Paper

An Electronic Ballast Using Modified Two-Switch Boost Converter

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ABSTRACT

This paper proposes a modified two-switch boost converter with high power factor, and makes a report concerning the application of it to electronic ballast. First, the behavior of the boost converter with two switching devices is analyzed and experimental results will be shown. The experimental results show that the circuit can decrease the harmonic distortion of the input current like a former boost converter. But the problematic points possessed by the circuit are to be scrutinized. Next, a modified boost converter circuit that can improve the problem is proposed. The proposed circuit has both function of boost chopper and charge pump. The experimental results show that the circuit can improve the power factor.

Lastly, it is shown that these two switching devices can be used not only as active switches of the modified boost converter but also as active switches of a half-bridge type inverter for fluorescent lamp. As a result, it is revealed that the harmonic distortion of the input current obtained by the proposed electronic ballast sufficiently satisfies the maximum limit of IEC 1000-3-2 class C. And the electronic ballast realized the high power factor of 0.99.

1. Introduction

Today, the high frequency inverters are widely used in the electronic ballast for fluorescent lamps because of small size, lightweight and high efficiency. For the electronic ballast, resonant inverters are utilized to providing fluorescent lamps with high-frequency current having stabilized sinusoidal waves. From this reason, capacitor-input-type DC smoothing circuits have conventionally been used on the inlet. However this has resulted in occurrence of some trouble in generation of harmonic distortion. To evade such difficulty, international standards restricting harmonic current have been established (IEC1000-3-2). Especially, in connection with illuminant equipment, a target value is very strict.

To satisfy the target, countermeasures such as installation of power factor correction (PFC) circuits on the input portion side have been taken. However demerits have been pointed out with such a matter of the circuits that have been complicated than before and with the equipment that have become too large in their size. Such being the case, people's attention has been attracted to development of a variety of one-converter methods allowing both inverter circuit and PFC circuit to be synthesized with an intention of being equipped with common

components^{1)~5)}.

This paper proposes a two-switch boost converter with high power factor, and makes a report concerning the application of it to electronic ballast. Paying attention to the fact that two switching devices are used for the lamp-lighting inverter circuit in case of half-bridge type, the rectifier circuit and smoothing circuit are employed in a reformed style so that these switching devices will commonly be used for PFC circuit.

2. Basic circuit configuration

Fig. 1(a) Basic circuit configuration.

Fig. 1(b) A two-switch boost converter.

Fig. 1(c) A modified two-switch boost converter.

Fig. 1(d) A former boost converter.

In Fig.1 (a), a schematic diagram of the basic circuit configuration of the proposed electronic ballast is illustrated. In Fig.1(b), another schematic diagram of the boost converter circuit that is taken out from the basic circuit configuration is illustrated. (This circuit shall hereafter be called a two-switch boost converter.) This is a circuit conventionally proposed as a method of dither rectifier⁶⁾, but analysis is made in this paper as a boost converter. Thus the problematic points possessed by the circuit are to be scrutinized. To the subject in question, a circuit to which capacitors and diodes are added for the improvement of the power factor as shown in Fig.1(c) is proposed. (This circuit shall hereafter be called a modified two-switch boost converter.)

The two-switch boost converter circuit is comprised of four diodes, an inductor, two switches, and a smoothing capacitor. Turning the positive and negative voltage of the input voltage into on/off makes it possible to obtain the result the same as that of the former boost converter action shown in Fig.1(d). By employing FET for the switching devices makes it possible to substitute a body diode for the flywheel.

3. Two-switch boost converter circuit

(a) State a (T1:on,T2:off, power source: plus)

(b) State b (T1:off, T2:on/off, power source: plus)

(c) State c (T1:off,T2:on, power source: minus)

(d) State d (T1:on/off, T2:on, power source: minus)

Fig-2 Equivalent circuits for states of behavior

Illustrated in Fig.2(a) - Fig. 2(d) is an equivalent circuit in each state of the two-switch boost converter circuit shown in Fig.1(b). The circuit is composed of two switching devices (T1,T2), 4 diodes (D1,D2,D5,D6), an inductor (L), and a smoothing capacitor (C6).

