# A PULSE-WIDTH CONTROLLED DC-DC CONVERTER POWERED BY A CONSTANT-CURRENT SOURCE

KOHJI KUWABARA and TOMOO SUZUKI

FUJITSU LIMITED
Kawasaki, JAPAN

## ABSTRACT

A pulse-width control method is used to regulate output voltage for a DC-DC converter powered by a constant-current source. In a constant-current input converter, the output voltage rises as the transistor switching duty ratio is decreased and falls when the duty ratio is increased. Regulation is achieved by increasing the duty ratio when the output current decreases and decreasing the duty ratio when output current increases. This is the reverse of the technique used with constant-voltage input.

## 1. INTRODUCTION

In telecommunication, repeaters and data terminals are operated by feeding a constant-current source from a central office. In this case a DC-DC converter is needed to supply regulated power to the system. The usual voltage controlling method uses a parallel voltage regulator in the output. This method is easy, but the parallel voltage regulator itself dissipates unnecessary power when the output current decreases, because the input voltage is always constant.

If output voltage is regulated by a pulse-width controller, the input voltage varies depending on the output current. Thus the conversion efficiency become very high.

This paper describes DC-DC converter characteristics for constant-current input and shows the experimental results.

## 2. TWO TYPES OF POWER CONVERSION CIRCUITS

There are two types of switching power conversion circuits for constant-current input, a parallel type as in Fig. 1 and a series type as in Fig. 2. The parallel type shorts the input to remove power from the load ($R_0$) when switch S is closed, and supplies power to the load when S is open. The peak current flowing through the load *does not change even if the duty ratio* (D) of the switch changes. The effective power ($P_s$) used by the load is as follow:

$$P_s = R_0 I_s^2 (1 - D) \qquad (1)$$

The series type requires a capacitor Cs on the input, as shown in Fig. 2, because it chops the input constant-current, and supplies power to the load ($R_0$) when switch S is closed. The average current flowing through the load ($I_1$) is equal to the input current ($I_s$). Therefore, the lower the duty ratio, the higher the peak value of $I_1$, as shown in Fig. 2-b. The effective power ($P_s$) used by the load is as follows:

$$P_s = R_0 I_s^2 / D \qquad (2)$$

For both types, conversion power increases with decreased duty ratio. The series type can convert more power than the parallel type.

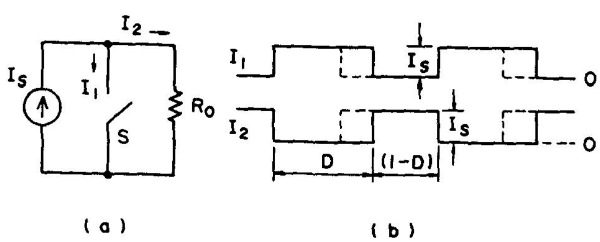


Fig.1 Parallel-type conversion circuit

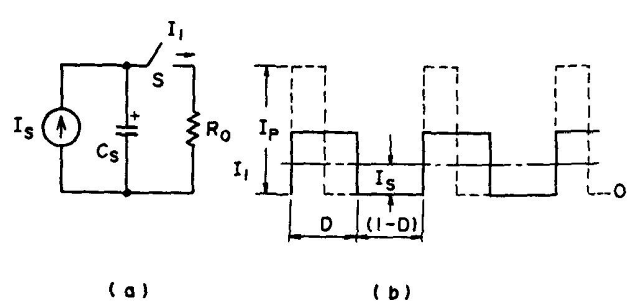


Fig.2 Series-type conversion circuit

## 3. INPUT AND OUTPUT VOLTAGES OF THE CONSTANT-CURRENT INPUT DC-DC CONVERTER

There are two basic types of DC-DC converter circuits, Boost and Buck. These two types are distinguished by whether the current flowing into the input and out of the output are continuous or discontinuous. Also, the output voltage is higher than the input voltage for Boost-type converter, and lower for Buck-type converter.

