# Output Voltage Control for PWM Inverter with Electric Double Layer Capacitor as DC Power Supply

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*Abstract*--**In general, chopper circuits are necessary for the inverter system whose input voltage fluctuates such as solar power energy, wind power energy, capacitor energy and so on. Therefore, the inverter system becomes larger, the energy losses of power converter increase, and control circuit is complicated. In this paper, to overcome these problems, a control scheme of PWM inverter to get the constant R.M.S. AC voltage on inverter output without chopper circuit is proposed.**

**At first, R.M.S. value calculation method and feedback control procedure are investigated to realize proposed system. Next, the simulation results of the system are shown and characteristics of power converter using proposed control scheme are discussed. At last, experimental results of proposed control system using fluctuating voltage source are shown. Finally, availability of the newly developed system is confirmed.**

*Index Terms*--**PWM inverter, R.M.S. value calculator, Electric double layer capacitors, Output voltage regulation**

## I. INTRODUCTION

In recent years, new energy resources such as photovoltaic generation, wind force power generation and fuel cell have been developed. They generate DC power[1]. Such a voltage type inverter and its control technique are necessary to convert into AC power for power source[2]. Energy storage approaches have been studied to smooth power generated by new energy resources. Electric double layer capacitors have been paid attention as the electrical energy charge devices which are kind to the global environment. Therefore, they have been applied to some newly produced equipments such as hybrid EV and UPSs and so on[3][4].

However, the voltage of capacitor falls down when electrical power is supplied to load. Usually, dc-dc converter such as step-up or down type chopper circuit is applied for this system to keep constant voltage of inverter input voltage. However, this method need both chopper circuit and inverter circuit, therefore it is concerned that power conversion efficiency is decreased, circuit sizes are too much larger and control system becomes complicated.

When output voltage of inverter is controlled, PI control with sine-wave target value is used. However, it is impossible to control of high precision by only this way, because error by phase shifting is caused. D-q transformation is effective for three-phase system, but it is not adaptive single-phase system[5]. Consequently, control method of single-phase inverter with Hilbert transformation is suggested[6]. It is a control method with the DC target value. Therefore, it is possible to control the system without stationary error. However, it is complicated because this method require more than one control system.

In this paper, to solve these problems, the control scheme which compensates a drop-down of the capacitor voltage only with inverter is suggested, and it is intended to realize a power conversion circuit keeping a constant output voltage of the inverter. A feedback control method and operation circuit which calculates the R.M.S value of inverter output voltage in real time are considered to realize these system[7].

At first, the theory to detect as DC voltage value from R.M.S. value of inverter output voltage was suggested, and the effectiveness of proposed method was confirmed by using simulation analysis. Next, the circuit parameter of this control system is determined by simulation analysis, and the effectiveness of power conversion circuit which designed by using proposed scheme was confirmed by experimental results.

## II. CONTROL SYSTEM

Fig.1 shows the outline of the conventional inverter system which output the constant voltage value. In this figure, chopper circuit is connected between electric double layer capacitors (EDLCs) which are used as DC voltage source and PWM inverter circuit. In this case, the modulation ratio of the PWM inverter is kept constant, and the output voltage of chopper circuit is controlled as constant value for fluctuation of the input voltage of the chopper circuit. This scheme is easy to construct because the feedback control value is DC value. However, this control scheme needs both chopper circuit and inverter circuit.

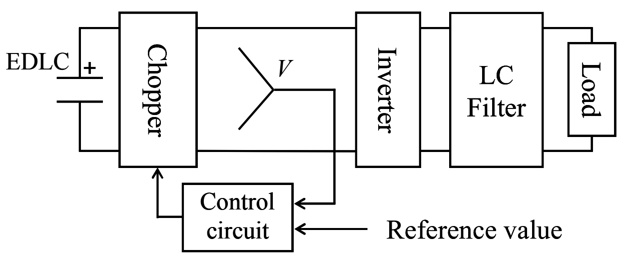



Fig. 1. Configuration of the conventional control system.

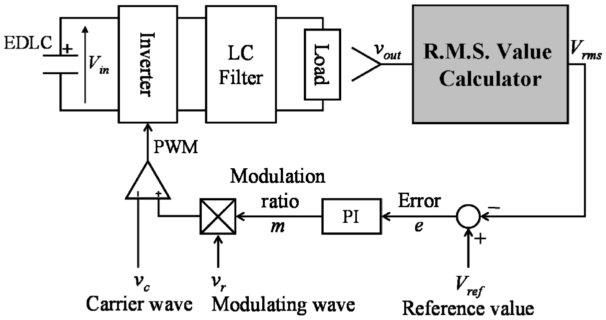


Fig. 2. Configuration of the proposed control system.

