A HIGH POWR FACTOR CONVERTER WITH ZERO CURRENT SWITCHING

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ABSTRACT

In this paper, we propose an improved high power factor converter that can be performed with the Zero Current Switching both at turn-on and turn-off. Moreover, in order to reduce the third harmonics, the modulated switching frequency control will be investigated theoretically and experimentally.

1. INTRODUCTION

Diode rectifier circuits with large smoothing capacitors in the dc output terminals flow out numerous harmonic currents into the ac source and they cause the serious interferences. In order to reduce their harmonics and improve the power factor, several high power converters have been already proposed(1). A boost converter with only a switching device into the usual diode rectifier can be regarded as one of the simplest high power converters. Though the switching speeds for devices tend to be increased recently to improve them effectively, it may cause the new serious trouble, that is, the electro-magnetic interference. It is caused by that the device currents have remarkably larger di/dt because the hard switching must be applied at turn-on and turn-off.

Though the reduction of switching frequency has been proposed(2), it is a more effective countermeasure to employ the soft switching such as Zero Current Switching (ZCS) or Zero Voltage Switching (ZVS) at turn-on and turn-off. Even if the discontinuous conduction control is employed to the usual boost converter, the soft switching at turn-off is impossible though the ZCS operation can be performed only at turn-on(3). In this paper, we propose the improved converter where the ZCS operation also at turn-off can be performed by adding only the resonant circuit into the conventional boost converter(4).

The application of the discontinuous conduction control cannot be avoid increasing the third harmonics in the input ac current as compared with the continuous conduction control. In order to improve the above problem, the modulated switching frequency control will be proposed moreover in this paper. The effects of the proposed control will be investigated theoretically and then discussed by experiments.

2. CIRCUIT CONSTRUCTION AND PERFORMANCES

2.1 Circuit construction

Fig.1 shows the circuit construction proposed in this paper. The basic circuit is the same as the usual boost converter, where a switching device S with a reverse diode Ds, a boost reactor Ls and a blocking diode Db are added to the diode rectifier D_1-D_4 with a smoothing capacitor Cd on the output dc terminals. A resonant circuit enclosed with dotted lines in Fig.1 is connected to the device S in parallel. It is consisted of a resonant capacitor Cr and a resonant reactor Lr. The ordinary boost converter must employ a snubber circuit to protect the device S. The proposed circuit can be obtained by exchanging the snubber circuit for the resonant circuit only. A reactor Lf and a capacitor Cf are the ac filter.

2.2 Application of discontinuous conduction control

In order to control for the ordinary boost converters, two schemes have been proposed. One is the continuous conduction control in which the reactor current i_L should be controlled so as to follow the reference sine wave. It is comparatively easy to obtain the input ac current with the almost sinusoidal wave and to obtain the higher power factor. This scheme, however, is forced to become the complex system because the current sensor must be attached to detect i_L and it is moreover necessary to add the comparators and so on into the control circuit.

The other scheme is the discontinuous conduction control as shown in Fig.2. If the device S is turned on

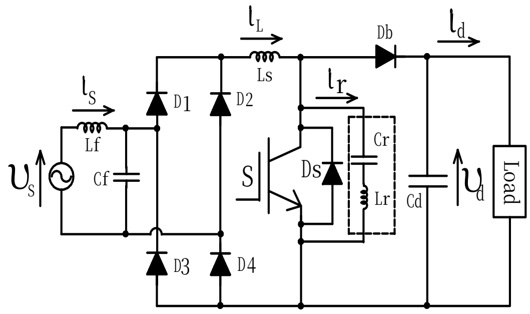


Fig.1 Circuit construction.

during i_L=0, the reactor current i_L becomes the discontinuous waveform consisted of the numerous sharp triangles. The input ac current can be reformed to be continuous by the ac filter. The system composition in this scheme is simpler as compared with the former scheme because the current sensor, the comparators and so on are unnecessary. Therefore, we will apply the latter control scheme into the proposed converter.