3.1 Circuit analysis

Combination is available in 6 ways in a circuit state owing to existence of two pieces of On and Off together with plus/minus of AC power source (being concurrently On is impossible with the switching devices), but substantial actions of the circuit are classified into four states shown in Fig.2(d) according to Fig 2(a). Analysis is hereunder made dependent on the equivalent circuit in the individual states.

Fig.3 Behavior of the inductor current

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In Fig.3, illustration is made with a relationship between the inductor current and the switching time in Discontinuous Inductor Current Mode (DICM). Since switching is done at high frequency, let supposition be made that the power source voltage is constant during the individual switching periods. The symbols T_{on} and T_{off} individually indicate the period length in case that the switch is On or Off. On the other hand, the symbols t_{on} and t_{off} individually indicate the period length while the inductor current flows in each state of the switch. Therefore as illustrated in Fig.3, it follows with DICM that $T_{on} = t_{on}$, $T_{off} \geq t_{off}$. Supposition is made in this paper that a duty ratio is constant, it follows that $T_{on} \doteq T_{off}$.

1) State a (T_1 : on, T_2 : off, power source: plus)

The current (i_1) flows through the inductor L in a direction shown in Fig.2(a), and the current increases in proportion to the elapsed time. Supposing that the current at $t=0$ is $i_0=0$, the stored energy (p_{on}) in the inductor L during the period is given as shown below.

$$p_{on} = \frac{L}{2} i_{1p}^2 = \frac{V_{in}^2}{2L} t_{on}^2 \quad (1)$$

2) State b (T_1 : off, T_2 : on or off, power source : plus)

When the circuit is switched, the current (i_2) flows in a direction shown in Fig. 2(b), and the energy is released from the inductor L. Concurrently with this, the smoothing capacitor is boosted. The terminal voltage V_L' of the inductor becomes $V_L' = V_{cs} - V_{in}$. Accordingly the energy (p_{off}) released from the inductor L is given as

$$p_{off} = \frac{V_{in} (V_{out} - V_{in})}{2L} t_{off}^2 \quad (2)$$

where let it be understood that $V_{out} = V_{cs}$.

Also in case that the AC power source shown in Fig.2(c) and Fig.2(d) is negative, it is easily understandable that the same action is made.

3) Input/output power

The input energy (p_n) at the n-th period switched with high frequency can be calculated by the equation shown below.

$$p_n = \int_0^{t_{on}} p_{on}(t) dt + \int_0^{t_{off}} p_{off}(t) dt \quad (3)$$

If the power source voltage at that time is expressed by $V_{in}(t_n) = V_I \sin \omega t_n$, then the input power W_{in} can be expressed as shown below.

$$W_{in} = \sum_{n=0}^f p_n = \frac{V_I^2 \cdot D^2}{2\pi f L} \int_0^\pi \frac{\sin^2 \theta}{1 - a \sin \theta} d\theta \quad (4)$$

$$\text{where } a = \frac{V_I}{V_{out}}, \quad D = \frac{T_{on}}{T_{on} + T_{off}} = T_{on} \cdot f.$$

Meanwhile supposing that the load resistance is R, an equation is established as shown below.

$$W_{in} = \frac{V_I^2 \cdot D^2}{2\pi f L} \int_0^\pi \frac{\sin^2 \theta}{1 - a \sin \theta} d\theta = \frac{W_{out}}{\eta} = \frac{V_{CS}^2}{\eta R} \quad (5)$$

From the above equation, another equation can be obtained as shown below.

$$\int_0^\pi \frac{a^2 \sin^2 \theta}{1 - a \sin \theta} d\theta = \frac{2\pi f L}{\eta R D^2} \quad (6)$$

where η indicate the efficiency, and a shows the ratio of the maximum power source voltage to the output voltage. Furthermore a takes a value less than 1. It is perceived that the boost action of the two-switch boost converter circuit fundamentally exhibits the behavior the same as that of the former boost converter circuit.