For the Boost-type converter shown in Fig. 3-a, the current flowing into Ⓐ is continuous, and the current flowing out Ⓑ is discontinuous. The output current is equal to the averaged current flowing out Ⓑ. Therefore, even if the duty ratio (D) is changed, the peak current flowing through the transistor (TR) does not change, just as with the parallel type in Fig. 1.

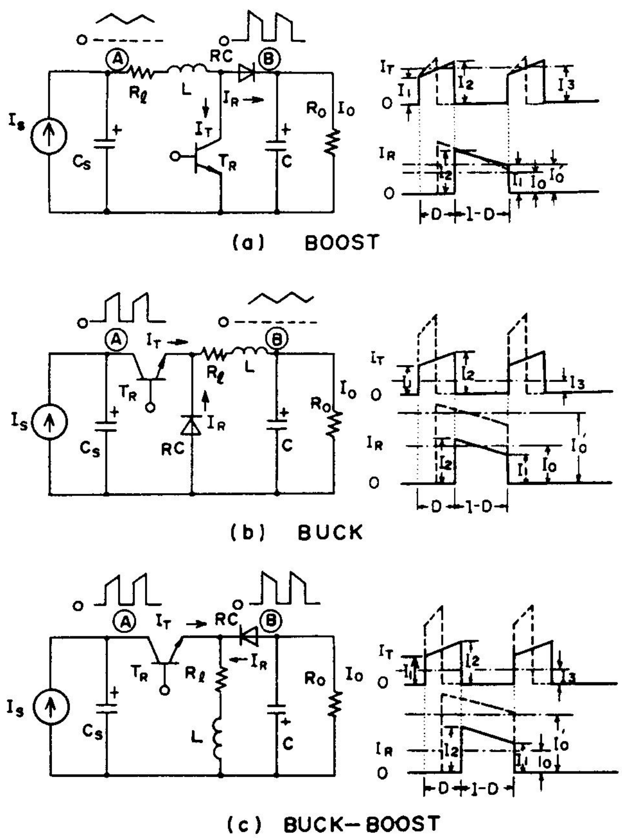


Fig.3 Three types of DC-DC converters with constant-current input

Table 1 Input and Output voltages

| DC/DC | BOOST | BUCK | BUCK-BOOST |
|---|---|---|---|
| $V_O$ | $I_S R_O (1-D)$ | $I_S R_O \frac{1}{D}$ | $I_S R_O \frac{1-D}{D}$ |
| $V_S$ | $I_S[R_\ell + R_O(1-D)^2]$ | $I_S(R_O+R_\ell)\frac{1}{D^2}$ | $I_S\left[\frac{R_\ell}{D^2}+R_O\left(\frac{1-D}{D}\right)^2\right]$ |

For the Buck-type converter shown in Fig. 3-b, unlike the Boost-type, the current flowing into Ⓐ is discontinuous and the current flowing out from Ⓑ is continuous. This converter, similar to the series-type in Fig. 2, chops the input current, and the lower duty ratio increases the peak current flowing through the transistor (TR), as the input current (Is) is equal to the averaged current flowing into Ⓐ. Since the output current is continuous, it is equal to the peak current flowing through TR.

There is also the Buck-Boost type converter shown in Fig. 3-c. The current flowing into Ⓐ and out from Ⓑ are both discontinuous. The input current (Is) is equal to the averaged current flowing through TR, and the output current (Io) is equal to the averaged current flowing out from Ⓑ as with the Boost-type.

Figure 3 also shows the current waveforms for these three types when the duty ratio (D) is changed. For any type, the output current (Io) is inversely proportional to the duty ratio.

