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High Efficiency Operation for H-Bridge DC-DC Converter

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Abstract-- **This paper presents two methods of switching operation for higher conversion efficiency and seamless control for wide range of the input voltage in a H-Bridge DC-DC Converter. This converter consists of buck and boost blocks and a feedforward control from the input voltage is employed for the boost block to realize seamless transition between step down and step up operation mode. From the view point of the conduction loss and the switching loss, two methods of the desirable duty ratio of the boost section and different switching frequencies are examined. As a result, higher efficiency was obtained by minimizing the duty ratio of the boost block for wide range of the input voltage and by decreasing the switching frequency of the buck block without increasing output ripple voltage.**

Index Terms—**H-Bridge DC-DC Converter, Feedforward, Efficiency, Frequency**

I. Introduction

Since the terminal voltage of the rechargeable battery such as a Li-Ion type considerably varies depending on the state of its charging condition, electronic circuits in the portable devices often require a power converter having both step-down and step-up functions. An H-bridge DC-DC converter, that is a non-inverting buck-boost converter, is suitable for applications powered by batteries because it works as a buck or a boost converter by controlling two pair of switches. This converter consists of buck and boost blocks, and is generally controlled by the feedback to the buck or the boost block depending on the condition of convergence ratio. It is not easy to design a phase compensation of the feedback controller working both for the buck and boost operations. In addition, large transient voltage appears on the output when the operating mode changes between the buck and boost modes according to the change of input voltage level.

This paper proposes new methods of the switching operation that provides excellent stability over the wide range of the input voltage with keeping higher conversion efficiency by introducing a feedforward control from the input to the boost block. Initially the basic operation and steady state characteristics of the converter are investigated. Based on the analytical result, the feedforward control method from the input voltage to the duty ratio of the boost block is proposed to minimize the conduction loss. The feedforward control also enables the seamless transition between two operating modes for the large variation of the input voltage. Next focusing the switching loss, two different switching frequencies in the buck and the boost blocks are experimentally examined to reduce the switching loss.

II. Steady State Performance

Fig. 1 shows the H-bridge synchronous buck-boost converter with single inductor-capacitor and two pairs of the switches. Switches S_3, S_4 are used for synchronous rectification. Symbols D_1, D_2 and f_1, f_2 designate duty ratios and the switching frequencies of the switch S_1 and S_2, respectively. A pair of switch S_1 and S_3 works as a synchronous buck mode and that of S_2 and S_4 works as a boost mode in this converter.

Fig. 2 shows the timing chart of drive signals of the switch S_1, S_2, the inductor current i_L and the output

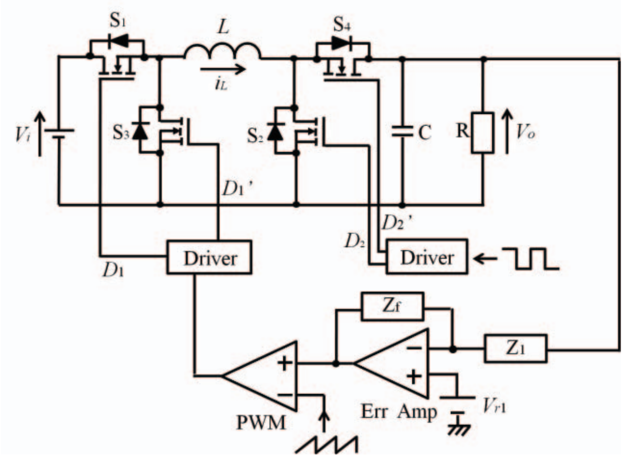

Fig. 1. Circuit configuration of H-bridge buck-boost converter.

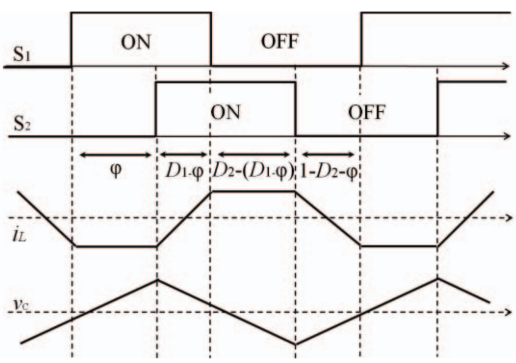

Fig. 2. Timing chart of drive signals, ripple current and voltage.