Next, the configuration of the proposed control scheme in this paper is shown in Fig.2. In this case, PWM inverter circuit and EDLCs are directly connected, and output voltage of the inverter is controlled to constant R.M.S. value only with the modulation ratio of the PWM inverter. In this scheme, detection of the R.M.S. value of the inverter output voltage is necessary to control the modulation ratio to the target value. However, output voltage of the PWM inverter is AC voltage, therefore it is difficult to detect the R.M.S. value from the instantaneous value of the inverter output voltage. Therefore, a new calculation method of R.M.S. value using the instantaneous value of inverter output voltage has been proposed in chapter 3.

The operation circuit realizing this newly proposed calculation method is named an "R.M.S. value calculator". The DC voltage value $V_{rms}$ which is calculated by "R.M.S. value calculator" is compared with reference voltage $V_{ref}$. Modulation ratio $m$ of the PWM inverter is determined with feedback control which is calculated from PI controlled value of the error $e$ which is the difference of $V_{rms}$ and $V_{ref}$. Here, $m$ is obtained from the ratio of carrier wave amplitude and modulating wave amplitude. R.M.S. value of PWM inverter output voltage is adjustable by using $m$[8].

## III. R.M.S. Value Calculator

The calculation of the R.M.S. value of the inverter output voltage is necessary for controlling the modulation ratio of the PWM inverter to get settled voltage on inverter output.

In this paper, we propose a new way to have R.M.S. value of the inverter output voltage as a DC value. The R.M.S. value is calculated from the sinusoidal instantaneous value of the inverter output voltage by using analog operational circuit shown as R.M.S. value calculation circuit in Fig.2.

If the instantaneous value of $v_1(t)=\sqrt{2}V\sin(\omega t+\theta)$ and $v_2(t)=\sqrt{2}V\cos(\omega t+\theta)$ are known, then the R.M.S. value of the inverter output voltage $V$ is calculated by using trigonometric function, shown in equation (1).

$$\left\{\sqrt{2}V\sin(\omega t+\theta)\right\}^2+\left\{\sqrt{2}V\cos(\omega t+\theta)\right\}^2=\left(\sqrt{2}V\right)^2 \quad (1)$$

When the inverter output voltage $v_1(t)=\sqrt{2}V\sin(\omega t+\theta)$ is

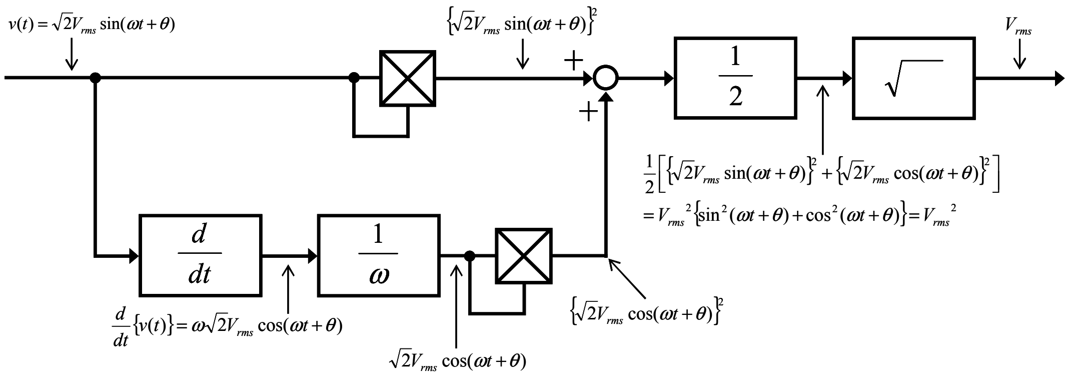


Fig. 3. Block diagram for calculating R.M.S. value of the inverter output voltage.