The input voltage (Vs) and output voltage (Vo) can be obtained by the Averaging method [1]. The state-vector X is represented in the following equation:

$$X = (i, Vs, Vo)^t \quad \text{.....................} \quad (3)$$

where i, Vs and Vo are the current flowing through the inductor, input voltage and output voltage respectively. The state equation is below:

$$dx/dt = Ai \cdot X + bi \cdot Is \quad \text{................} \quad (4)$$

where Is is the input current and Ai and bi are i-th state matrixes. i=1 is the state when the transistor is on and i=2 is the state when it is off. On the boundary between two states, the state vector is continuous, therefore

$$dx/dt = A \cdot X + b \cdot Is \quad \text{..................} \quad (5)$$

where

$$A = D \cdot A_1 + (1 - D) \cdot A_2$$

$$b = D \cdot b_1 + (1 - D) \cdot b_2$$

In the steady-state, dx/dt = 0 and X is obtained from the following equation;

$$X = -A^{-1} \cdot b \cdot Is \quad \text{......................} \quad (6)$$

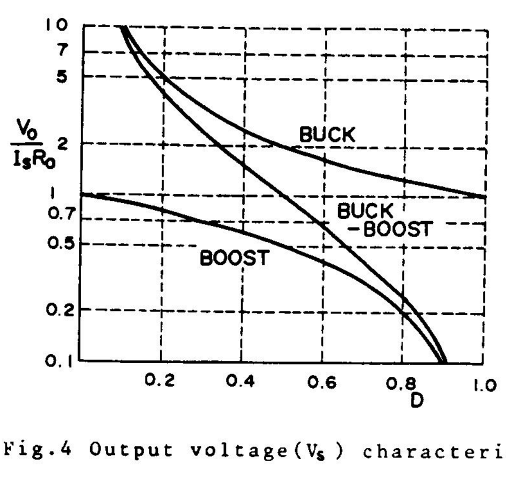


Fig.4 Output voltage($V_s$) characteristics

For three types of converters, Boost, Buck and Buck-Boost, we calculate the matrix Ai, bi (i=1, 2). Then the input voltage (Vs) and the output voltage (Vo) shown in Table 1 are obtained.

Figure 4 shows the relationship between the output voltage (Vo) and the duty ratio (D). We can see that for all three types, when the input current (Is) and load (Ro) are constant, the output voltage (Vo) is inversely proportional to the duty ratio (D). The figure also shows that the Buck-Boost type converter has the widest controllable range.

The inductor internal resistance (Rℓ) is not included in the output voltage equation, but in the input voltage equation. Figure 5 shows, for the Buck-Boost type converter, duty ratio characteristics to keep the output voltage constant when the load changes, and the input voltage variations at that time, depending on the inductor internal resistance.

Based on these results, when the output voltage is regulated by controlling the duty ratio (D), the inductor internal resistance is not related to the duty ratio and affects only the input voltage.

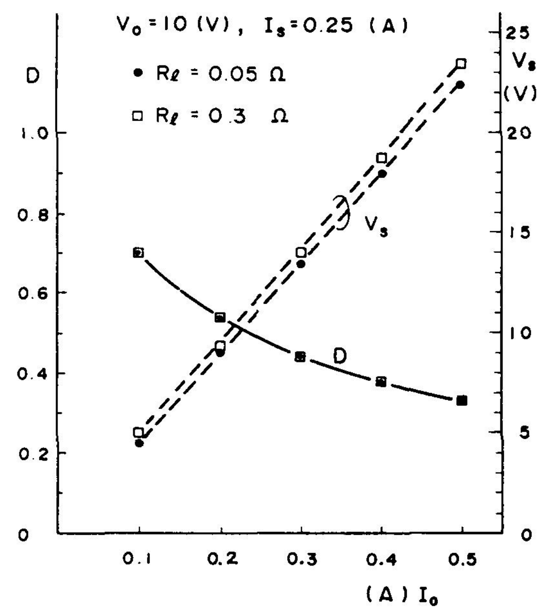


Fig.5 Duty ratio(D) and input voltage(Vs) characteristics for Buck-Boost type converter

