Power Flow Control of Modular Multilevel Converter based on Double-Star Bridge Cells Applying to Grid Connection

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***Abstract* — The Modular Multilevel Converter (MMC) with full bridge cells is available for utility interactive inverter in high voltage line. When it is interconnected with power line, it is possible to control the active power flow so as to supply or charge the power in the power line. This research applied the MMC to grid connection system of distributed generator. Theory of the power flow control of the MMC rerated to control capacitor voltage on arm cells is proposed. And effectiveness of the control method is presented by simulation.**

***Index Terms* —modular multilevel converter, grid connection, power flow control, voltage balance control**

I. Introduction

By global warming and radiation damage in the earthquake of Eastern-Japan 2011, renewable energy has been focused at the global level. Thus photovoltaic and wind power generations have studied in the world, and it is expected to become increasingly popular in the future. If that happen, also increases the importance of interconnection equipment. Meanwhile, the multi level converter without transformer is developed. A modular multilevel converter (MMC)[1]-[4] is one of the transformer-less converter and applies to high voltage and high power conversion. The MMC is characterized by cascaded switching device modules with capacitors. Among MMC family, the MMC based on Double-Star full Bridge cells (MMC-DSBC) operates as a bidirectional power converter. Therefore the MMC-DSBC can be applied to interconnection between a distributed generator and main power line. Above all, since the MMC suits using high voltage and high power, it is able to apply for mega solar, wind power and other distributed generators. However because these generators have a problem of voltage fluctuation by unstable output, a voltage conditioner is required. In the case of MMC, input voltage does not affect output. Thus the MMC become valid on unstable power and voltage. When the MMC is applied as a grid connection inverter, a step-up transformer is not necessary for interconnection equipment. Therefore grid connection equipment can be realized smaller and lighter than general converter with a transformer.

In this paper, applying the MMC-DSBC to the grid connection inverter, a control method of regulating capacitor voltages of arm cells is explained and indicated simulation result of typical cases of supplying and charging power in the distributed generator.

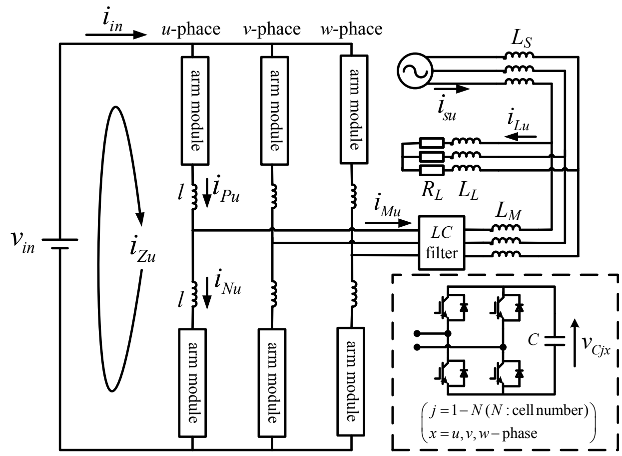


Fig. 1 Configuration of MMC-DSBC

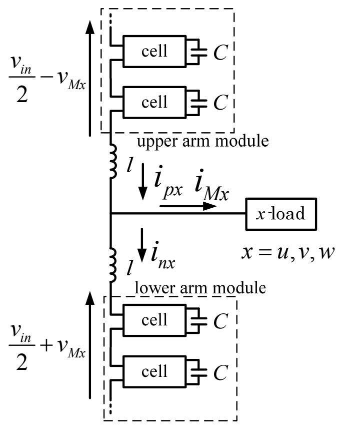


Fig. 2 Principle of output voltage (u-phase)

II. Configuration of Circuit

Fig.1 shows the configuration of circuit that the distributed generator is connected to main grid line and load on AC bus via MMC-DSBC. This connection type of the MMC is the double star connection, which can be applied to a utility interactive inverter, STATCOM, BTB system and so on. An arm module of the MMC-DSBC has full-bridge cells connected in series. Number of cells can be selected optionally. High voltage can be obtained in proportion to the number of cells. In addition, because the MMC-DSBC has several cells, it can output multilevel voltage and obtain smooth current waveform without distortion. When the MMC-DSBC output voltage, respective arm module output voltages as shown in Fig.2. Here, upper arm voltage v_{px} and lower arm voltage v_{nx} become (1) and (2) respectively.

$$v_{px} = \frac{v_{in}}{2} - v_{Mx} \quad (1)$$

$$v_{nx} = \frac{v_{in}}{2} + v_{Mx} \quad (2)$$

v_{in} is input voltage for the MMC-DSBC, v_{Mx} is output voltage from the MMC-DSBC. Paying attention to each cell, it has a capacitor as a DC voltage source. When all the capacitors are controlled to keep constant, the MMC-DSBC can appropriately operate.