4) Input power factor

When the power source voltage is expressed by $V_{in}(t_n) = V_I \sin \omega t_n$, the average current $I_{ave}(t_n)$ at the said cycle is given as shown below.

$$I_{ave}(t_n) = \frac{\frac{1}{2} i_p(t_n) \cdot (t_{on} + t_{off})}{T_{on} + T_{off}} = \frac{T_{on}^2 V_{out} V_I \sin \omega t_n}{2L(T_{on} + T_{off})(V_{out} - V_I \sin \omega t_n)} \quad (7)$$

If the value of $I_{ave}(t_n)$ is in proportion to the power source voltage at each cycle, then it is permissible to state that accomplish of the power factor 1 can be made. Suppose the constant of proportionality is α . Then

$$I_{ave}(t_n) = \frac{DT_{on} V_{out} V_I \sin \omega t_n}{2L(V_{out} - V_I \sin \omega t_n)} = \alpha V_I \sin \omega t_n \quad (8)$$

Converting the above into an equation concerning T_{on} makes it possible to do expression as shown below.

$$T_{on} = \frac{2\alpha}{D} \left(1 - \frac{V_I}{V_{out}} \sin \omega t_n\right) \quad (9)$$

It is comprehended from the equation referred to above that in heightening the power factor, it is necessary to lengthen the application period of the switch when the power source voltage is low. It is likewise comprehended that it is necessary to shorten the application period of the switch when the power source voltage is high. Therefore on the assumption that the duty ratio is constant, it is understood that none of the average value is in proportion to the power source voltage just by applying the input current to a low pass filter. Thus a problem arises that none of sinusoidal wave is formed especially in the vicinity of the low voltage.

3.2 Experimental results of the two-switch boost converter circuit

Fig. 4 Characteristic comparison of the two-switch boost converter(TBC) and an active filter circuit(AFC).

To examine the characteristics of the two-switch boost converter circuit, an experiment was conducted by changing the load current under the condition of the power source voltage 100V and frequency 60Hz. Two power MOSFETs are driven by the gate-driver IC under the condition of the duty ratio 50% as constant. At that time, a low pass filter is installed on the input side of the commercial power source.

In Fig.4, characteristics of the circuits are sketched with the output power (W_{out}) taken on the abscissa and with the input power (W_{in}), output voltage (V_{out}), power factor ($\cos \phi$), and efficiency (η) taken on the ordinate. Description is likewise made with the former boost converter circuit obtained under the same condition. In this connection, the inductor L_1 is $944 \mu\text{H}$, whereas the smoothing capacitor C_s is $20 \mu\text{F}$.

As the value of the load resistance becomes small, output power becomes big and an output voltage decreases so that it may be understood from eq.(5) and eq.(6). And, as for the input power and the output power, it is understood that it is in the relations of the direct proportion. Though efficiency and power factor are below a little in comparison with the former boost converter, it is revealed that the tendency is almost the same as that of the former boost converter is exhibited.

Fig.5 gives exemplification of the input current waves entering the two-switch boost converter. As shown in Eq.(9), it is conceived that an interval where no input current flows is

generated in a region of low power source voltage in the case that the duty ratio is constant.

I:540mA/div, H:2ms/div

Fig. 5 Observed input current waveform of the two-switch boost converter.

4. Modified two-switch boost converter circuit

To compensate the flaw referred to above, proposal is made with a modified two-switch boost converter circuit illustrated in Fig.1(c) where the capacitors C_1 and C_2 together with the diodes D_3 and D_4 are added to the two-switch boost converter circuit. The boost action of the proposed circuit is the same as that of the two-switch boost converter with which explanation is made in the previous chapter. However since the capacitors C_1 and C_2 are respectively inserted to plus and minus voltage of the power source voltage in parallel, the individual capacitors are compelled to repeat charge and discharge in accordance with ON and OFF of the two switches. While each switch is OFF, the boost action is done, and at the same time each capacitor, which copes with a switch, is charged from the power supply. The accumulated charge is discharged to the load in the period that the switch is ON. Charge that couldn't be discharged during the period was discharged completely through the diode that was arranged in parallel to the switch. It is deduced from this that charge by a power source voltage is to be conducted to the capacitors even while the power source voltage is so much low. In other words, each capacitor works as charge pump that repeats charge/discharge by the high frequency switches. By dint of the said charge/discharge current, faults of the former boost converter can be compensated.