In this scheme, the ZCS operation at turn-on can be easily performed, because i_L increases from zero current. When turned off in the conventional converter, however, the device S must cut off the maximum peak current of i_L. The device may have the heavy stress and furthermore the electro-magnetic noise might be possibly emitted such as the former control scheme. Therefore, it is preferable that the ZCS operation can be performed also for the turn-off. The proposed circuit can be replied to this request.

2.3 Circuit performance in proposed converter

The control scheme for the proposed circuit is quite the same as the ordinary discontinuous conduction control. The reactor current i_L becomes the same discontinuous triangles as Fig.2. The resonant current ir from Cr and Lr flows simultaneously with the turn-on of device S.

Fig.3 shows the oscillogram of the enlarged waveforms for i_L and ir. By comparing both currents, the circuit performance can be divided to the following five modes. The dc current id flows continuously from the smoothing capacitor Cd through the whole modes.

Mode A: When the device S is turned on during i_L=0, i_L increases rapidly on the straight from zero. The resonant current ir flows through Cr-S-Lr simultaneously. After the direction of ir is alternated, the device S can be turned off naturally when i_L=ir.

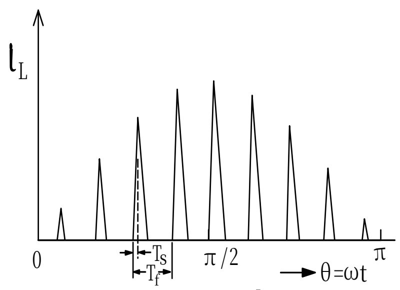
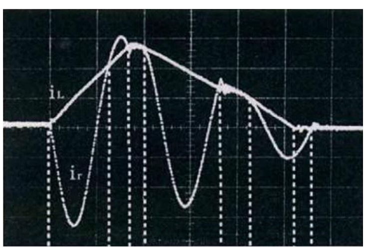


Fig.2 Discontinuous conduction control.



Mode: A B C D C D E

Fig.3 Oscillogram of i_L and ir.

Mode B: After the device S is turned off, both currents i_L and ir can be continued to flow through the reverse diode Ds because i_L<ir. The control signal into the device S should be shut off during this mode. After ir decreases, the diode Ds can be turned off naturally when i_L=ir again. Thus, the ZCS operation can be completed.

Mode C: i_L flows into the resonant circuit and charges Cr. When the resonant circuit voltage Vr exceeds the dc capacitor voltage Vd, the blocking diode Db can be turned on and the circuit mode shifts to the next.

Mode D: i_L flows into the dc smoothing capacitor Cd through Db and reduces on the straight. The resonant current ir flows also into Cd through Db, because i_L>ir, and it can be formed as the oscillated wave. When i_L=ir again, Db must be turned off and the circuit mode returns to Mode C. By the oscillation of Vr, Mode C and Mode D are repeated alternately.

Mode E: When i_L falls to zero in Mode D, the circuit shifts to this mode. The resonant current ir only flows through Db and the stored energy in resonant circuit is transmitted into Cd. Db is turned off when ir=0 and the whole circuit modes have been completed.

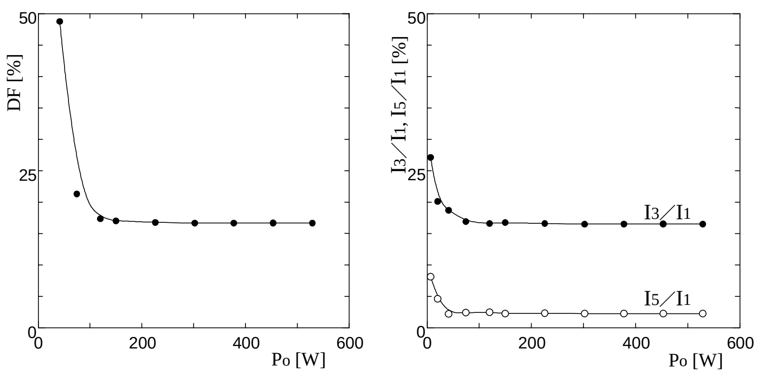
3. THEORETICAL DISCUSSIONS FOR BASIC CONTROL

3.1 Approximation for reactor current i_L

We will discuss theoretically the characteristics of proposed converter under the following assumptions.