There are two currents of i_{px} and i_{nx} in the MMC-DSBC arm, which can be detected by sensors. Two currents of output current i_{Mx} and loop current i_{Zx} are necessary to control the MMC-DSBC. Therefore i_{Mx} and i_{Zx} are obtained by a following equation from i_{px} and i_{nx}.

$$\begin{bmatrix} i_{Zx} \\ i_{Mx} \end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} i_{px} \\ i_{nx} \end{bmatrix} \quad (3)$$

Beside (3), the inverse transform becomes (4).

$$\begin{bmatrix} i_{px} \\ i_{nx} \end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 1 & -1/2 \end{bmatrix} \begin{bmatrix} i_{Zx} \\ i_{Mx} \end{bmatrix} \quad (4)$$

III. CONTROL OF MMC-DSBC

The control strategies of the MMC-DSBC for a grid connection inverter contain two principal ways. One control is to keep capacitor voltage balance of each cell. Moreover, the capacitor voltage control can be divided into

(a) Total control,
(b) Partial control.

These control methods reference averaging control and balancing control[1][2]. The Total control plays a role of comprehensive reference for arm modules. And the Partial control plays a role of reference for individual cells in arm modules. Another control is to regulate power flow between the distributed generator and main grid. This power flow is controlled by dividing into active power and reactive power. The active and reactive power is calculated by PQ-transform[5]. Fig.3 shows a relation of two controls in the overall system. These control theories are configured from power flow of inside of the MMC-DSBC. First, theory of power flow of the MMC-DSBC is explained. After that the control methods of capacitor voltage and power flow to the main grid are described.

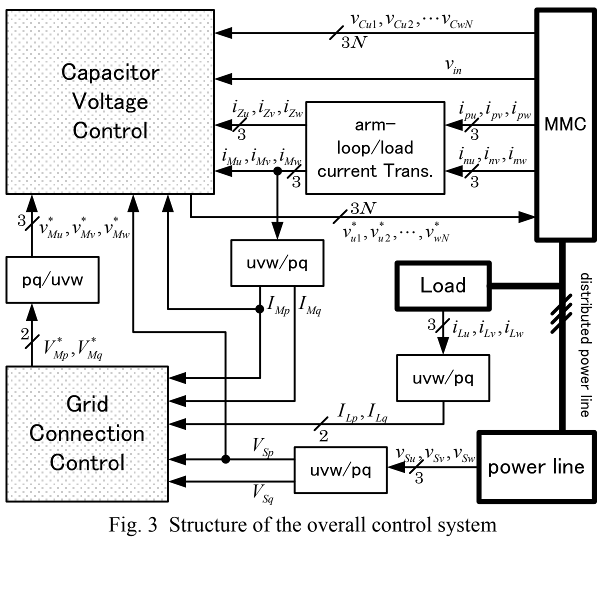


Fig. 3 Structure of the overall control system

A. Theory of Power Flow

Power flow of the MMC-DSBC is the most important for the control because there are several components of power in each cell and module, which can be handled by the Total and the Partial control. Since controls of u, v, w-phase are the same method in principle, the theory about u-phase is discussed in this section. The instantaneous power of an upper and a lower arm module can be represented by the following equations.

$$\begin{aligned} v_{pu} i_{pu} &= \left(\frac{v_{in}}{2} - v_{Mu}\right)\left(i_{Zu} + \frac{i_{Mu}}{2}\right) \\ &= \frac{v_{in} i_{Zu}}{2} + \frac{v_{in} i_{Mu}}{4} - v_{Mu} i_{Zu} - \frac{v_{Mu} i_{Mu}}{2} \end{aligned} \quad (5)$$

$$\begin{aligned} v_{nu} i_{nu} &= \left(\frac{v_{in}}{2} + v_{Mu}\right)\left(i_{Zu} - \frac{i_{Mu}}{2}\right) \\ &= \frac{v_{in} i_{Zu}}{2} - \frac{v_{in} i_{Mu}}{4} + v_{Mu} i_{Zu} - \frac{v_{Mu} i_{Mu}}{2} \end{aligned} \quad (6)$$

Note that i_{Zu} is superimposed by DC and AC components with several frequencies. i_{Zu} is given in (7).

$$i_{Zu} = \overline{i}_{Zu} + \tilde{i}_{Zu} \quad (7)$$

, where $\overline{i}_{Zu}$ is the DC component of i_{Zu}, $\tilde{i}_{Zu}$ is the AC component of i_{Zu}. Considering this relation, the first term in (5) and (6) implies input power to the MMC-DSBC. If v_{in} is DC, it constitutes the active power by $\overline{i}_{Zu}$.

