Effect of Clamp Capacitor on the Stability of Active-Clamp DC-DC Converters

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Abstract

This paper discusses the effect of an active-clamp circuit on the dynamic characteristics of a basic converter topology such as a buck-boost converter. The buck-boost converter has instability problems such as a jumping phenomenon and an oscillation of the output voltage. Recently we have found an unstable phenomenon due to inserting an active-clamp circuit in the buck-boost converter with a large conversion ratio. The effect of the clamp capacitance and the leakage inductance of the transformer on the oscillatory instability is made clear through the analytical and experimental considerations. Then the effects of the other parameters are examined for designing sufficiently stable soft-switched converters.

1. Introduction

DC-DC converters have a severe difficulty of surge occurrence due to transformer's leakage inductance and diode's reverse recovery. In order to absorb the surge energy and suppress the voltage stress and to achieve the ZVS operation, the active-clamp technique has been proposed[1,2] and widely used as an extremely effective scheme. Previously a stability analysis of converters with the active-clamp circuit was reported[3]. However, the clamp capacitor was assumed to be a constant voltage source. The effect of the clamp capacitance on the converter stability has not been sufficiently discussed before. Recently we have found an unstable phenomenon due to inserting an active-clamp circuit in a buck-boost converter with a large conversion ratio.

This paper generalizes the effect of an active-clamp circuit on the dynamic characteristics of a basic converter topology such as a buck-boost converter. The buck-boost converter has instability problems such as a jumping phenomenon and an oscillation of the output voltage[4]. The effect of the clamp capacitance and the leakage inductance of the transformer on the oscillatory instability is made clear through the analytical and experimental considerations. Then for designing the sufficiently stable soft-switched converters, the effects of the other parameters are examined numerically.

2. Circuit topology and operation

Figure 1 shows a typical buck-boost converter with an active-clamp circuit. One switching period is divided into three states as shown by the key waveforms in Fig.2. Equivalent circuits corresponding to these states are shown in Fig.3. Operation in each state is described in the followings.

State 1 : T1 (S_1:off, S_2:on, D:on)

By turning off of the main switch S_1, the positive current of i_{S2} begins to flow through the body-diode D_{S2}. ZVS of the sub-switch S_2 is achieved by turning S_2 on before the current i_{S2} reverses. In this state, the diode D is on, then the power is supplied to the load circuit. By turning S_2 off, the circuit operation moves from State 1 to State 2.

State 2 : T2 (S_1:on, S_2:off, D:on)

After S_2 is turned off and the stored charges in parasitic capacitances across S_1 are discharged in a short time, the negative current of i_{S1} begins to flow through D_{S1}. In the same way as above, ZVS of S_1 is achieved by turning S_1 on before the current i_{S1} reverses. Besides, the power is supplied to the load circuit. When the diode current i_2 becomes

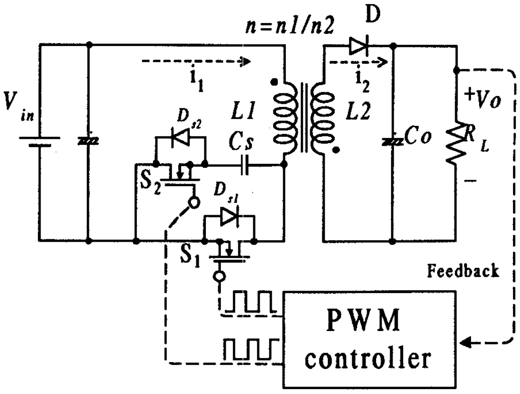

Fig. 1. Buck-boost converter with an active-clamp circuit (V_{in} = 50V, C_o = 470μF, N = 10, f_{sw} = 100kHz)

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zero, the circuit operation moves from State 2 to State 3.

<u>**State 3** : T3 (S_1:on, S_2:off, D:off)</u>

In this state, as the diode D is in off-state, the power is not supplied to the load from the transformer. So a smoothing capacitor of C_o supplies power to the load. The power source V_{in} magnetizes the magnetizing inductor L_p. By turning S_1 off, the circuit operation moves from State 3 to State 1 again.