1. Switching device and diodes are ideal, that is, forward drops and switching losses are negligible.
2. The smoothing capacitor Cd has so large capacitance that the dc output voltage can be regarded as ripple free.
3. Resistances of the reactors and the capacitors can be negligible.

Though the circuit performance is divided into five modes, the reactor current i_L can be approximated to the following three functions. In Mode A and B, i_L increases by the linear function. It seems in Mode C and D that i_L decreases on the straight approximately as shown in Fig.3. From Mode E until the next Mode A, i_L is no current.



(a) Distortion factor. (b) Harmonic currents.

Fig.4 Calculated input characteristics.

Consequently, i_L can be regarded to be the discontinuous triangle waves approximately. Then the input ac current i_S can be obtained as the continuous waveform by considering the ac filter performance.

3.2 Calculated results

The conducting period Ton of device S should be constant because it depends on the resonant frequency. The device S is turned on at every interval Tf that is basically constant for the phase angle θ. This control will be called as "the basic control" hereafter. By adjusting Tf, that is, the switching frequency *f*sw, the output power Po can be regulated.

Fig.4 shows the input characteristics calculated under the circuit constants in Table 1. Fig.4(a) is the distortion factor DF of input ac current i_S and Fig.4(b) is the third harmonics I_3 and the fifth harmonics I_5 in i_S for the fundamental component I_1. DF together with I_3/I_1 and I_5/I_1 at the lowest output power reach the larger ratios because I_1 is just a little included. Even if the output power increases, however, DF cannot be enough fallen and becomes steady to the comparative higher level. As a result, TPF reaches only less than 99%. It is the reason that the third harmonic current is included in large quantities even though the fundamental component can be grown. Therefore, it is necessary to cancel principally the third harmonics from the reactor current i_L.

In order to cancel the above third harmonics, it can be considered to superpose inversely the third harmonics into i_L. The circuit construction, however, is forced to be complicated because the current sensor and the inverse third harmonics generator must be attached. This countermeasure spoils the simplicity of proposed converter. Accordingly, we will propose an effective method to change only the control scheme without extra equipments in the next section.

4. THEORETICAL DISCUSSIONS FOR IMPROVED CONTROL

4.1 Modulated switching frequency control

Respective triangle peak values of i_L are proportional to the instantaneous source voltage. Therefore, it is supposed that the density around θ=π/2 in Fig.2 is too much so as to make the sinusoidal wave as far as the switching interval Tf is constant for the phase angle θ. If Tf around π/2 can be extended, that is, the switching frequency *f*sw=1/Tf can be reduced, as compared with the other phase angle, it is expected to lower the density around π/2 and to decrease the third harmonics.

The improved control scheme to realize the above idea is proposed in Fig.5. The device S should be turned on by the switching frequency *f*sw(θ) that is modulated for the phase angle θ as follows:

$$fsw(\theta) = f\,\mathrm{max} \times \left(1 - m\left|\sin\theta\right|\right) \qquad (1)$$

Where *f*max is the maximum frequency at θ=0 or π. m means the modulation factor and it equals the amplitude of sine wave frequency *f*m(θ) in proportion to the full-wave rectified source voltage as shown in Fig.5.