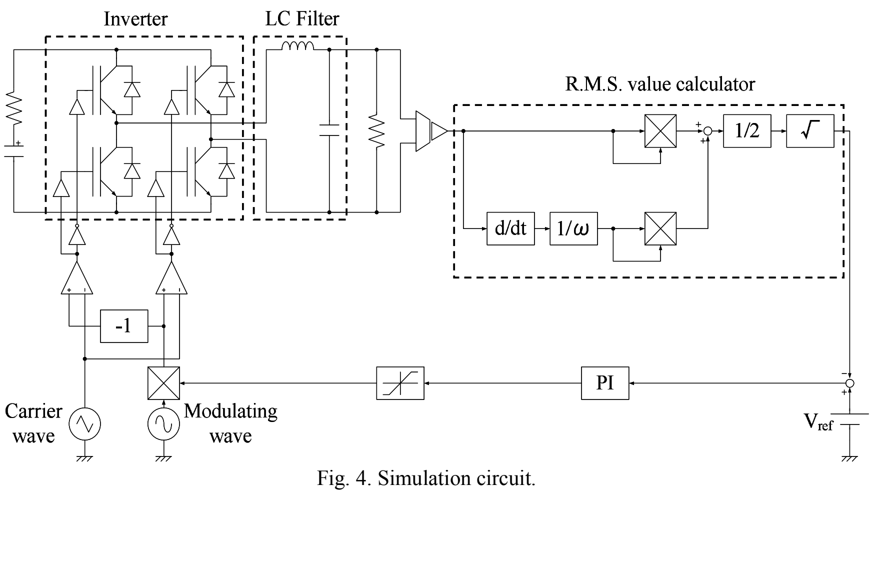


Fig. 4. Simulation circuit.

sensed by the circuit shown in Fig.2, then the voltage $v_2(t) = \sqrt{2}V\cos(\omega t + \theta)$ can be calculated by differentiating $v_1(t)$ and dividing by $\omega$. Therefore, the R.M.S. value is obtained by the following equation.

$$V = \sqrt{\frac{1}{2}\left\{ v(t)^2 + \left( \frac{1}{\omega} \cdot \frac{dv(t)}{dt} \right)^2 \right\}} \tag{2}$$

Equation (2) shows that the R.M.S. value of the inverter output voltage $V$ is calculated from the instantaneous value of $v_1(t)$. A detailed block diagram of R.M.S. value calculation circuit is shown in Fig.3.

## IV. Simulation Results

The proposed feedback control system is simulated using PSIM. This simulation is implemented under the condition of Table 1. The simulated circuit is indicated in Fig.4 and the result is shown in Fig.5.

TABLE I
SIMULATION CONDITION

| | Value |
|---|---|
| Output voltage frequency | 60 [Hz] |
| Sampling frequency | 10 [kHz] |
| Proportional gain | 0.05 |
| Integration gain | 0.002 |
| Load | 500 [W] |

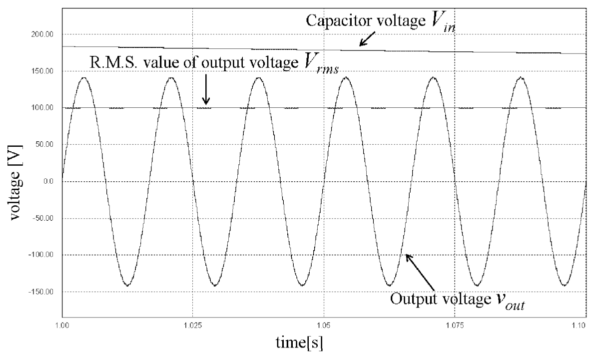



Fig. 5. Simulation results.

From this result, it is understood that the output voltage is kept at constant R.M.S. value in case that the input capacitor voltage decreases. Therefore, proposed control system is effective to control the output voltage to constant.

## V. Experimental Results

The effectiveness of the proposed control system is confirmed from the simulation results in chapter 4. Next, it is considered whether the output value of the PWM inverter kept to constant R.M.S. value in experimental setup.

### A. Experimental Circuit

The appearance of the experimental setup is shown in Fig.6. The inverter part of this experimental setup is configured by PWM inverter and control circuit. IGBTs are used as switching devices of this inverter. The R.M.S.