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ripple voltage v_C. The output ripple voltage of this circuit is synchronized with the switch S_2 in the boost block. For the simplicity of the analysis, it is assumed that both switch are driven with same frequency in this paper.

Applying the state-space averaging method, the following state equation is obtained.

$$\frac{d\bar{\mathbf{x}}(t)}{dt} = \boldsymbol{A}\bar{\mathbf{x}}(t) + \boldsymbol{b}V_i \qquad (1)$$
$$v_O = \boldsymbol{C}\bar{\mathbf{x}}$$

$$\bar{x}(t) = \begin{bmatrix} \bar{i}_L(t) \\ \bar{v}_C(t) \end{bmatrix}, \quad \boldsymbol{A} = \begin{bmatrix} -\frac{r}{L} & -\frac{(1-D_2)\alpha}{L} \\ \frac{(1-D_2)\alpha}{C} & -\frac{\alpha}{CR} \end{bmatrix}$$

$$\boldsymbol{b} = \begin{bmatrix} \frac{D_1}{L} \\ 0 \end{bmatrix}, \quad \boldsymbol{C} = [(1-D_2)\alpha r_C \quad \alpha], \quad \alpha = \frac{R}{R + r_C}$$

$$r = 2r_S + r_L + (1-D_2)\alpha r_C$$

where symbols r_S, r_C and r_L designate the on resistance of the switches, ESR of the capacitor C and the resistance of the inductor winding, respectively. From the dc analysis of (1), the dc output impedance Z_O is expressed by (2). Neglecting all internal resistances of the circuit, the steady-state output voltage and inductor current are expressed as follows.

$$Z_O = \frac{r}{(1-D_2)^2\alpha} \qquad (2)$$

$$V_O = \frac{D_1}{1-D_2}V_i \qquad (3)$$

III. Steady State Caracteristics

Power loss of DC-DC converters is mainly divided by the switching loss and the conduction loss. It is seen from the analytical results that the dc output impedance, that is proportional to the conduction loss, increases with the duty ratio D_2. Then two approaches for realizing higher efficiency are carried out as follows.

A. *Control method of boost block*

Fig. 3 shows the conduction loss calculated from (2) for the load current taking D_2 as a parameter. It is obvious that D_2 should be as small as possible for minimizing the conduction loss. On the other hand, the output voltage is determined both by duty ratios D_1 and D_2 independently as shown by (3). This means that the output voltage can be regulated with the feedback to the buck block by properly adjusting the duty ratio D_2 even when the input voltage V_i is lower than the output voltage V_O. For stable operation by normal voltage mode control in this converter, this paper proposes a feedforward control from the input voltage to the boost block shown in Fig. 4 to adjust D_2 so that the buck block can regulate the output voltage by the feedback in wide range of the input voltage. In order to maintain higher efficiency by feedback controlling the buck block, D_2 should be kept small as possible. For this purpose, in the range of the input voltage from slightly higher than the output to its possible lower operating voltage, D_2 is adjusted by the feedforward signal from the input voltage through the feedforward control circuit so that D_1 in the steady state stays at a certain value such as 0.8 or 0.9 for example. This means that when the maximum duty ratio of D_1 in the steady state is assigned as D_{1m}, D_2 is determined as follows.

$$D_2 = 1 - \frac{V_i}{V_o}D_{1m} \qquad (5)$$

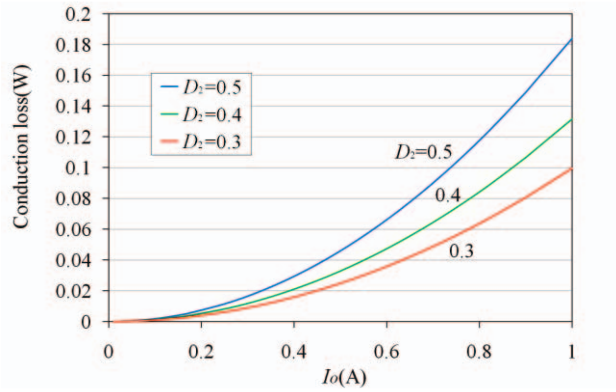


Fig. 3. Conduction loss for load current taking D_2 as a parameter (V_i=V_O=3.3 V)