By applying the above function instead of the constant switching frequency, the density around θ=π/2 in i_L can be diminished. This control scheme will be called as "the modulated switching frequency control" hereafter. The average switching frequency *f*av for the above *f*sw(θ) can be obtained as follows:

$$fav = f\,\mathrm{max} \times \left(1 - \frac{2\times \mathrm{m}}{\pi}\right) \qquad (2)$$

By adjusting *f*av, the output power Po can be regulated.

4.2 Discussion for the modulation factor m

We will discuss theoretically the effect of the above control. Fig.6 shows the calculated characteristics for the modulation factor m under the same circuit constants as Table 1. The third harmonics can be decreased in haste by increasing m, as shown in Fig.6(a), as expected. As the fifth harmonics shown have the same properties, the distortion factor DF can be also reduced when the higher m is employed, as shown in Fig.6(b). As a result, the higher total power factor TPF near to the unit can be obtained by increasing m, as shown in Fig.6(c).

If employed m more than the optimum value m_O, they must be rapidly grown worse because the density around θ=π/2 becomes too scanty for the appropriate. The modulation factor should be selected so as to keep the lowest DF and the highest TPF. Consequently, the

Table 1 Circuit constants.

source voltage Vs	100 [V]
filter reactor Lf	3.0 [mH]
filter capacitor Cf	3.2 [μF]
boost reactor Ls	50.0 [μH]
dc smoothing capacitor Cd	4700 [μF]
resonant frequency fr	100 [kHz]
output voltage Vd	200 [V]

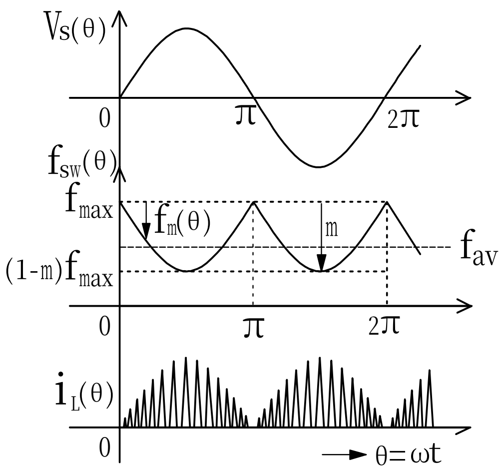


Fig.5 Modulated switching frequency control.

optimum modulation factor m_O for the above condition can be obtained from 0.6 to 0.7 approximately.

5. EXPERIMENTAL RESULTS

5.1 Characteristics for modulation factor

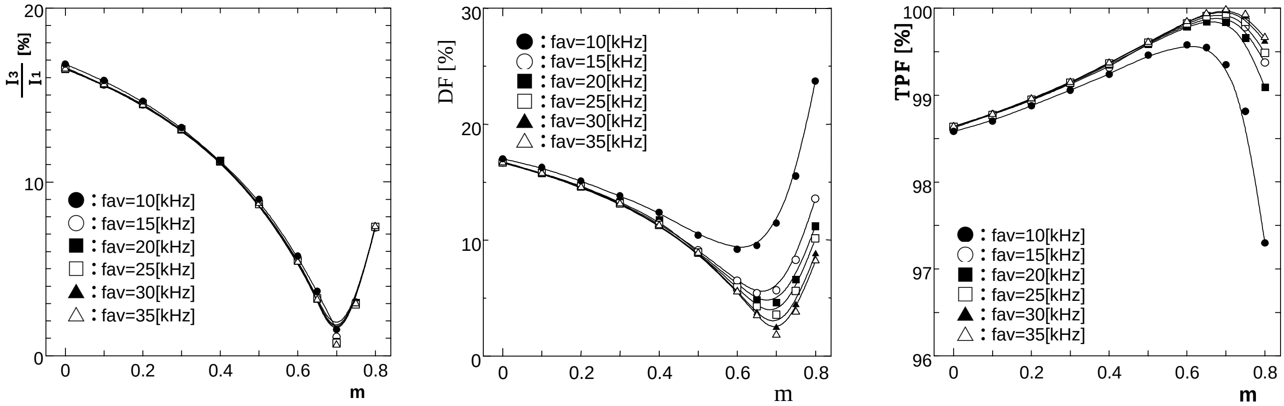
Fig.7 shows the measured characteristics for the modulation factor m under the same circuit constants as Table 1. In comparison with Fig.6, it is made clear that they have the same characteristics as the theoretical results. That is, the distortion factor DF together with the third harmonics I_3 can be fallen sharply until the optimum modulation factor m_O. The total power factor TPF near to the unit can be also obtained around mo. By these experimental results, m_O can be selected from 0.6 to 0.65, which is almost the same as the theoretical m_O. Thus, it can be ascertained experimentally that the modulated switching frequency control is effective for reducing the third harmonics and obtaining the higher power factor.