Table 2 Conversion Power

| DC/DC | BOOST | TRANSFORMER-COUPLED BUCK (FORWARD) | TRANSFORMER-COUPLED BUCK-BOOST |
|---|---|---|---|
| $V_o$ | $I_s R_o (1-D)$ | $\frac{N_1}{N_2} I_s R_o \frac{1}{D}$ | $\frac{N_1}{N_2} I_s R_o \frac{1-D}{D}$ |
| $P_o$ | $I_s^2 R_o (1-D)^2$ | $(\frac{N_1}{N_2})^2 I_s^2 R_o \frac{1}{D^2}$ | $(\frac{N_1}{N_2})^2 I_s^2 R_o (\frac{1-D}{D})^2$ |
| $P_o$ (D=0.5) | $0.25 I_s^2 R_o$ | $0.25 I_s^2 R_o$ $(\frac{N_1}{N_2} = \frac{1}{4})$ | $0.25 I_s^2 R_o$ $(\frac{N_1}{N_2} = \frac{1}{2})$ |

N1:Transformer primary winding
N2:Transformer secondary winding

The three types of DC-DC converter differ in conversion power. If a transformer with a 1:4 turns ratio is used for the Buck-type converter, and a transformer with a 1:2 turns ratio is used for the Buck-Boost type converter, the conversion power becomes the same for all types when the duty ratio (D) is 0.5. Table 2 shows the conversion power for the three types of converter.

## 4. A PULSE-WIDTH CONTROLLED OUTPUT VOLTAGE

Even in the case of a DC-DC converter with constant-current input, it is possible to regulate output voltage by a pulse-width control method, as in the case of a conventional constant-voltage input converter. Regulation is achieved by increasing the pulse width when the output current decreases and decreasing the pulse-width when the output current increases. This is the reverse of the technique used with constant-voltage input.

The output voltage cannot be regulated over the entire range of output current. Regulation is possible within a limited range only. This range depends on the maximum pulse width and the minimum pulse width. The output current is minimum when the pulse width is maximum and the output current is maximum when the pulse width is minimum.

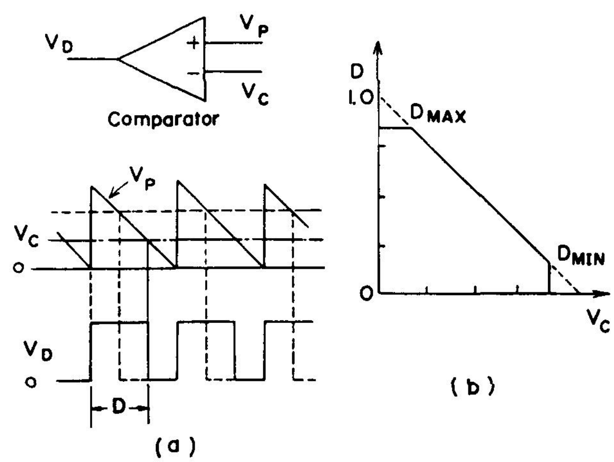


Fig.6 Linear pulse-width modulator(PWM)