The second term in (5) and (6) implies power to exchange between upper- and lower-arm modules. If v_{in} is DC, following calculation of average power in a cycle is as follows.

$$\frac{1}{T}\int_{t_o - T}^{t_o} \frac{v_{in} i_{Mu}}{4} dt = 0 \quad (8)$$

This means that the term $v_{in}i_{Mu}$ does not affect voltage fluctuation of cell capacitors.

The third term in (5) and (6) produces active power from v_{Mu} and $\tilde{i}_{Zu}$ synchronized to the phase of v_{Mu}. It means that the active power is exchanged between upper- and lower-arm. Thus i_{Zu} is controlled to be the same phase of v_{Mu} [4].

The fourth term in (5) and (6) implies output power from the same phase component of v_{Mu} and i_{Mu}.

B. Total control

Fig.4 shows a block diagram of the Total control. Capacitor voltages are comprehensively controlled by this control. The control method is divided into two components. One is given as $\overline{i}_{Zu}^*$ to control DC component of i_{Zu}.

$$\overline{i}_{Zu}^* = K_1 (v_C^* - \overline{v}_{Cu}) + K_2 \int (v_C^* - \overline{v}_{Cu}) dt \quad (9)$$

$$\overline{v}_{Cu} = \frac{1}{2}(\overline{v}_{Cpu} + \overline{v}_{Cnu}) \quad (10)$$

$$\overline{v}_{Cpu} = \frac{1}{T}\int_{t_0 - T}^{t_0} \frac{2}{N}\sum_{j=1}^{N/2} v_{Cju}\,dt \tag{11}$$

$$\overline{v}_{Cnu} = \frac{1}{T}\int_{t_0 - T}^{t_0} \frac{2}{N}\sum_{j=N/2+1}^{N} v_{Cju}\,dt \tag{12}$$

, where v_C^* is a reference of cell voltage value, $\overline{v}_{Cu}$ is moving average (MA) value of all the cell capacitors from $\overline{v}_{Cpu}$ and $\overline{v}_{Cnu}$. $\overline{v}_{Cpu}$ and $\overline{v}_{Cnu}$ are also MA values. The cut off frequency of MA is 60Hz, which means the same as output voltage frequency. In this case, T in (11) and (12) becomes 1/60. i_{Zu} being controlled to $\overline{i}_{Zu}$, the average value of all the capacitor voltages can be adjusted to v_C^*. And the other component $\tilde{i}_{Zu}^*$ is calculated by (13).

$$\tilde{i}_{Zu}^* = K_3(\overline{v}_{Cpu} - \overline{v}_{Cnu})\sin\omega_u t \tag{13}$$

, where ω_u is an angular frequency synchronized to output v_{Mu}. This makes AC component synchronized to v_{Mu} to control active power from the third term of (5) and (6).

Finally, a loop current reference is given as (14).

$$i_{Zu}^* = \overline{i}_{Zu}^* + \tilde{i}_{Zu}^* + \frac{P_M}{3v_{in}} \tag{14}$$

, where P_M is active power of the MMC-DSBC output, P_M / $3v_{in}$ means feedforward control of P_M. The details will be described later.

Then the Total control reference v_{Tu}^* is given as (15).

$$v_{Tu}^* = K_4(i_{Zu} - i_{Zu}^*) \tag{15}$$

This control can regulate capacitor voltages to the reference value per arm module.

C. Partial control

In case of ideal system, the Total control can maintain voltages of capacitors approximately. However in practical, there is variation in the capacitor voltage due to individual differences of capacitance and switching delay and so on. Therefore the Partial control should be introduced adding to the Total control. Fig.5 shows a block diagram of the Partial control. These controls of upper and lower arm are given by (16) and (17) respectively.

$$v_{Pju}^* = K_5(\hat{v}_{Cpu} - v_{Cju})\,i_{pu} \Big/ \sqrt{{I_{Mp}^*}^2 + {I_{Mq}^*}^2} \tag{16}$$

$$v_{Pju}^* = K_5(\hat{v}_{Cnu} - v_{Cju})\,i_{nu} \Big/ \sqrt{{I_{Mp}^*}^2 + {I_{Mq}^*}^2} \tag{17}$$