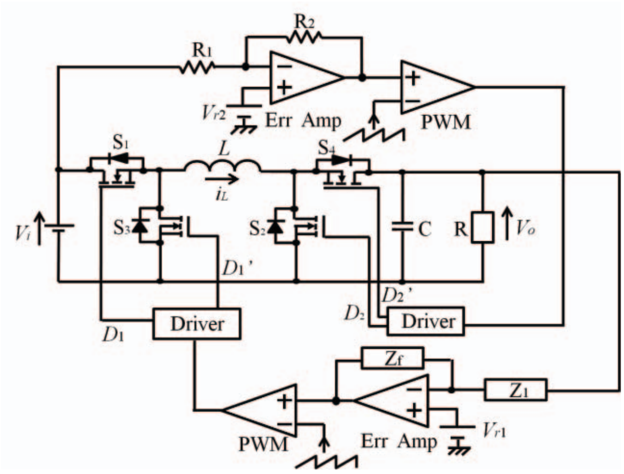


Fig. 4. Circuit configuration of H-bridge buck-boost converter with feedforward control.

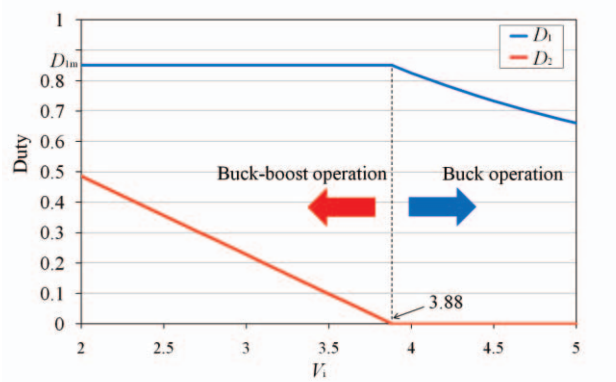


Fig. 5. Duty ratios D_1 and D_2 for input voltage.

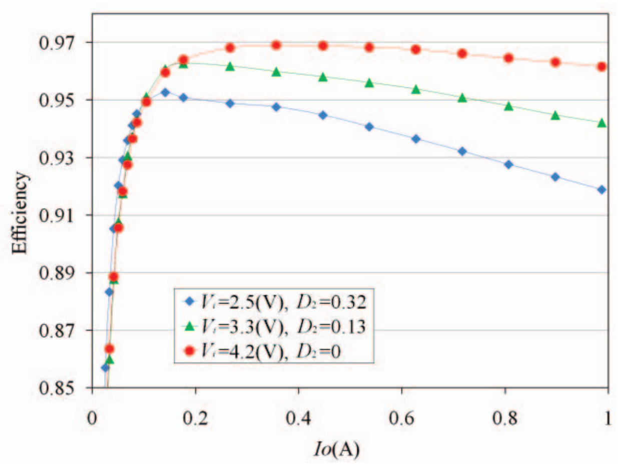


Fig. 6. Conversion efficiency for load current taking V_i as a parameter.

TABLE I
Circuit parameters used in experiments

Input voltage	V_i	2.5, 3.3, 4.2V
Output voltage	V_O	3.3V
Switching frequency	f	1MHz
Output capacitor	C_O	47μF
Inductor	L	6μH
Direct inductor resistance	r_L	25mΩ
On resistance (FET:S_1~S_4)	r_S	14mΩ
Output capacitor ESR	r_C	3mΩ