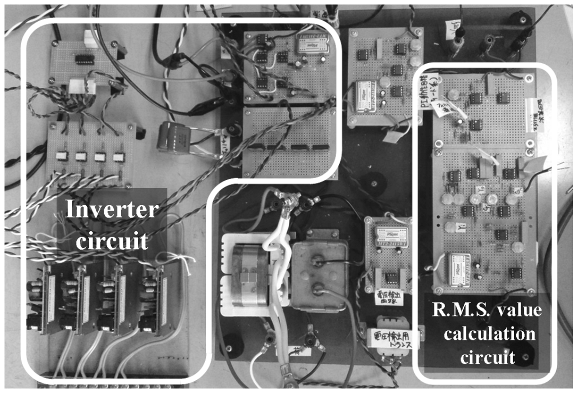



Fig. 6. Picture of inverter and control circuit.

value calculator is configured by analog devices. For example, operational amplifier is used for differentiation, amplification and addition. Multiplication IC is used for multiplication and square root extraction. Here, it is important that designing of differentiation and amplification circuit, and adjustment of the offset of operational amplifier.

### B. Characteristics of R.M.S. Value Calculator

Fig.7 shows the output waveforms of the R.M.S. value calculator indicated in Fig.2 in case that input R.M.S. value of the sinusoidal waveform is 5 [V]. From this output waveforms, it is understood that DC value which depends on the R.M.S. value is obtainable from the AC waveform.

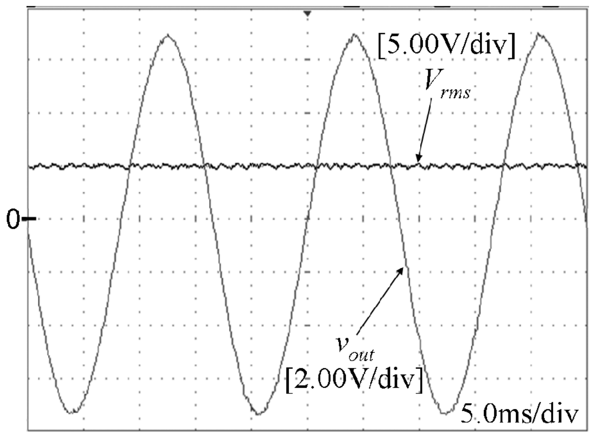



Fig. 7. The input and output voltage waveforms of R.M.S. value calculation circuit.($V_{out}$=5.00 [V], $V_{rms}$=5.00 [V])

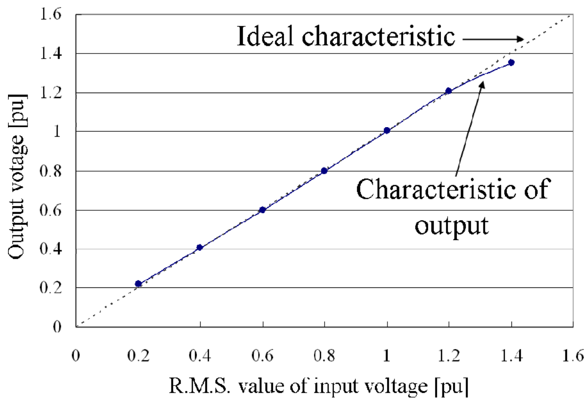
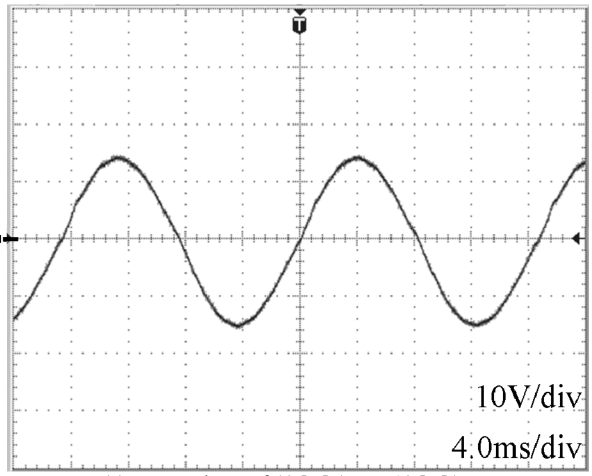
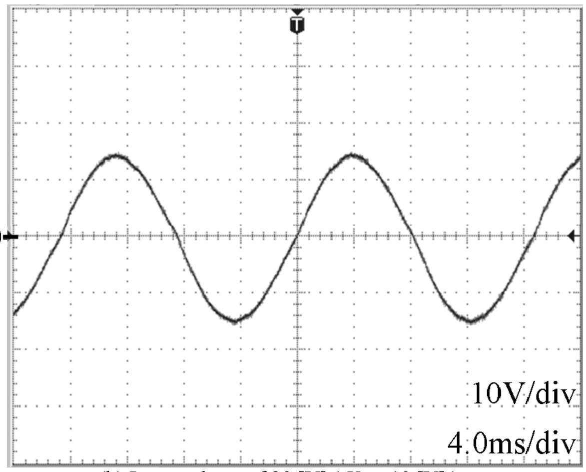



Fig. 8. Input-output characteristic of R.M.S. value calculation circuit.