3. Analysis

Although one switching period has three states as shown in the previous section, State 2 is neglected for simplicity of analysis. Because the interval of State 2 is much shorter than the others, it is considered that this neglect gives little effects on the low-frequency characteristics.

3.1 State equations

Assuming a magnetizing inductor L_p, a clamp capacitor C_s and an output capacitor C_o as a constant current source $\hat{i}_L$ and constant voltage sources $\hat{v}_s$ and $n\hat{v}_c$ during one switching period as seen in the equivalent circuits shown in Fig.4 (a) and (b), we choose these current and voltages as state variables representing the low-frequency characteristics. From these equivalent circuits, the circuit equations are obtained as follows:

<u>State 1</u>

$$V_{in} = \hat{v}_s + l_1 \frac{di_{s2}}{dt} + v_L + r_t \hat{i}_L \tag{1}$$

$$n\hat{v}_c + l_2 \frac{d(\frac{i_2}{n})}{dt} + v_L + r_t \hat{i}_L + n^2 r_c (\frac{i_c}{n}) = 0 \tag{2}$$

$$i_{s2} + \frac{i_2}{n} = \hat{i}_L \tag{3}$$

$$n\hat{v}_c + n^2 r_c (\frac{i_c}{n}) = (\frac{i_2}{n} - \frac{i_c}{n}) n^2 R_L \tag{4}$$

$$n v_o = n\hat{v}_c + n^2 r_c (\frac{i_c}{n}) \tag{5}$$

Initial conditions

$$\begin{cases} i_{s2}(0) & = & \hat{i}_L \\ \frac{i_2}{n}(0) & = & 0 \end{cases} \tag{6}$$

<u>State 3</u>

$$V_{in} = v_L + r_t \hat{i}_L \tag{7}$$

$$n\hat{v}_c + n^2 (R_L + r_c) \frac{i_c}{n} = 0 \tag{8}$$

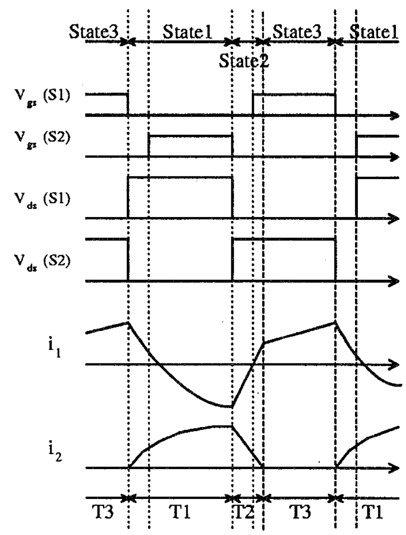
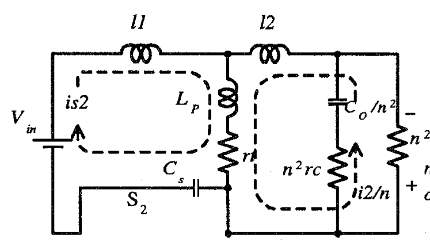
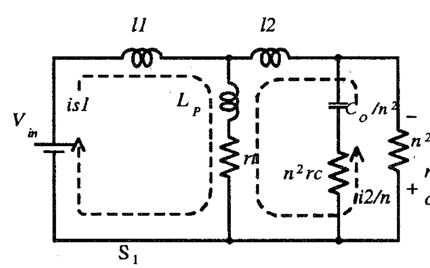


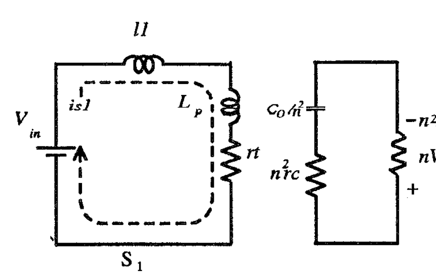
Fig. 2. Key waveforms



(a) State 1



(b) State 2



(c) State 3

Fig. 3. The equivalent circuits corresponding to the three States

$$nv_o = \frac{R_L}{R_L + r_c} n\hat{v}_c \quad (9)$$

In this state, the followings hold.

$$i_{s2} = \frac{i_2}{n} = 0 \quad (10)$$

From equations (1)-(10), we obtain the averaged values of v_L, i_{s2} and $\frac{i_c}{n}$ in one switching period, and denote them by $\bar{v}_L$, $\bar{i}_{s2}$ and $\frac{\bar{i}_c}{n}$, respectively.