Though the output power Po can be regulated by *f*av, it must be varied by m also. Po is gradually decreased by increasing m, as shown in Fig.8. Therefore, the average switching frequency must be heightened than *f*sw in the basic control, corresponding with m=0 in Fig.8, in order to output the same larger power from the converter operating under $m=m_O$.

5.2 Characteristics for the resonant frequency

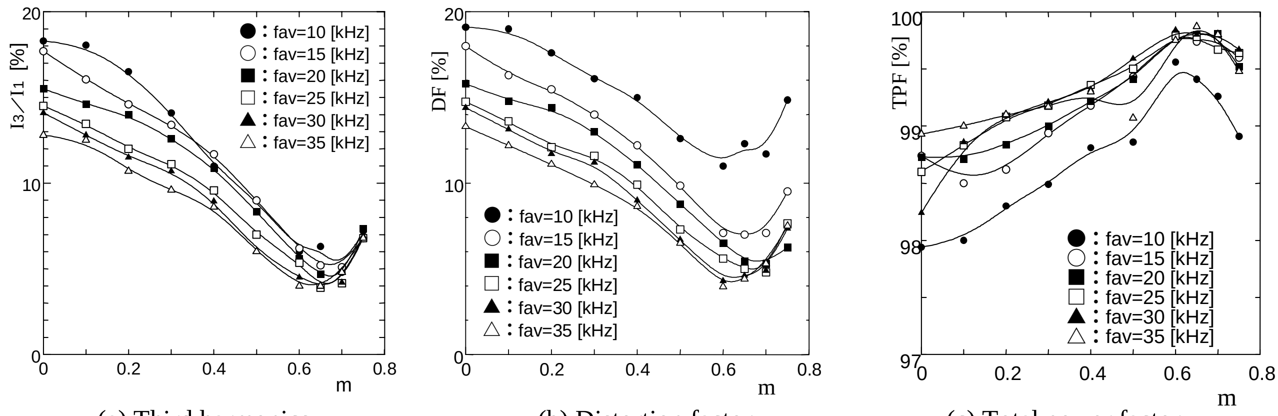
Next, we will discuss the effect of resonant frequency to the proposed converter. The conducting period Ton of the switching device S must be changed for the different resonant frequencies. The boost reactor Ls also should be adjusted so as to maintain the same peak value of i_L. Table 2 shows the proper circuit constants satisfied with the above conditions for the various resonant frequencies.

Fig.9 shows the measured characteristics of distortion factor DF on the several input power Pin for the resonant frequency *f*r obtained by Table 2. The other constants are the same in Table 1 and m is kept to 0.6 or 0.65. Though DF can be decreased by applying the higher *f*r, it becomes to be almost constant more than 150 kHz. The output power Po on the several *f*r can be regulated almost in proportion to *f*av shown in Fig.10, where *f*av is normalized with *f*r. The larger Po can be obtained by selecting the higher *f*r until 200kHz. By both figures, the resonant frequency should be selected as 200 kHz.



(a) Third harmonics. (b) Distortion factor. (c) Total power factor.

Fig.6 Calculated characteristics for m.