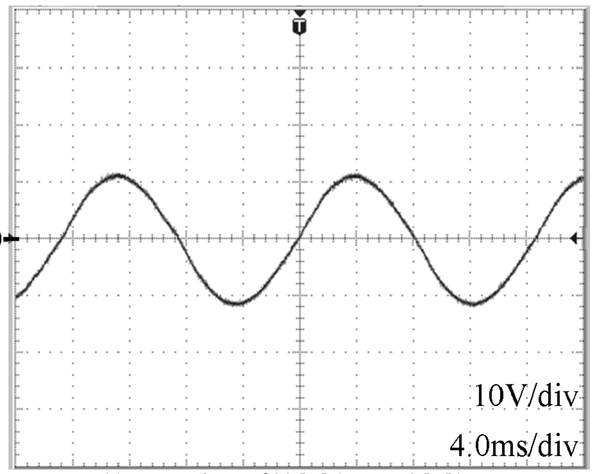
Next, Fig.8 shows the input and output characteristic of R.M.S. value calculator. From this figure, it is understood that output voltage conforms to input value, and accords with ideal line when the range of input voltage is from 0.6 to 1.0 [pu]. On the other hand, in the range except these, it is recognized that the characteristics are incongruent from an ideal straight line. These causes attribute the offset of operational amplifier and the error of the calculation circuit. However, it is understood that the error near to 1.4 [pu] and 0.4 [pu] is no problems when the target value of R.M.S. value calculator is designed around 1.0 [pu].



(a) Input voltage of 40 [V] ( $V_{rms}$=10 [V] )



(b) Input voltage of 30 [V] ( $V_{rms}$=10 [V] )



(c) Input voltage of 20 [V] ( $V_{rms}$=7.8 [V] )

Fig. 9. Experimental results of the output waveforms with reference voltage of 10 [V].

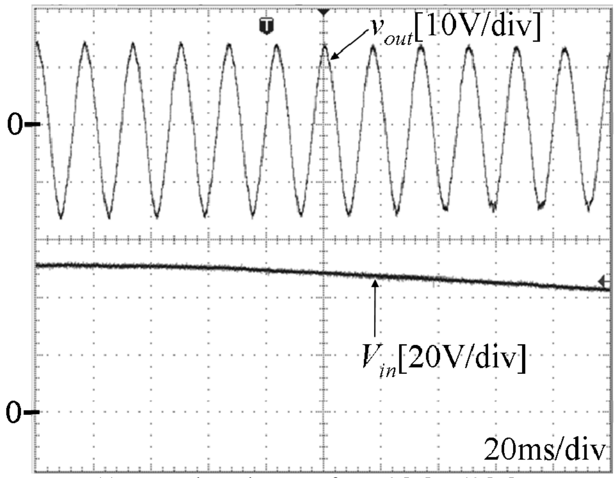
### *C. Low Output Voltage Characteristics*

Fig.9 shows the inverter output voltage waveforms when inverter input voltage changed. In this experiment, target R.M.S. value of output voltage set to 10 [V].

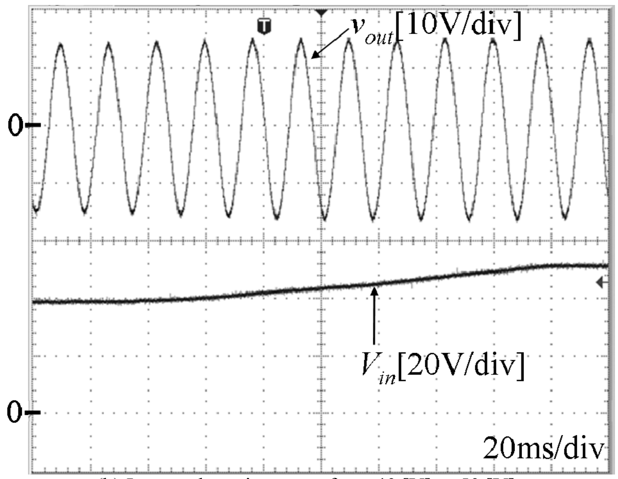
When the input DC voltage is 40 [V] and 30 [V], it is understood that 10 [V] output voltage is obtainable from PWM inverter, and control system operates according to the design. However, in case that the input DC voltage is 20 [V], it is sure that 10 [V] output voltage is not obtainable from PWM inverter. This feedback control circuit has the output limitation so that output waveform is not distorted. This limitation depends on PI gain limitation. Therefore, in case that calculated PI gain is much larger than limitation value, modulation ratio of the PWM inverter is not conformed to desired value.