Here, we take the following replacements.

$$\hat{x} = \begin{bmatrix} \hat{i}_L & \hat{v}_S & n\hat{v}_c \end{bmatrix}^T$$

$$\bar{y} = \begin{bmatrix} \bar{v}_L & \bar{i}_{s2} & \frac{\bar{i}_c}{n} \end{bmatrix}^T$$

So, the differential equation is obtained as

$$\frac{d\hat{x}}{dt} = \begin{bmatrix} \frac{1}{L_p} & 0 & 0 \\ 0 & \frac{1}{C_s} & 0 \\ 0 & 0 & \frac{n^2}{C_o} \end{bmatrix} \bar{y} \quad (11)$$

Deriving the vector $\bar{y}$ averaged over one switching period for the high frequency variables v_L, i_{s2} and $\frac{i_c}{n}$ by using (1) to (10) and substituting it into (11), the following state-space averaged equations are obtained [5]:

$$\frac{d\hat{x}}{dt} = A\hat{x} + BV_{in} \quad (12)$$

$$nv_o = C\hat{x} + dV_{in} \quad (13)$$

where A, B, C and d are written as follows:

$$A = \begin{bmatrix} \frac{1}{L_p} & 0 & 0 \\ 0 & \frac{1}{C_s} & 0 \\ 0 & 0 & \frac{n^2}{C_o} \end{bmatrix} \begin{bmatrix} -r_t & -\left((1-D) - \frac{l_1}{R_s}\lambda\right) & -\frac{l_1}{n^2 r_c}\lambda \\ 1-D & -\frac{(1-D)-\frac{(l_1+l_2)}{R_s}\lambda}{R_s} & \frac{(1-D)-\frac{(l_1+l_2)}{R_s}\lambda}{n^2 r_c} \\ 0 & \frac{(1-D)-\frac{(l_1+l_2)}{R_s}\lambda}{n^2 r_c} & -\frac{R_L\left((1-D)-\frac{l_1}{R_s}\lambda\right)}{n^2 r_c (r_c+R_L)} - \frac{1}{n^2(R_L+r_c)} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L_p} & 0 & 0 \\ 0 & \frac{1}{C_s} & 0 \\ 0 & 0 & \frac{n^2}{C_o} \end{bmatrix} \begin{bmatrix} 1 - \frac{l_1}{R_s}\lambda \\ \frac{(1-D)-\frac{(l_1+l_2)}{R_s}\lambda}{R_s} \\ \frac{-\left((1-D)-\frac{l_1+l_2}{R_s}\lambda\right)}{n^2 r_c} \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & (1-D) - \frac{(l_1+l_2)}{R_s}\lambda & \frac{R_L}{R_L+r_c}\left(D + \frac{(l_1+l_2)}{R_s}\lambda\right) \end{bmatrix}$$

$$d = -\left((1-D) - \frac{(l_1+l_2)}{R_s}\lambda\right)$$

$$R_s = (n^2 r_c // n^2 R_L)$$

$$\lambda = \frac{\left(1 - \exp\left(-\frac{R_s}{(l_1+l_2)(1-D)T_{sw}}\right)\right)}{T_{sw}}$$