(a) Third harmonics. (b) Distortion factor. (c) Total power factor.

Fig.7 Measured characteristics for m.

The oscillograms of input ac current at *f*r=200kHz, operating under the circuit constants obtained in Table 2, are shown in Fig.11. The other parameters are the same in Table 1. Fig.11(a) shows on the basic control, and Fig.11(b) is on the modulated switching frequency control at m=0.6. It is made clear in comparison with both figures that the proposed control is considerably effective for reducing the current harmonics and the input ac current with almost sinusoidal waveform can be obtained.

6.CONCLUSION

In this paper, the improved boost converter and the effective control scheme have been proposed. It can be performed the ZCS operations both at turn-on and turn-off. By applying the modulated switching frequency control, the proposed converter can be decreased the harmonic currents and obtained the higher power factor.

If the exceedingly high average switching frequency, however, is selected to output the larger power, the ZCS operation at turn-on cannot be practiced, because the reactor current changes to be continuous and the zero current period must be disappeared. It is necessary to improve the above problem in order to magnify the output power. We will make it clear in the future.

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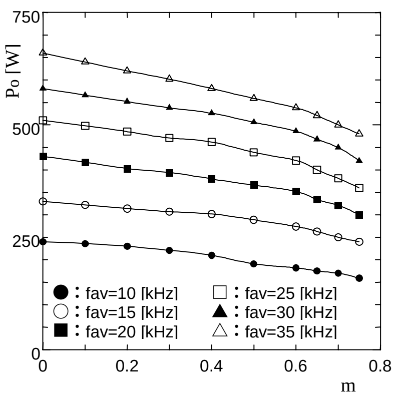


Fig.8 Measured characteristics of Po for m.

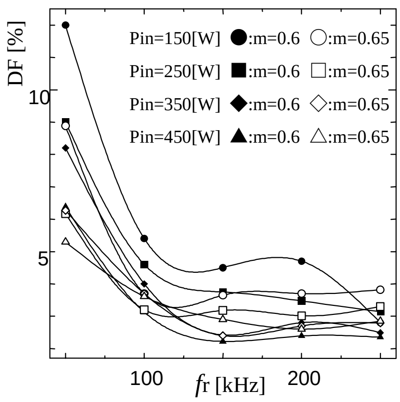


Fig.9 Measured characteristics of DF for *f*r.

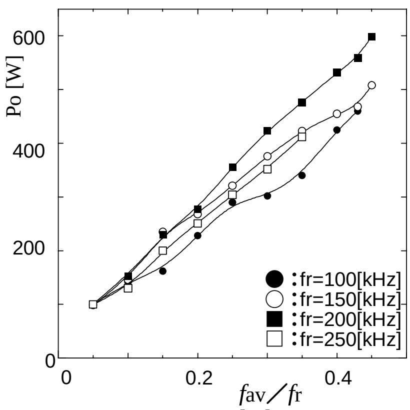
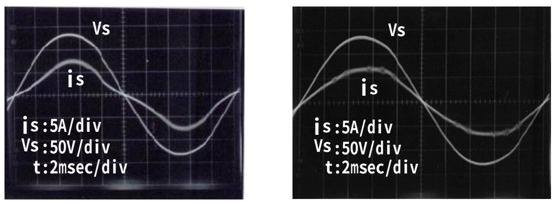


Fig.10 Measured characteristics of Po for *f*av.

Table 2 Circuit constants for various resonant frequencies.

resonant frequency fr [kHz]	50	100	150	200	250
resonant reactor Lr [μH]	25.3	8.44	5.60	4.22	3.38
resonant capacitor Cr [μF]	0.40	0.30	0.20	0.15	0.12
boost reactor Ls [μH]	143.8	50.0	35.5	25.3	20.5
conducting period Ton [μs]	15.0	7.5	5.0	3.75	3.0



(a) Basic control. (b) Proposed control.

Fig.11 Oscillograms of input ac current.