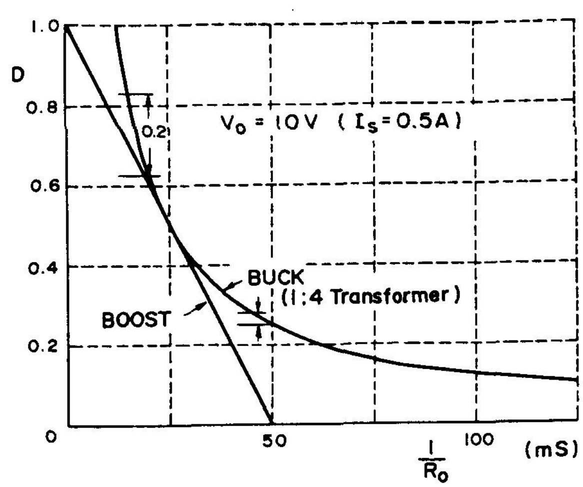


Fig.7 Duty ratio(D) characteristics for Boost-type and Buck-type converters

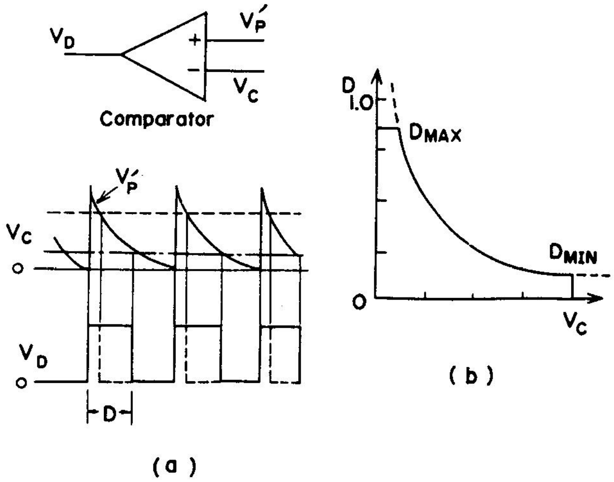


Fig.8 Nonlinear pulse-width modulator

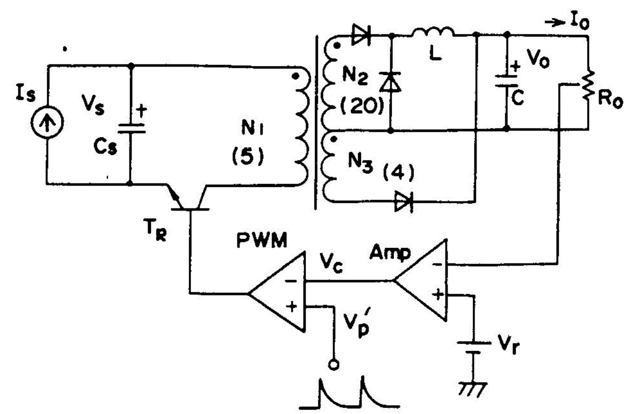


Fig.10 Buck-derived(Forwerd) converter with regulated output voltage

The relationship between the output voltage and the duty ratio (D) of the Boost type converter is linear. Thus, a linear pulse-width modulator circuit, shown in Fig. 6, is suitable for output voltage regulation.

In the Buck-type converter, the output voltage has a nonlinear relation to the duty ratio. Therefore if a linear pulse-width modulator circuit is used to the output voltage, unstable operation results. Figure 7 shows the duty ratio characteristics to keep the output voltage constant when the load resistance changes in the Boost and Buck type converters. From this figure, it is seen that the ralationship between the load (1/Ro) and the duty ratio is always constant in the Boost type. In the Buck-type, however, the relationship is not constant. When 1/Ro changes from 15 to 20 (mS), D must change by 0.2 in order to regulate the output voltage and when 1/Ro changes from 45 to 50 (mS), only 0.028 change of D is sufficient for regulation.

The relationship between the input voltage (Vc) and output pulse width (D) in the nonlinear pulse width modulator is required to use the following equation:

$$V_c = K \cdot 1/D \quad (K = \text{constant}) \quad \text{..........} \quad (7)$$

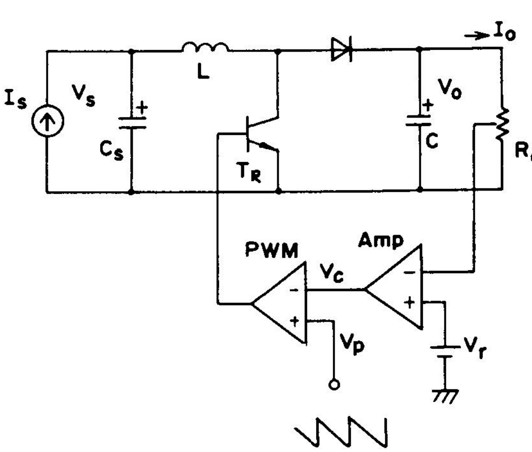


Fig.9 Boost-type converter with regulated output voltage

In this case, the pulse width modulator gain becomes high for a light load and becomes low for a heavy load. Figure 8 shows an example of a nonlinear pulse width modulator circuit, using exponential sweep instead of the sawtooth sweep used for the Boost-type converter.