3.2 Characteristic equation

The steady-state characteristics are obtained by using $\frac{d\hat{x}}{dt} = 0$ in (12). Next, from (12) and (13), a small-signal transfer function of output voltage $n\hat{v}_o$ to duty-ratio D is obtained as follows:

$$\frac{\Delta n\hat{v}_o}{\Delta D} = C(sI-A)^{-1}\left(\frac{\partial A}{\partial D}\hat{x} + \frac{\partial B}{\partial D}V_{in}\right) + \left(\frac{\partial C}{\partial D}\hat{x} + \frac{\partial d}{\partial D}V_{in}\right) \quad (14)$$

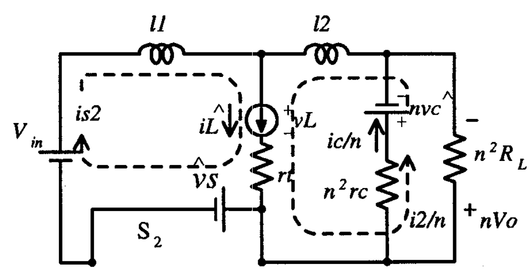
For simplicity of analysis, the feedback control circuit is assumed to be ideal, and then its transfer function is represented as a constant $(-K)$. Hence, the open-loop transfer function $H(s)$ is obtained by multiplying the transfer function $(\frac{\Delta n\hat{v}_o}{\Delta D})$ of the converter and the constant feedback gain $(-K)$ as follows:

$$H(s) = -\frac{\Delta n\hat{v}_o}{\Delta D}K \quad (15)$$

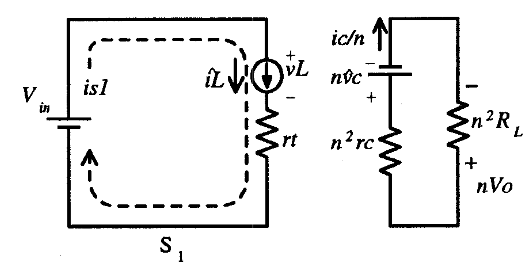
Therefore, the characteristic equation is expressed as

$$1 - H(s) = 0 \quad (16)$$

Consequently, we can obtain the boundary condition for stability by means of numerically calculating the above characteristic equation.



(a) State 1



(b) State 3

Fig. 4. Equivalent circuits with constant voltage/current sources

4. Experimental confirmation

A breadboard circuit of a buck-boost converter with an active-clamp circuit was implemented for experimentally confirming the above-mentioned analysis. Definitions and values of symbols used here are shown in Table 1.

4.1 Steady-state characteristics

The steady-state characteristics are shown in Fig.5. It is shown that the clamp capacitance has no effect on the steady-state characteristics of the converter.

Table 1. Definitions and values of symbols

Symbol	Definition	Value
V_{in}	Input voltage source DC	50V
L_p	Magnetizing inductance	4.42/12.4mH
l_1, l_2	Leakage inductances referred to primary	13.6/7.6μH
n	Turns ratio of windings $(\frac{n_1}{n_2})$	10
r_t	Equivalent winding resistance reflected in the primary side	18/2Ω
C_o	Output smoothing cap.	470μF
r_c	ESR of smoothing cap.	20 mΩ
i_1	Current flowing through the primary winding	—
i_2	Current flowing through the secondary winding	—

(transformer 1 / transformer 2)

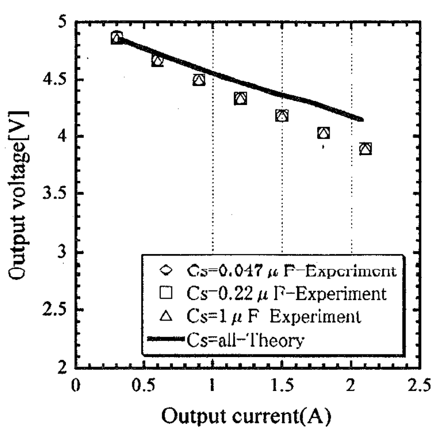


Fig. 5. Steady-state characteristics with the transformer 1

4.2 Dynamic characteristics

4.2.1 Stable region

Figures 6 and 7 show the comparison of analytical and experimental results for the stable region for two kinds of transformers. Both the analytical and the experimental results agree well. From these figures, it becomes evident that the clamp capacitor has an effect on the converter stability. In case where the clamp capacitance is smaller than the output smoothing capacitance (region I), the stable region becomes wider. On the other hand, in the case where the clamp capacitance is as large as the equivalent output capacitance referred to the primary (region II), the stable region becomes narrow. Furthermore, in the case where the clamp capacitance is larger than the equivalent output capacitance (region III), the stable region becomes wider again.