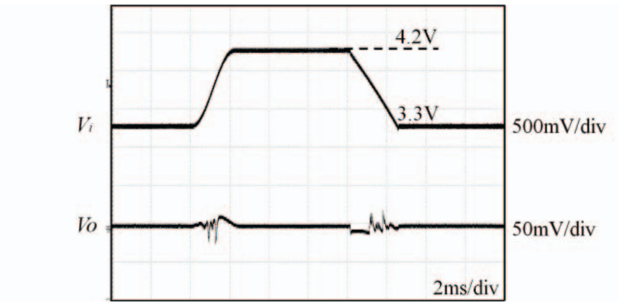
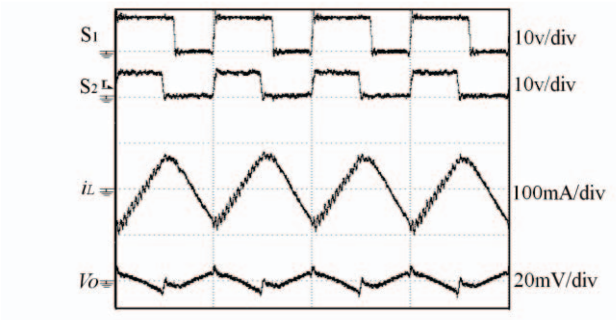
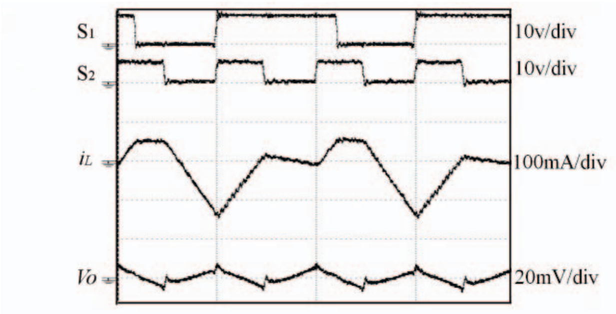


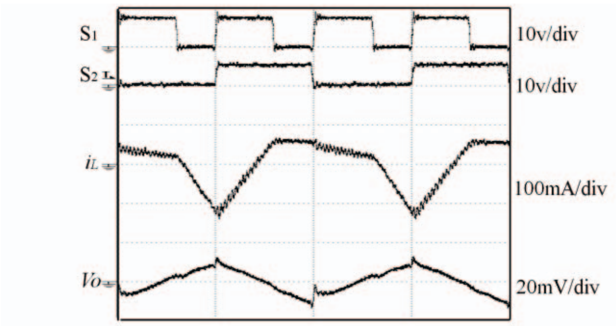
Fig. 7. Transient output voltage for the change of input voltage.



(a) f_1=1 MHz, f_2=1 MHz



(b) f_1=500 kHz, f_2=1 MHz



(c) f_1=1 MHz, f_2=500 kHz

Fig. 8. Waveforms of the inductor ripple current and output ripple voltage.

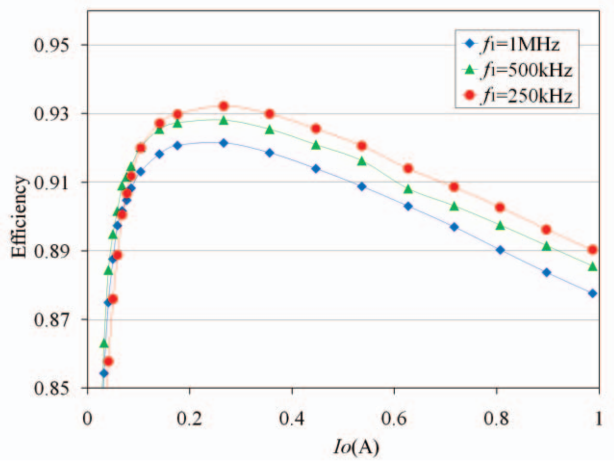
Fig. 5 shows the variations of duty ratios D_1 and D_2 for the input voltage when D_{1m} is set 0.85. Fig. 6 shows the conversion efficiency for the load current taking V_i as a parameter with using circuit parameters listed in Table 1. As can be seen from these results that good maximum efficiencies higher than 95 % are achieved from the input voltage of 2.5 V to 4.2 V for the 3.3 V of the output voltage.

Fig. 7 shows the output transient voltage for the large variation of the input voltage. Smaller than 1 % of the transient peak voltage is observed. The feedforward control proposed in this paper realizes seamless transition between step down and step up operation mode for the change of the input voltage.