And, it is recognized that output waveform is distorted around zero. This is considered to be influence of voltage drop of switching devices and diodes because designed output voltage is low as 10 [V].

Next, Fig.10 shows the output voltage waveform of



(a) Input voltage decreases from 50 [V] to 40 [V]



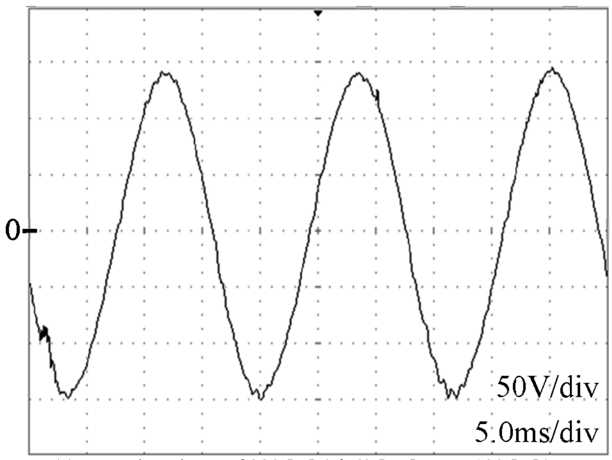
(b) Input voltage increases from 40 [V] to 50 [V]

Fig. 10. Input and output waveforms of inverter in the case of decreasing and increasing input voltage.

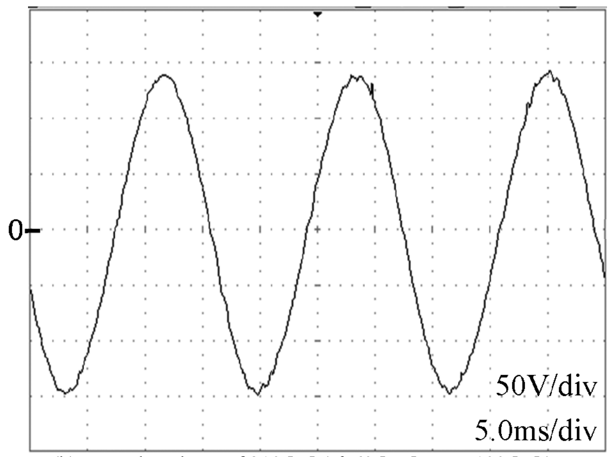
PWM inverter when input voltage is increased from 40 to 50 [V], and decreased from 50 to 40 [V]. In these results, it is understood that the output voltage of PWM inverter follows designed value 10 [V] in both cases.

### D. *Experiment for Output Voltage of 100 [V]*

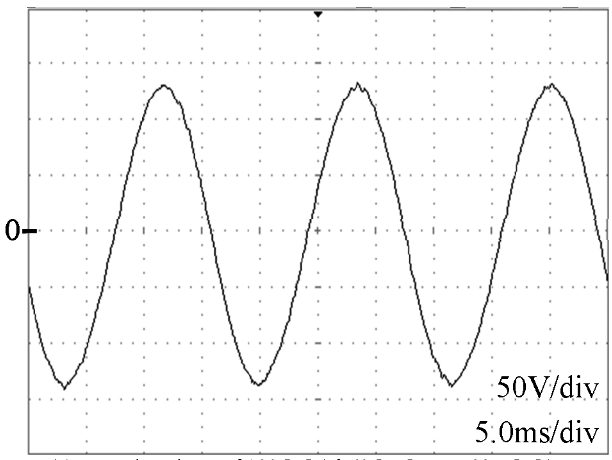
Fig.11 shows the case that the output voltage waveform when the input voltage of the PWM inverter was changed. In this experiment, the targeted value of the output voltage set 100 [V], and the load of inverter is 200 [W] resistive load.