, where $\hat{v}_{Cpu}$ and $\hat{v}_{Cnu}$ are average voltages of each arm cell capacitor. i_{pu} and i_{nu} are obtained by sensors. I_{Mp}^* is the active current of the MMC-DSBC output. As i_{pu} and i_{nu} are shown by (4), (16) and (17) are expanded.

$$\begin{aligned} v_{Pju}^* &= K_5'(\hat{v}_{Cpu} - v_{Cju})\cdot(i_{Zu} + \frac{i_{Mu}}{2}) \\ &= K_5'(\hat{v}_{Cpu} - v_{Cju})i_{Zu} + \frac{K_5'}{2}(\hat{v}_{Cpu} - v_{Cju})i_{Mu} \end{aligned} \tag{18}$$

$$\begin{aligned} v_{Pju}^* &= K_5'(\hat{v}_{Cnu} - v_{Cju})\cdot(i_{Zu} - \frac{i_{Mu}}{2}) \\ &= K_5'(\hat{v}_{Cnu} - v_{Cju})i_{Zu} - \frac{K_5'}{2}(\hat{v}_{Cnu} - v_{Cju})i_{Mu} \end{aligned} \tag{19}$$

$$K_5' = K_5 \Big/ \sqrt{{I_{Mp}^*}^2 + {I_{Mq}^*}^2} \tag{20}$$

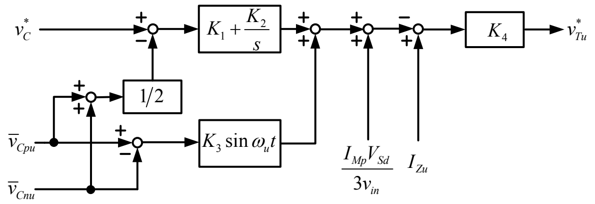
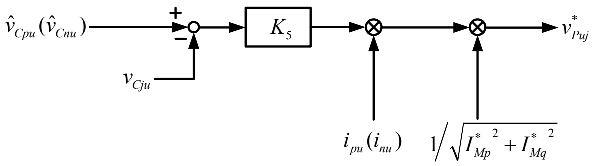


Fig. 4 Block diagram of the Total control



$$\left[\hat{v}_{Cpu} = \frac{2}{N}\sum_{j=1}^{N/2} v_{Cju},\ \hat{v}_{Cnu} = \frac{2}{N}\sum_{j=N/2+1}^{N} v_{Cju}\right]$$

Fig. 5 Block diagram of the Partial control

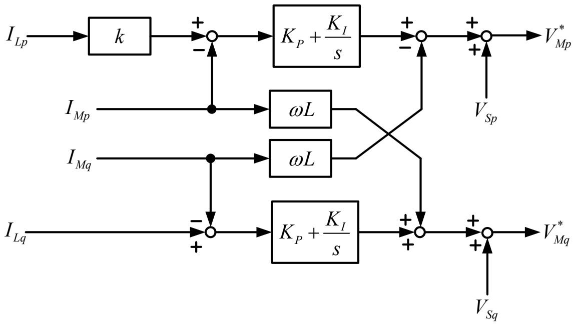


Fig. 6 Block diagram of the two-axis control

These equations show that each cell outputs the active power. The first terms in (18) and (19) produce the active power by i_{Zu}. This means that the term adjust power from the distributed generator. The second terms in (18) and (19) also produce the active power by i_{Mu}. This means that the term is able to adjust the power to load and cells in the arm module according to capacitor voltages. In (16), (17) and (19), $\sqrt{{I_{Mp}^*}^2 + {I_{Mq}^*}^2}$, which has a lower limit to avoid becoming 0, means the standardization because i_{pu} and i_{nu} are proportional to I_{Mp}^* and I_{Mq}^* respectively.

In addition, because the Partial control references are average value of all the arm capacitor voltages, it does not interfere with the Total control. When all the Partial control references are added, a following equation is satisfied.

$$\sum_{j=1}^{N} v_{Pju}^* = 0 \tag{21}$$

Therefore, the Partial control is independent of the loop current and only plays a role of assistant of the Total control for the capacitor voltage control.