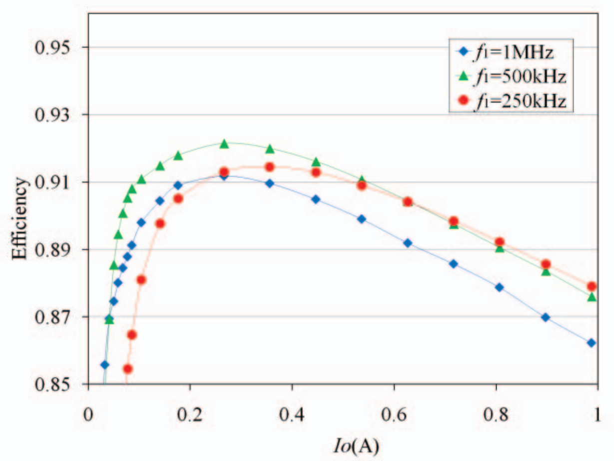
B. Switching frequency

It is known that the higher switching frequency reduce the size of the LC filter and the output ripple voltage while the switching loss increases. Since the H-bridge dc-dc converter can be operated with different switching frequencies for both blocks with keeping the basic characteristics as a buck-boost converter, two different switching frequencies are examined here by focusing the efficiency and the output ripple voltage. Fig. 8 shows experimental waveforms of the inductor ripple current and the output ripple voltage when the switching frequency f_1 of the switch S_1 is (a) equal to f_2 of the switch S_2, (b) a half of f_2 and (c) double as f_2. The load current is 0.1 A. As described before, the output ripple voltage only follows the action of the switch S_2 in the boost block and is almost independent of the state of the switch S_1 in the buck block. Therefore the output ripple voltage is the same with the case that both switches operate at the same switching frequency.

Fig. 9 shows experimental results of the efficiency for the load current when the duty ratio D_2 is fixed at 0.5 taking the switching frequency f_1 of the switch S_1 as a parameter. In this figure, the input voltage V_i is (a) lower than the output voltage V_O, and (b) higher



(a) V_i=2.5 V, f_2=1 MHz (D_2=0.5)



(b) V_i=4.2 V, f_2=1 MHz (D_2=0.5)

Fig. 9. Conversion efficiencies for load current taking f_1 as a parameter.

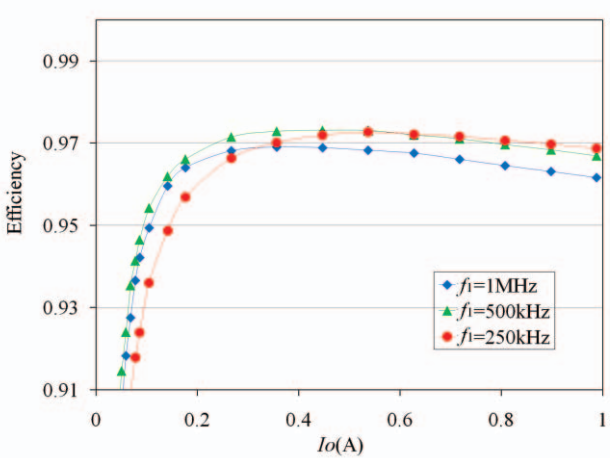


Fig. 10. Conversion efficiencies for load current taking f_1 as a parameter with feedforward control to boost block.

Than V_O. No increase of the output ripple voltage is observed in these experiments. The lower switching frequency provides higher efficiency in both cases. However, the efficiencies with 1/4 of f_1 in the light load condition became lower compared to that same with f_1. This is because of the increase of the ripple current passed through the switches. From these

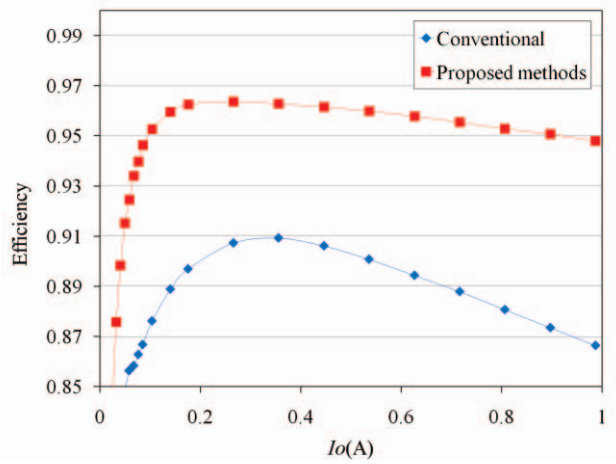
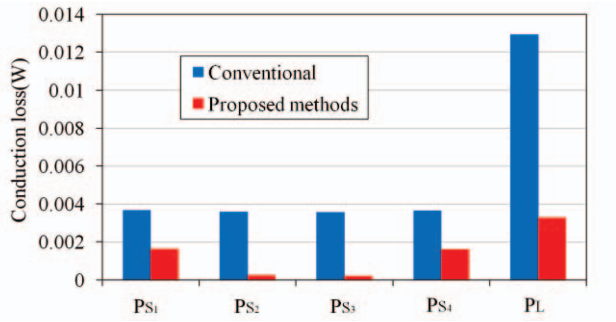