There are two kinds of unstable phenomena as shown in Fig.6. One is a jumping phenomenon [4], and the other is an oscillatory phenomenon.

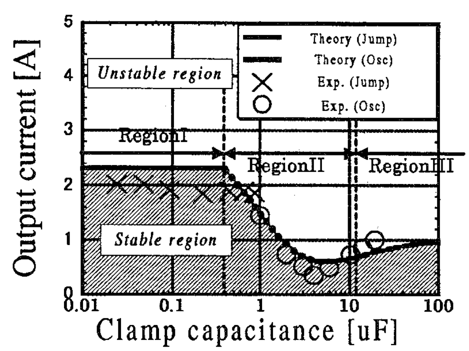


Fig. 6. Clamp capacitance and the stable region with the transformer 1

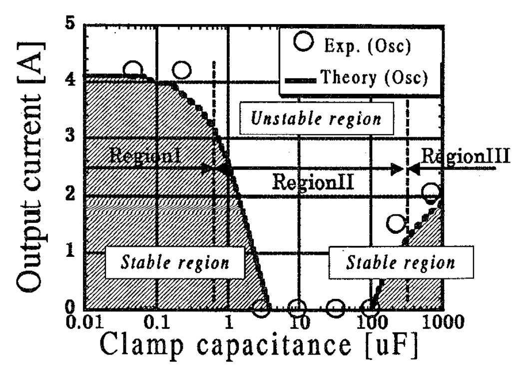


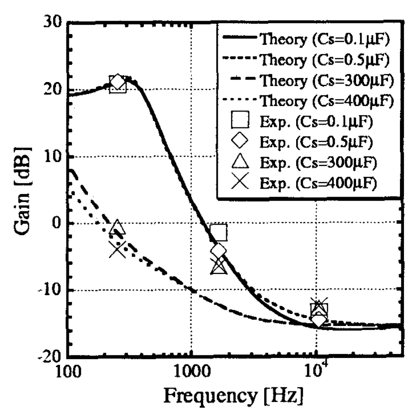
Fig. 7. Clamp capacitance and the stable region with the transformer 2

4.2.2 Phase margin

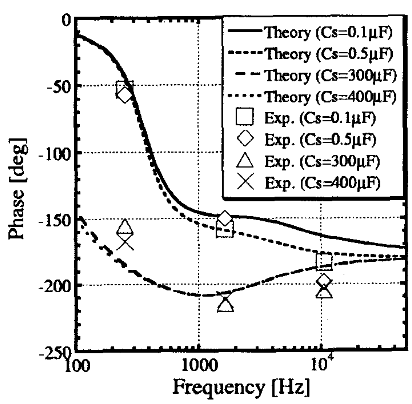
Figures 8 (a) and (b) show the frequency characteristics of the open-loop transfer function for some values of the clamp capacitance when the output current is 1A in Fig.7. The phase margin of this transfer function is obtained from Fig.8, and is shown in Table 2. Consequently, its variation vs. clamp capacitance is similar to the result of Fig.6 and 7.

Table 2. Phase margin and clamp capacitance

Clamp capacitance[μF]	Phase margin [deg]
0.1	33.7
0.5	23.4
300	2.4
400	4.3



(a) Gain



(b) Phase

Fig. 8. Frequency characteristics of the open-loop transfer function with the transformer 2

5. Effect of circuit parameters on Stable region

The above analysis is considered to have been verified from the good agreement between the analytical and the experimental results. So, the effect of circuit parameters in the stable region can be predicted by calculation based on the analysis.