D. Power flow control to the AC line

A control of power flow between the distributed generator and the main grid via the MMC-DSBC is performed by the PQ-transform, by which active power and reactive power are independently controlled. The PQ-transform is defined by (22).

$$\begin{bmatrix} F_p \\ F_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\omega_0 t & \sin(\omega_0 t - \frac{2\pi}{3}) & \sin(\omega_0 t + \frac{2\pi}{3}) \\ \cos\omega_0 t & \cos(\omega_0 t - \frac{2\pi}{3}) & \cos(\omega_0 t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} f_u \\ f_v \\ f_w \end{bmatrix} \quad (22)$$

, where F_p and F_q are active and reactive component respectively. f_u, f_v and f_w are three-phase component. And ω_0 is an angular frequency the same as u,v,w-phase one.

Active and reactive powers are controlled by the two-axis current of I_{Mp} and I_{Mq}, which are performed by (23) and (24).

$$V_{Mp}^* = K_p(kI_{Lp} - I_{Mp}) + K_i \int (kI_{Lp} - I_{Mp})\,dt + V_{Sp} - \omega_0 L I_{Mq} \quad (23)$$

$$V_{Mq}^* = K_p(I_{Lq} - I_{Mq}) + K_i \int (I_{Lq} - I_{Mq})\,dt + V_{Sq} + \omega_0 L I_{Mp} \quad (24)$$

, where $\omega_0 L I_{Mp}$ is a term for the non-interference control. L is given by (25).

$$L = L_f + \frac{l}{2} \quad (25)$$

A block diagram of this control is shown in Fig.6. V_{Mp}^* and V_{Mq}^* are voltage references for the MMC-DSBC control, I_{Lp} and I_{Lq} are load currents, I_{Mp} and I_{Mq} are active and reactive currents of the MMC-DSBC output. A constant k is a ratio of output power from the distributed generator via the MMC-DSBC. If k is positive, the active power is supplied from the MMC-DSBC. If k is negative, the active power is charged from power line via the MMC-DSBC.

E. Comprehensive description of all the control

These controls are individually handled. However all the controls have links each other. For example, the third term of (14) takes a role of feedforward for loop current reference. The term is based on the law of the conservation of power, which is shown in the following equation.

$$v_{in} i_{in} = P_M \quad (26)$$

, where i_{in} is the input current of the MMC-DSBC.

$$i_{in} = i_{Zu} + i_{Zv} + i_{Zw} \approx 3 i_{Zu} \quad (27)$$

$$P_M = V_{Mp} I_{Mp} \quad (28)$$

(27) and (28) are obviously satisfied, then the following equation is given by (26) - (28).

$$3 v_{in} i_{Zu} = V_{Mp} I_{Mp} \quad (29)$$

(30) is obtained from (29).

$$i_{Zu} = \frac{V_{Mp} I_{Mp}}{3 v_{in}} = \frac{P_M}{3 v_{in}} \quad (30)$$

(30) shows that the Total control uses component of power flow and can improve the control quality. Thus, the capacitor voltage control is interfered by the power flow control. In addition, load current is given by (3), which means that the currents supplied by the MMC-DSBC are able to be detected without any additional current sensors.

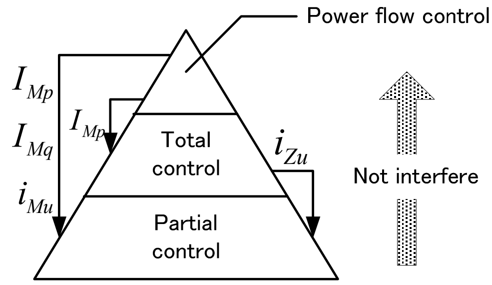


Fig.7 Hierarchy of the proposed control

Because the control methods are interfered, they are prioritized as below.

1. The power flow control to AC line
2. Total control
3. Partial control

This relationship of hierarchy is descried in Fig.7. Note that there are interferences from the upper class to lower class, however there are not interferences of the inverse in the hierarchy. When the relationship is satisfied, all the controls operate properly.

Finally, voltage references of upper and lower cells are given by (31) and (32).

$$v_{ju}^* = v_{Gu}^* + v_{Pju}^* - \frac{2v_u^*}{N} + \frac{v_{in}}{N} \quad (31)$$

$$v_{ju}^* = v_{Gu}^* + v_{Pju}^* + \frac{2v_u^*}{N} + \frac{v_{in}}{N} \quad (32)$$

IV. Simulation

Simulation is performed to verify the proposed control methods by using the circuit in Fig.1. Table 1 shows the parameters of the circuit, and table 2 shows the control gains. In this research, the MMC-DSBC has 4 full-bridge cells per arm (N=4), and is applied uni-pole PWM switching for each cell. Career waves are triangular waveform, which are shifted by 45 degrees. The MMC-DSBC can get multilevel output voltage by the PWM switching pattern.