Fig. 11. Comparison of conversion efficiency for load current at 3.3 V of the input voltage.

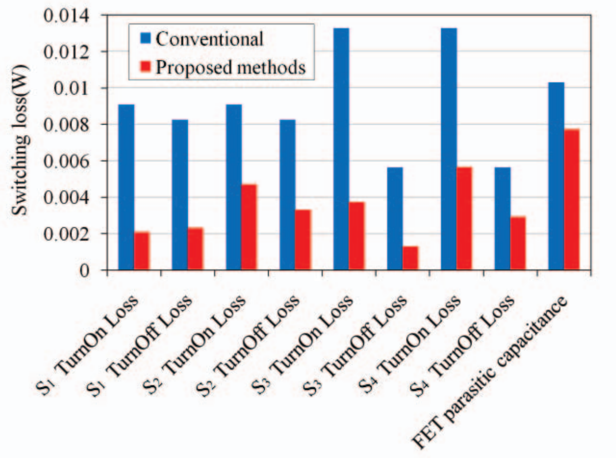
experiments, a half of the switching frequency in the buck block is reasonable to obtain better efficiency for wide range of the input voltage and of the load current. Fig. 10 shows experimental results of the efficiency for the load current taking the switching frequency f_1 of the switch S_1 as a parameter when the boost block is operated by the feedforward control from the input voltage. The effectiveness of two methods, i.e., the feedforward control and the different switching frequency, is observed in this figure.

C. Analysis of losses

Fig. 11 shows the comparison of the efficiency between the conventional buck-boost operation and that of proposed methods when the input voltage is same with the output voltage. Both cases are the buck-boost mode of operation. The experiment in the conventional method was carried out by synchronizing S_1 and S_2 with the same duty ratio. It is seen from this result that overall efficiency is greatly improved by employing proposed methods. Power loss at the maximum load current with proposed method is decreased to 34 % compared with the conventional one. Fig. 12 shows the calculated results of the conduction and switching losses of each element at the load current of 0.35 A. These losses are calculated by using theoretical current and voltage with parameters provided by data sheets. Of the conduction loss in (a), losses of the switch S_2 and S_3 are extremely reduced. The improvement of the conduction loss is manly contributed by the feedforward control method. For the switching loss, on the other hand, the lower switching frequency operation in the buck block also contributes to reduce it. The total losses are summarized in Fig. 13 where the improvements of 75 % and 60 % of the losses are accomplished.



(a) conduction loss



(b) switching loss

Fig. 12. Calculated conduction and switching losses in each element

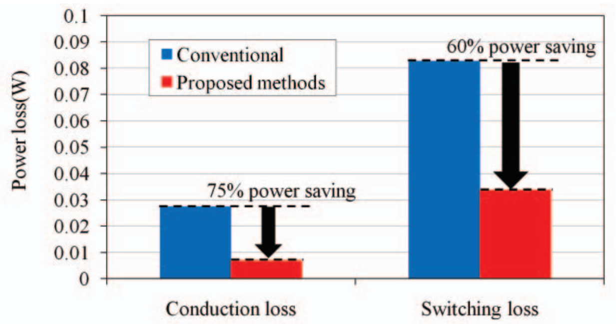


Fig. 13. Total amount of conduction and switching losses.

IV. CONCLUSIONS

This paper has proposed two operation methods for H-bridge DC-DC converter to obtain higher efficiency without spoiling the stable feedback control and the output ripple voltage. A feedforward control from the input voltage to the boost block provides better efficiency with stable operation for wide range of the input voltage. The parameters of the feedforward controller are easily designed by applying the theoretical result in III. In addition, changing the switching frequency of the buck block to a half of the boost block also improves the efficiency.

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