I:540mA/div, H:2ms/div

Fig. 6 Observed input current waveform of the modified two-switch boost converter.

Fig. 7 The power factor and the efficiency.

To confirm this action, another experiment was conducted under the condition the same as that in the previous chapter. In Fig.6, an example of the input current waveform onto the modified two-switch boost converter is sketched. It can be confirmed that currents flow even in a region where the power source voltage is so much low. In Fig.7, a result is shown with respect to the comparison between the efficiency and the power factor with both the two-switch boost converter and the modified two-switch boost converter in relation to two types of the capacitors. The case of the two-switch boost converter is expressed with $C1=C2=0$. The inductor $L1$ and smoothing capacitor Cs are the same as those in Fig.4. The power factor and the efficiency in the case of the modified two-switch boost converter were beyond the results obtained in the case of the two-switch boost converter. With the modified two-switch boost converter, the capacity of the capacitors $C1$ and $C2$ is settled to very small values in comparison with the capacity of the smoothing capacitor Cs . From this reason, $C1$ and $C2$ do not, despite the fact that they are engaged in composing a voltage doubler rectifier circuit, actually perform the said action. Thus it is imagined that the capacitors are in action as a so-called charge-pump making charge from the power source voltage and discharge with two switches ON.

5. Application to electronic ballast

The modified two-switch boost converter circuit referred to in the previous chapter is, it seems likely, never liberated from so many of the switching devices in comparison with the boost chopper circuit. However by sharing the two switching devices with a high-frequency inverter, an electronic ballast in accordance with a one-converter method can be realized as a result. The high-frequency inverter used for lighting a fluorescent lamp exhibits a shape of a typical half-bridge method.

5.1 Circuit action

Owing to the states of the individual switches and the directions of input power source, four states can be in consideration corresponding to the movement of the boost

(a) State A ($T1$: on, $T2$: off, power source: plus) (b) State B ($T1$: off, $T2$: on/off, power source: plus) (c) State C ($T1$: off, $T2$: on, power source: minus) (d) State D ($T1$: on/off, $T2$: off, power source: minus)

Fig. 8 Current direction in each state.

converter referred to in the previous chapter. In Fig.8(a) through (d), flows of the current in each state are shown.

1) State A (T_1 : on, T_2 : off, power source: plus)

In this case, not only energy is stored in the inductor of the boost converter, but also power is supplied also from the smoothing capacitor Cs to the load. On the other hand, discharge is made from the capacitor $C1$.

2) State B (T_1 : off, T_2 : on/off, power source: plus)

Onto this state, either case that T_2 is on or off is included. The stored energy in the inductor during state A is released, and the smoothing capacitor Cs is boosted. Concurrently with this, power is supplied also to the load. On the other hand, the capacitor $C1$ is charged with the power source voltage.

3) State C (T_1 : off, T_2 : on, power source: minus)

In this case, current in a direction reverse to the state A flows through the inductor of the boost converter, and energy is stored in the inductor. Concurrently with this, power is supplied from the smoothing capacitor Cs to the load. On the other hand, discharge is made also from the capacitor $C2$.

4) State D (T_1 : on/off, T_2 : off, power source: minus)

To this state, either case of T1 being on or off is included. The stored energy in the inductor during state C is released, and the smoothing capacitor is boosted. Concurrently with this, power is supplied to the load. On the other hand, the capacitor C2 is charged by power source voltage.

5.2 Experimental results

It was confirmed by the experiment that the modified two-switch boost converter referred to in the previous chapter could be applied to the electronic ballast. The power is supplied from 100V AC power line through Low Path Filter. Power MOSFET is used as a switching device that is driven by gate-driver IC with 50% duty cycle. Meanwhile for the diodes D5 and D6 illustrated with the basic circuit configuration in Fig.1 (a), their body diodes are utilized. The fluorescent lamp used as the load is slim-light FLR42T6W. Circuit parameters are the same because it was known that the input power, which is necessary for the lamp lighting, could be supplied from the modified two-switch boost converter. The resonance frequency is approximately 62KHz that was obtained by trial and error.

V:50V/div, I:540mA/div, H:2ms/div

Fig. 9 Observed waveform of input current and input voltage.

Fig. 10 Input current harmonic distortion characteristics.