First, we show the effect of the equivalent winding resistance r_t referred to the primary side of the transformer on the stable region in Fig.9, where the parameters values shown in Tables 1 and 3 were used. It is evident from this figure that the jumping phenominon is influenced by this internal resistance, but has no relation to the clamp capacitance.

Next, the effects of the other parameters are shown in Figs.10-13, where each parameter was varied for two cases of the equivalent winding resistance of 7Ω and 23Ω.

Table 3. Definitions and values of symbols used for calculation

Definition	Symbol	Value
Magnetizing inductance	L_p	2.42mH
Leakage inductance	l_1,l_2	25.3μH
Smoothing capacitance	C_o	470μF
ESR of smoothing capacitor	r_c	20mΩ

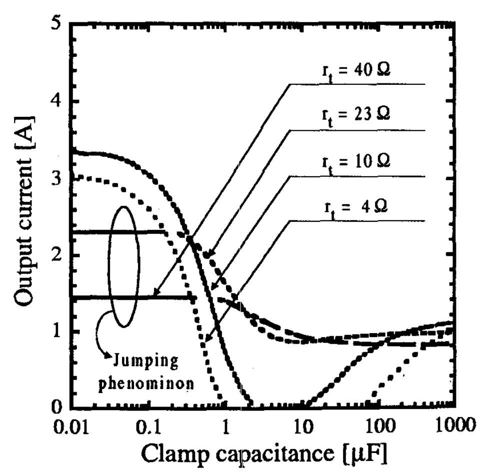
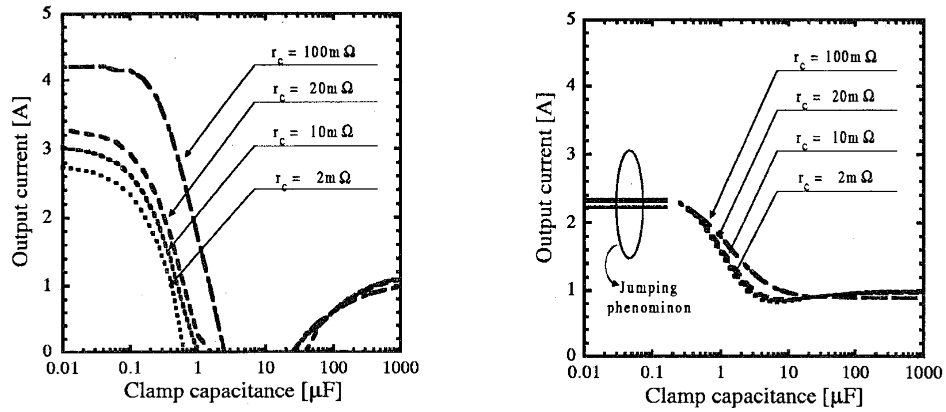
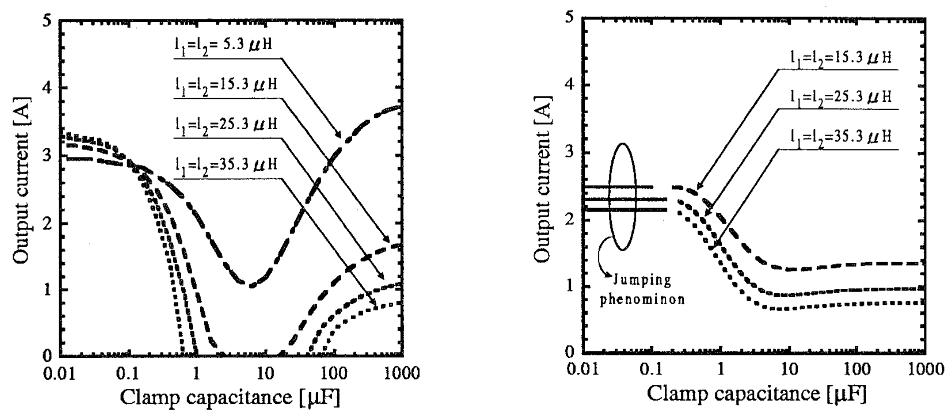