Fig.8 shows a result in case that distributed generator supplies power to the load via the MMC-DSBC. As the power ratio from the distributed generator can be adjusted by k. In the case of $k = 1.0$, it means all the power to the load is supplied by the distributed generator. As I_{Mq} is constantly controlled to the same value of I_{Lq}, the distributed generator can supply all the reactive power to the load. Therefore the power factor as seen from main power grid becomes 1. Output voltages from the MMC-DSBC in Fig.8 are multilevel waveforms. In theory, those phase voltages have 9 level ($2N$+1; N = 4), and line voltages have 17 level ($4N$+1; N = 4) at the maximum. However, the number of level changes by amplify ratio. i_{pu}, i_{nu} and i_{Mu} are satisfied with (3) and (4). Then i_{pu} and i_{nu} have DC offset of i_{Zu}. If capacitor voltages are controlled properly, i_{Zu} approaches DC waveform. Considering the PQ-quantity, I_{Mp}= I_{Lp}, I_{Sp}= 0, I_{Mq}= I_{Lq} and I_{Sq}= 0 are satisfied. This means that all the power of the load is supplied by the distributed generator via the MMC-DSBC.

Fig.9 shows result in case that the distributed generator charges power from the main grid via the MMC-DSBC. Almost all the relationship of voltage and currents are the same as the case of power charge. However only $I_{Sp} = I_{Mp}+I_{Lp}$ is satisfied on this mode.

In Fig.8 and 9, the same volume of capacitance are set. Thus cells in the same arm module work as the same operation in theory. Then v_{Pju}^* (j:1 - 4) constantly become 0. In this case, capacitor voltages can be controlled only by the Total control.

Fig.10 and 11 show transient responses by changing the ratio k. In Fig.10, the mode changes to supply from charge. In Fig.11, the mode changes to charge from supply. Both of results are verified to operate appropriately. Fig.12 shows result with variation of capacitance of each cell on supply mode. Amplitudes of capacitor voltages are different. And it is verified that v_{Pju}^* is not 0 and v_{Gu}^* is not affected. However, in this extreme case, v_{Pju}^* is nearly 0 in practical.

TABLE 1. Parameters of circuit

v_{in}	200V	Frequency	60Hz
V_S	100V	v_C*	100V
R_L	2.67Ω	L_L	5.38mH
l	1.5mH	C	5mF
L_S	0.16mH(3%)*1	L_M	53.8μH(1%)*1
L_f *2	3.0mH	C_f *2	20μF