(a) Input dc voltage of 220 [V] ($f$=60 [Hz], $V_{rms}$=100 [V] )




(b) Input dc voltage of 210 [V] ($f$=60 [Hz], $V_{rms}$=100 [V] )



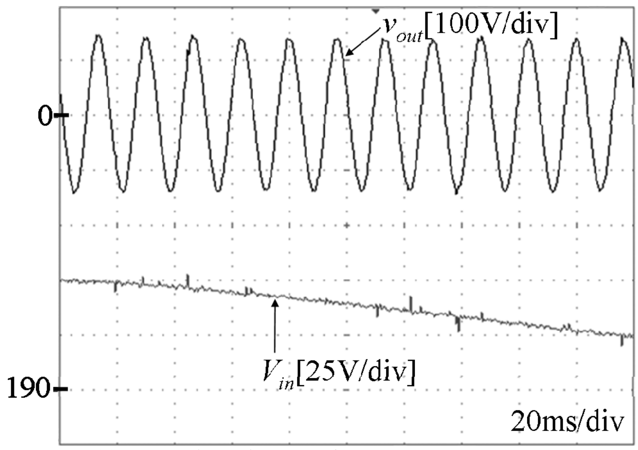

(c) Input dc voltage of 190 [V] ($f$=60 [Hz], $V_{rms}$=93.5 [V] )

Fig. 11. Experimental results of the output voltage waveforms with reference voltage of 100 [V].

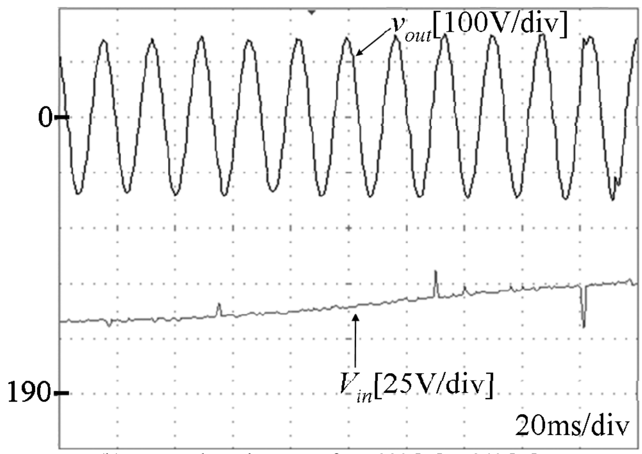
In case that the input voltage is 220 [V] and 210 [V], a sine wave of actual value 100 [V] is provided the output voltage, it is understood that the output voltage constant control were realized.

However, in the case that input voltage was 190 [V], actual value of the output voltage was less than 100 [V], and the output voltage constant control was not realized. This cause was the upper limitation of the modulation ratio, for proposed feedback system is set to 0.7. Therefore, the lower limitation value of the input DC voltage was 200 [V]. If the limitation of this feedback control system could be removed, it was considered that output voltage was provided from lower voltage than 200 [V]. In addition to this, the distortion around zero voltage which is appeared in low voltage experiment was not observed. It was considered that the effect of forward voltage drop is vanishingly lower than that of low voltage experiment.

Next, Fig.12 shows the output voltage waveform of PWM inverter when input voltage is increased from 220 to 240 [V], and decreased from 240 to 220 [V]. In these results, it is understood that output voltage of PWM inverter follows designed value 100 [V] in both cases.




(a) Input voltage decreases from 240 [V] to 220 [V]




(b) Input voltage increases from 220 [V] to 240 [V]

Fig. 12. Input and output waveforms of inverter in the case of decreasing and increasing input voltage.

## VI. CONCLUSIONS

In this paper, a control method about the capacitor source PWM inverter to stabilize the output voltage without using the chopper circuit was described. A R.M.S. value calculator was suggested to construct the proposed control scheme, and the effectiveness of the feedback control law was inspected by simulation and an experiment. As a result, it was confirmed that the stable output voltage was provided from PWM inverter when the voltage of capacitor was dropped.

However, this proposed control system was not useful when input DC voltage value is lower than the peak value of the output AC voltage. Therefore, the energy of the capacitor cannot be used effectively compared with the case of using a boost chopper circuit.

To solve this problem, it is considered a method to change the connection in parallel and series by value of the capacitor voltage. In this case, the input DC voltage becomes step voltage, therefore the characteristics of feedback control system such as step response must be reconsidered to stabilize the output voltage. And the power conversion efficiency of proposed control system must be evaluated as compared with the control system using chopper circuit.

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