V:100V/div, H:10μs/div

Fig. 11 Observed waveform of lamp current and lamp voltage.

Fig.9 shows an observed waveform of the current/voltage in the side of the input power source. Without control of duty ratio, pseudo sinusoidal wave comes to be formed, and more than 99% of the input power factor was successfully accomplished. Fig.10 depicts the harmonic distortion characteristics of the input current shown in Fig.9. It turns out that the maximum limits of the harmonic current in IEC 1000-3-2 Class C is sufficiently satisfied. Fig.11 depicts the terminal voltage/current waveform of the fluorescent lamp. It is observed that by means of the resonance of the capacitor Cr and inductor L2, pseudo sinusoidal wave is formed.

6. Conclusion

In the discussion in this paper, the points shown below are explained.

- 1) Analysis of the two-switch boost converter allows the characteristics the same as those of the active filter to be shown. On the other hand, necessity of attainment of higher power factor and duty ratio control was observed.
- 2) The proposal of the modified two-switch boost converter showed the possibility that was effective in the improvement of the input power factor and efficiency.
- 3) The two switching devices of the modified two-switch boost converter were concurrently used with the switching devices of the half-bridge-type lighting circuit, which made it possible, it is shown, to be applied to an electronic ballast in accordance with a one-converter method.
- 4) It is explained by an experiment that the harmonic distortion of the input current to the proposed electronic ballast fully satisfies the limit value of IEC Standards Class C, and power factor high enough to be 99% can be accomplished.

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Appendix: The calculation of the input power to the modified two-switch boost converter

The input energy in k -th period (p_k) can be calculated as follows if power supply voltage is $V_{in}(t_k)$ and the value of $V_{in}(t_k)$ can be assumed to be fixed within k -th period.

$$p_k = \int_0^{t_{on}} p_{on}(t)dt + \int_0^{t_{off}} p_{off}(t)dt = \frac{T_{on}^2 \cdot V_{out}}{2L} \cdot \frac{V_{in}(t_k)^2}{V_{out} - V_{in}(t_k)}$$

When the switching frequency is f , the input power (W_{in}) is calculated as follows.

$$W_{in} = \sum_{k=0}^f p_k = \frac{T_{on}^2 \cdot V_{out}}{2L} \sum_{k=0}^f \frac{V_{in}(t_k)^2}{V_{out} - V_{in}(t_k)}$$

When the commercial frequency is 60Hz, the input voltage within k -th period is expressed as

$$V_{in}(t_k) = V_{in}(k) = V_I \sin(120\pi \frac{k}{f}), \text{ therefore}$$

$$\sum_{k=0}^f \frac{V_{in}(t_k)^2}{V_{out} - V_{in}(t_k)} = 120 \cdot f \sum_{k=0}^{f/120} \frac{V_I^2 \sin^2(\frac{120\pi k}{f})}{V_{out} - V_I \sin(\frac{120\pi k}{f})} \cdot \frac{1}{f}$$

$$\text{If } \frac{120\pi k}{f} = \theta \text{ and } \frac{120\pi}{f} = \Delta\theta,$$

$$\theta = 0 \text{ when } k = 0 \text{ and } \theta = \pi \text{ when } k = f/120.$$

$$\text{Then, } \sum_{k=0}^f \frac{V_{in}(t_k)^2}{V_{out} - V_{in}(t_k)} = \frac{f}{\pi} \int_0^\pi \frac{V_I \sin^2 \theta}{V_{out} - V_I \sin \theta} d\theta$$

$$\begin{aligned} \text{Therefore, } W_{in} &= \frac{T_{on}^2 \cdot V_{out}}{2L} \cdot \frac{n}{\pi} \int_0^\pi \frac{V_I \sin^2 \theta}{V_{out} - V_I \sin \theta} d\theta \\ &= \frac{V_I^2 \cdot D^2}{2\pi f L} \int_0^\pi \frac{\sin^2 \theta}{1 - a \sin \theta} d\theta \end{aligned} \quad (4)$$

$$\text{where } a = \frac{V_I}{V_{out}}, \quad D = \frac{T_{on}}{T_{on} + T_{off}} = T_{on} \cdot f.$$