*1 percentages for the rated load
*2 LC-filter parameter on AC side

TABLE 2. Gains of control

K_p	15.0	K_i	150.0
K_1	1.0	K_2	10.0
K_3	0.1	K_4	8.0
K_5	0.5		

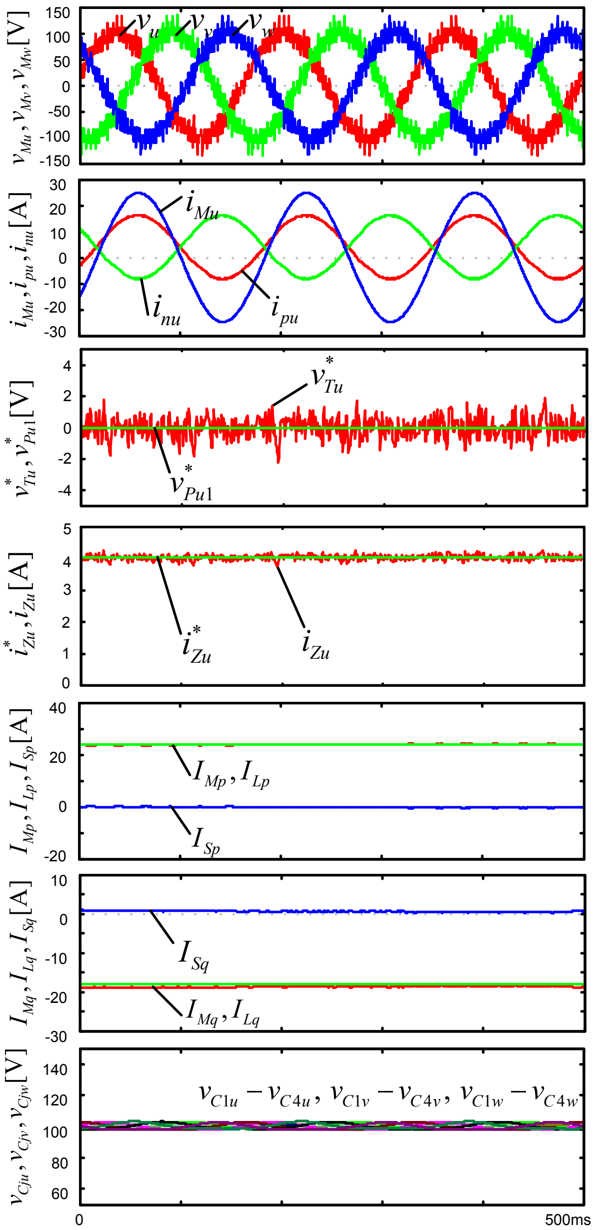


Fig. 8 Simulation result of power supply mode

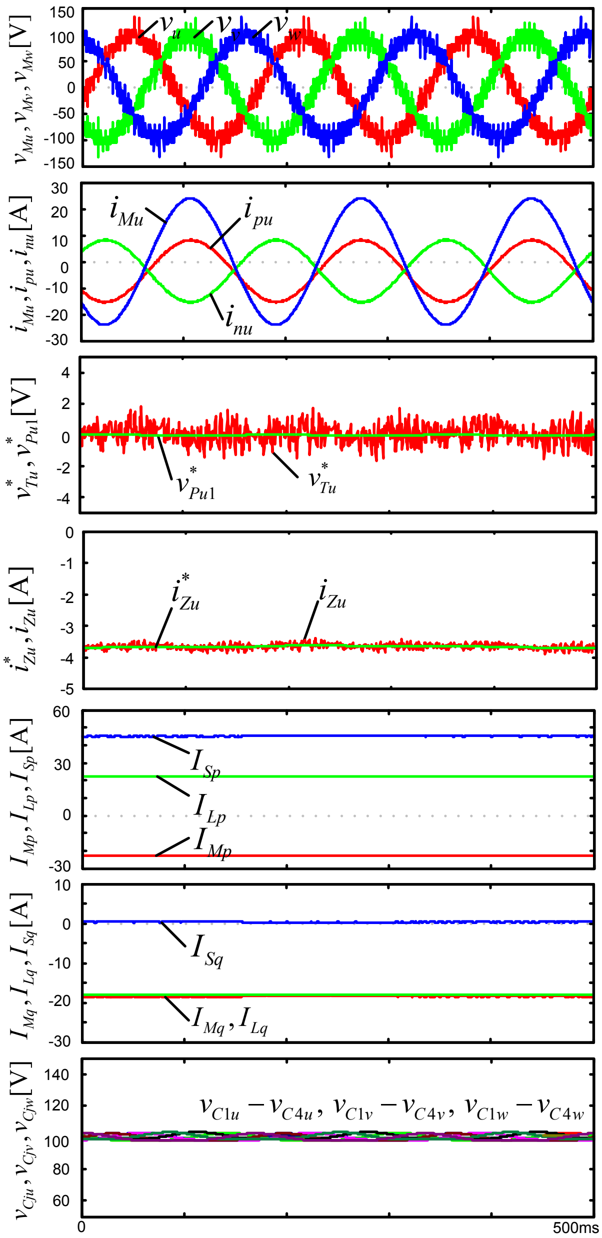


Fig. 9 Simulation result of power charge mode

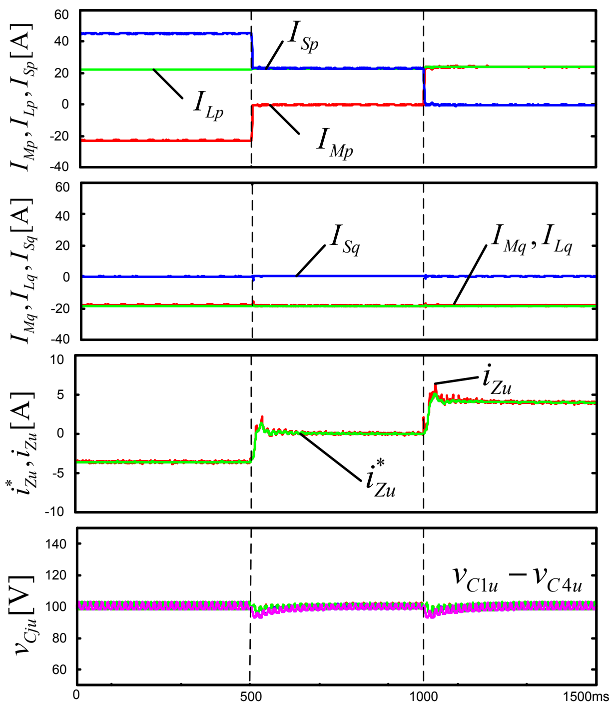


Fig. 10 Transient response while the output power change by step (k = −1 - 0 - 1)