Experiments were made on the Boost-type and the Buck-type converters shown in Fig. 9 and 10 respectively. In the Buck-type converter, a transformer with a 1:4 turns ratio is used and self-resetting energy is transferred to the output. In these experimental circuits, the input current (Is) is 0.5A and the output voltage (Vo) is regulated to 10V. The maximum duty ratio ($D_{MAX}$) is approximately 0.8 and the minimum is 0.2.

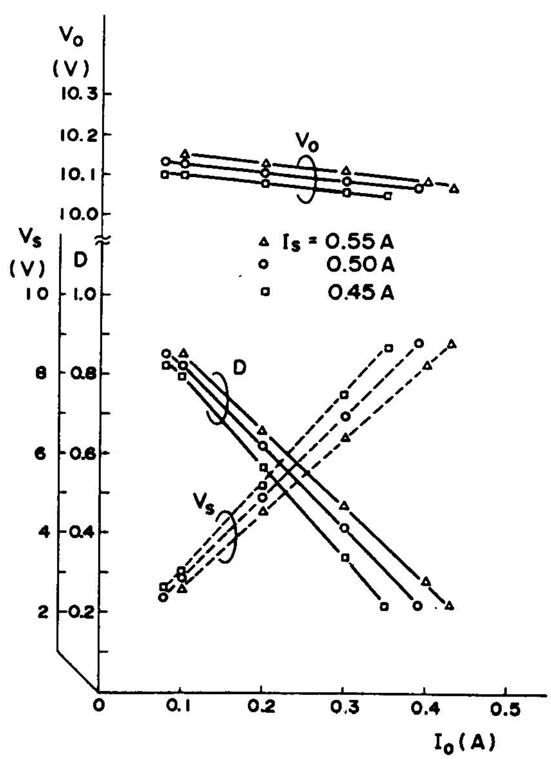


Fig.11 Experimental results for Boost-type converter in Fig.9

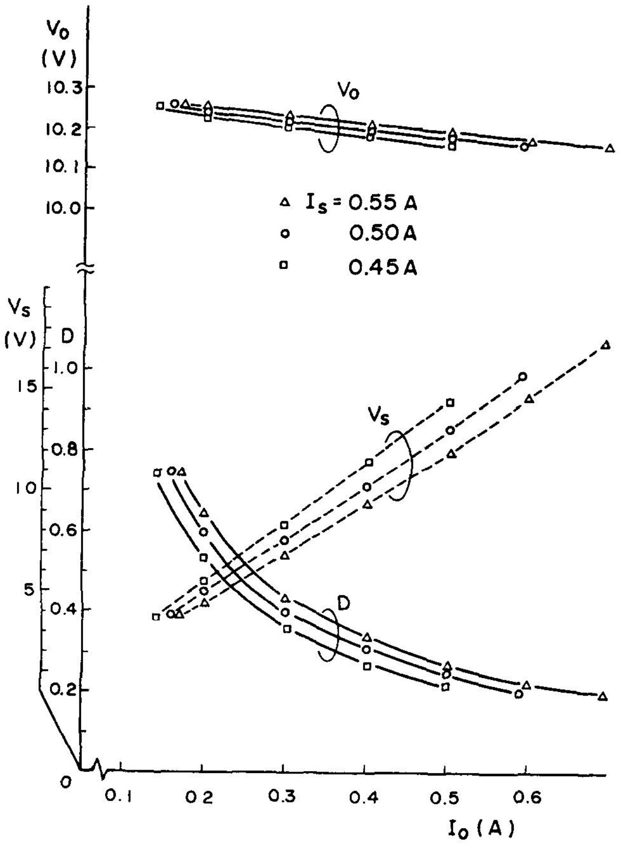


Fig.12 Experimental results for Buck-derived (Forward) converter in Fig.10

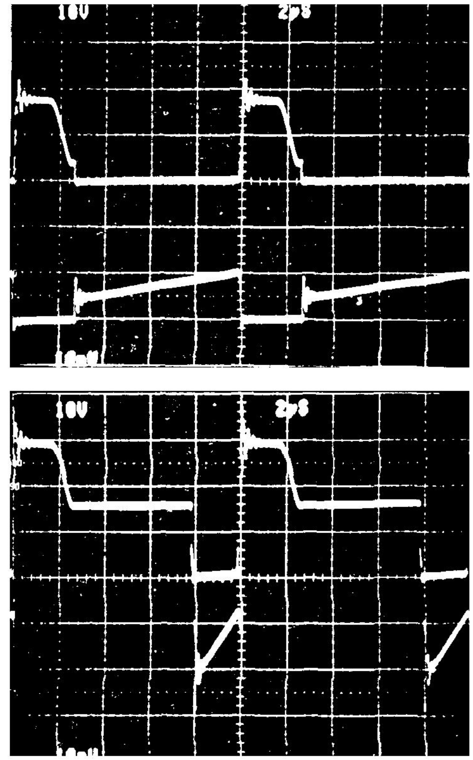


Fig.14 Waveforms of transistor switch($T_R$) in Buck-derived(Forward) converter

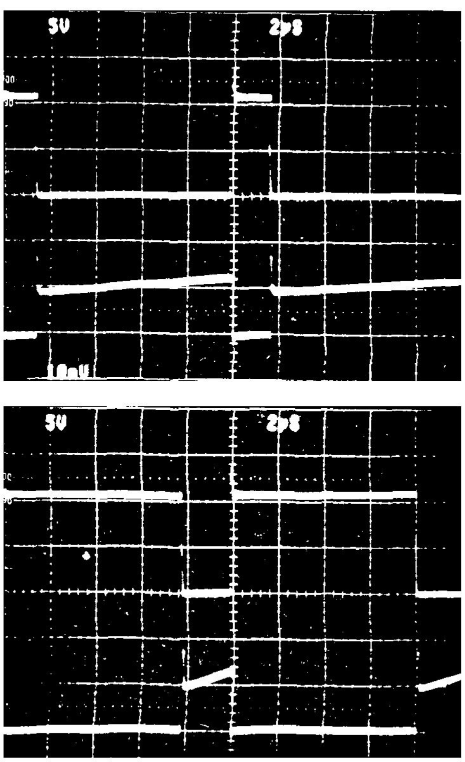


Fig.13 Waveforms of transistor switch($T_R$) in Boost-type converter

Figures 11 and 12 respectively show the output voltage load regulation characteristics for Boost-type and for Buck-type when the input current is changed. Measured values of the duty ratio (D) and input voltage (Vs) are also shown in these figures.

Waveforms of transistor voltage and current ($V_{CE}$, Ic) are shown in Fig. 13 and 14, when the output currents are minimum and maximum.

## 5. CONCLUSION

In a DC-DC converter with constant-current input, the output voltage can be regulated by a pulse width control method. In this case, the input voltage decreases when the output current decreases and increases when output current increases. Thus, the converter supplies only the power needed in the load, and has high conversion efficiency.

For output voltage control, a linear PWM can be used for the Boost-type and a nonlinear PWM can be used for the Buck type.

## REFERENCE

[1] R. D. Middlebrook and Slobodan Cuk, "A General Unified Approach to Modelling *Switching-Converter Power Stages,*" *PESC 1976 RECORD, pp.18-34*