Fig. 9. Boundaries of stable region taking the inner resistance r_t as a parameter



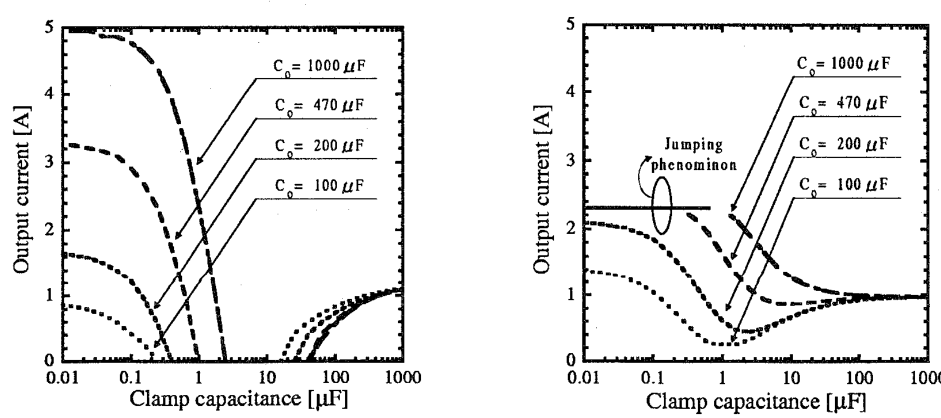
(a) $r_t = 7\Omega$ (b) $r_t = 23\Omega$

Fig.10. Boundaries of stable region taking the ESR of smoothing capacitor r_c as a parameter



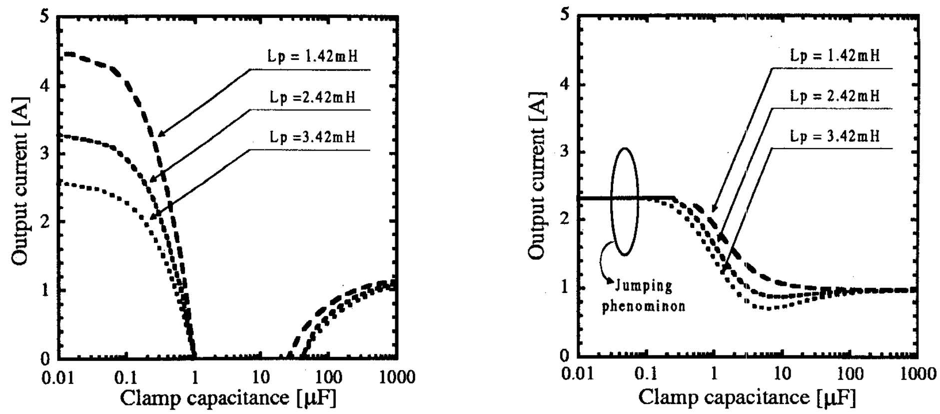
(a) $r_t = 7\Omega$ (b) $r_t = 23\Omega$

Fig.11. Boundaries of stable region taking the leakage inductance $l_1 = l_2$ as a parameter



(a) $r_t = 7\Omega$ (b) $r_t = 23\Omega$

Fig.12. Boundaries of stable region taking the Smoothing capacitance C_o as a parameter



(a) $r_t = 7\Omega$ (b) $r_t = 23\Omega$

Fig.13. Boundaries of stable region taking the magnetizing indactance L_p as a parameter

6. Conclusions

The stability of the buck-boost converter with active-clamp circuit has been examined analytically and experimentally. As a result, the following conclusions have been obtained:

1) The clamp capacitance has a large influence on the oscillatory instability.

2) For a certain value of the clamp capacitance, the stable region becomes minimum.

3) The clamp capacitance and leakage inductance have correlative effects on the converter instability.

4) The clamp capacitance has no effects on the steady-state characteristics and the jumping phenomenon.

The same analysis as above can be applied to the other converters, and it is the future work.

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