current shunts in to the each leg of the MMC. Generally, the shunted DC current is constant and same value among arms when cells equally divide the output DC voltage of the MMC. Furthermore, the DC current is considered as the zero phase current because the DC current is temporally not changed. On the other hand, from the previous section, the AC component of the arm current flows as the positive phase current is generated by the voltage averaging control system. From the above, the output power is controlled by the zero phase component of the arm current. The capacitor voltage is controlled by the positive phase component of the arm current.

In other words, it is not necessary to compensate the zero phase component of the arm current. Therefore, in the proposed control system, the zero phase current is controlled by open-loop control. On the other hand, in order to keep the capacitor voltage at constant, the system compensates only the positive phase current.

C. *Elimination System of Zero Phase Current*

Fig. 4 shows a schematic diagram of current waveform on of the arm. It is necessary to eliminate only the zero phase component from the arm current in order to control the capacitor voltage after the system detects all arm current. However, it is difficult for a high-pass filter to extract only the positive phase component because AC current cycle is very low. Methods in order to extract the positive phase component are shown in the following;

a) Add-subtract of three phase current

b) Application of rotational coordinate transform

First, a) is a method to calculate the zero phase component of the arm current by the addition and subtraction of three phase current. In the MMC, the each arm current is detected. On each of the upper side and the lower side, the zero phase current is extracted by addition of the three phase current because the addition value of the positive phase current is zero. Moreover, because the zero phase current which flows on each leg is equal. Thus, by subtracting the value of the zero phase current which divides into three equal parts from the detection value of each current, so that the positive current is extracted.

Second, b) is a method to extract the positive phase component by using the rotational coordinate transform. On each of the upper side and the lower side, by the rotational coordinate transform and the inverse transform, the zero phase current is eliminated and only the positive phase current is extracted. In this paper, b) is applied.

D. *Output Voltage Control Systm*

From the above, the output DC voltage is controlled by the open-loop control of the zero phase current. Thus, the command of the output DC voltage is added into the output value of the controller in the arm current control system. Moreover, the output DC voltage of the MMC is divided on each leg. Thus, the output DC voltage of a cell is fundamentally set V_{mmc}^{*}/n when the command of the MMC output voltage control is V_{mmc}^{*} and the number of cells in a leg is n.

E. *Voltage Balancing Control System*

The voltage averaging control system is used to keep the

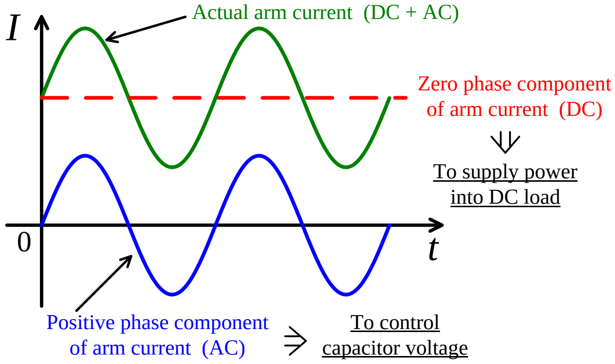

Fig. 4. schematic diagram of current waveform on of 1 arm.
Each arm current includes an AC component and a DC component.
In order to control the capacitor voltage, it is necessary to eliminate the AC components from the arm current.

voltage of all capacitor voltage. However, an unbalance voltage which occurs among capacitors in same arm cannot be suppressed by voltage averaging control system only, because the voltage averaging control system corrects only the error between the voltage command and the average value of the capacitors voltage in the arm. So far, some methods in order to balance each capacitor voltage have been reported [14]-[16]. However, in most of the conventional control systems, it is difficult to understand these control principle instinctively and design control parameters. Additionally, the positive phase current in order to keep the capacitor voltage flows to all cells which exist in 1 arm. Moreover, the common value of the positive phase current which flows each arm. Thus, it is difficult to adjust the arm current in order to balance on each cell.

Against the problem, in the proposed control system, the output DC voltage of the cell is varied depending on the capacitor voltage. This control principle is given by (5).

$$V_{mmc\_mki}^{*} = \frac{1}{2} \frac{v_{cmki}}{\sum_{x=1}^{n/2} v_{cmkx}} V_{mmc}^{*} \tag{5}$$

where $V_{mmc\_mki}^{*}$ is the output DC voltage command of each cell. i is the index of the cell number. Moreover, m, k and i are matched in both side of (5).

For example, the output DC voltage command of the cells is set into high when its capacitor voltage is higher than the command of the capacitor voltage. Thus, the output power of the cell becomes high and the value of the capacitor voltage discharges. In contrast, the output DC voltage command of the cells is set into low when its capacitor voltage is lower than the command of the capacitor voltage. Thus, the output power of the cell becomes low and the capacitor voltage charges. Moreover, the output DC voltage of a cell is set V_{mmc}^{*}/n when the voltage value of all capacitor in the arm is same.