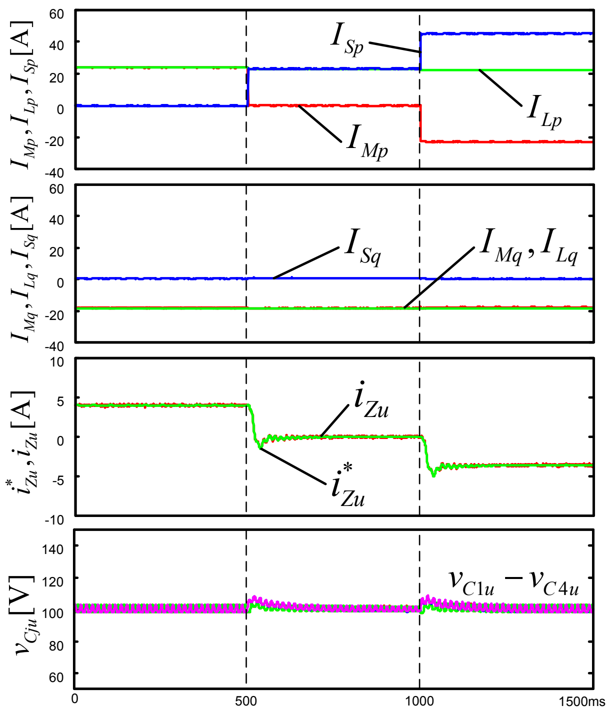
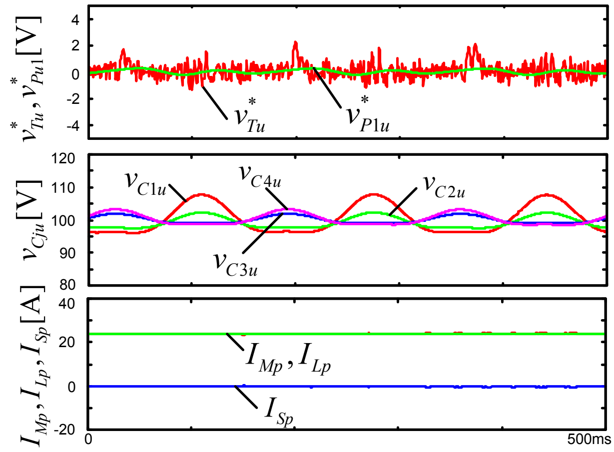


Fig. 11 Transient response while the output power change by step (k = 1 - 0 - −1)

Fig.13 shows transient responses of changing input voltage v_{in}. In this case, the MMC-DSBC operates properly and supplies power to the load the same as Fig.8. Therefore it is proved that the MMC operation by the proposed control can achieve in the typical conditions. These results confirm that the MMC-DSBC is suitable for utility interactive inverter.



[C_1=2mF, C_2=5mF, C_3=8mF, C_4=5mF]

Fig. 12 Simulation result with variation of capacitors

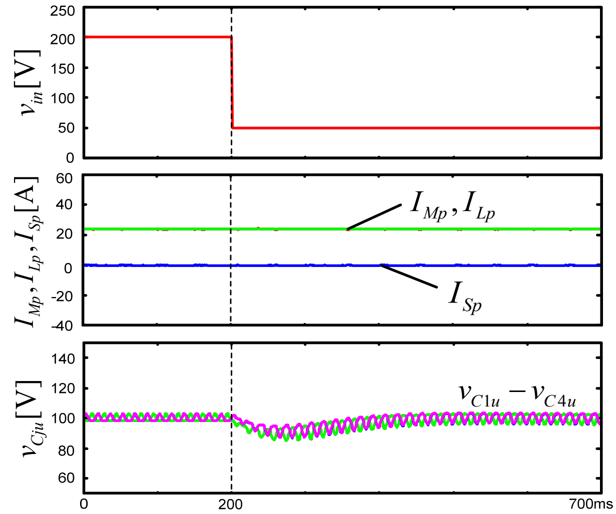


Fig. 13 Transient response while input voltage change by step

V. Conclusion

This paper applied the MMC-DSBC to grid connection system of the distributed generator, and proposed how to control of the voltage of the MMC and the power flow. The simulation demonstrated that the proposed control method is able to supply and charge the power properly in the typical situations.

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