F. Capacitor Voltage Determination

The output DC voltage command of the MMC V_{mmc}^* that uses to obtain the output DC voltage is added to the output block of the input current control. The change of voltage value in each cell depends on the number of cells at each leg since the cells are connected to the load in parallel. In addition, each capacitor voltage also depends on the input and output voltage. The capacitor voltage command v_c^* is given by (6). Note that $V_{mmc\_mki}^*$ is a little different among cells. However, v_c^* is given by the modulation factor λ and the modulation factor λ is set to 0.8 or less. Thus, the different of $V_{mmc\_mki}^*$ among cells is ignored because the voltage margin of the capacitor is fully large compared with the different of $V_{mmc\_mki}^*$ among cells.

$$v_c^* \geq \frac{1}{n\lambda}\left(2\sqrt{\frac{2}{3}}E + V_{mmc}^*\right) . \quad (6)$$

IV. Fundamental Experimental Result

In order to evaluate the effectiveness of the proposed control system, a fundamental experiment result by using the prototype of the MMC is shown. In the experiment, the prototype is connected to the power grid of 200 V as substitute for the wind power generator in order to evaluate the step-down rectification by the MMC. Moreover, the resistance load is connected on the output DC side.

Table I shows the experiment condition of the prototype. In the experiment, the output voltage command is 65 V. Moreover, the leg is constructed by four cells and the prototype has twelve cells in the three legs.

Fig. 5 shows waveforms of the input phase voltage, the input current and the output DC voltage. Firstly, from the waveforms of the input phase voltage and the input current, it is confirmed that the unity power factor is obtained in the input stage. Moreover, the total harmonic distortion (THD) of the input current is approximately 11.9%. Thus, as a future work, it is necessary to reduce the total harmonic distortion of the input current.

Second, the waveform of the output DC voltage in lower side of Fig. (5) shows that the prototype convert from input voltage of 200 V into output DC voltage of 65 V. From this waveform, the output DC voltage is kept at constant. Therefore, the prototype of the MMC achieves the step-down rectification.

Fig. 6 shows the waveforms of the cell capacitor voltage which are connected to r-phase leg. The cell capacitor voltage is controlled according to the capacitor voltage command v_c^*. As a result, the proposed system maintains the capacitor voltage of each H-bridge cell to the voltage command of 120 V. Furthermore, the maximum voltage error between the voltage command of the cell capacitor and the measured voltage is 10% or less. As a future work, it is necessary to consider the cause of the error between the voltage command of the cell capacitor.

TABLE III. EXPERIMENTAL CONDITIONS AND CIRCUIT PARAMETERS

Output power P_O	700 W	Input voltage rms E	200 V
Input voltage frequency f	50 Hz	Output voltage v_{mmc}	65 V
Number of cell per leg n	4	DC capacitor C	1300 µF
Load R	5.8 Ω	Carrier frequency f_S	8 kHz
Buffer reactor L_b	4 mH		

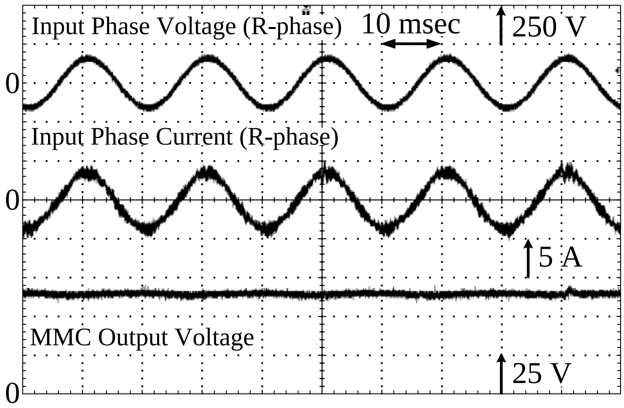

Fig. 5. Waveforms of input voltage, input current and output voltage. The unity power factor is be obtained in the input stage. On the other hand, as a future work, it is necessary to reduce the total harmonic distortion of the input current.

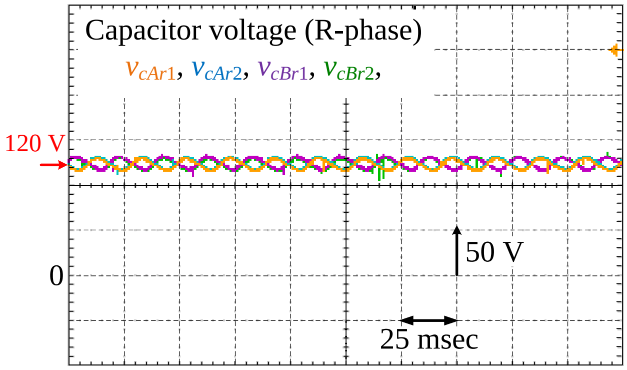

Fig. 6. Waveforms of the capacitor voltage in r-phase leg. The proposed system maintains the capacitor voltage of each H-bridge cell to the voltage command of 120 V. In addition, the maximum voltage error between the voltage command of the cell capacitor and the measured voltage is 10% or less.

V. Conclusion

This paper discusses the step-down converter using a modular multilevel converter topology for the wind power generation system connected to the micro-grid. The system converts from a three-phase AC voltage of the generator into DC bus voltage of 340 V by step-down operation. Moreover, the proposed control system is very simple because the control system is applied to the each arm of the MMC. Finally, from the fundamental experiment, the proposed control maintains the capacitor voltage at constant. In the future work, the control method to reduce of the total harmonic distortion of the input current and will be discussed.

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