A Dimming Method for Hot Cathode Fluorescent Lamp Using a Resonant Inverter Operating at Fixed Switching Frequency

Mitsuhiro Kadota, *Member, IEEE*, Hiroyuki Shoji, and Sachio Furuya

***Abstract*—This paper describes a dimming method for hot cathode fluorescent lamp (HCFL) using a resonant inverter operating at fixed switching frequency. The proposed method is based on burst dimming and decreases the inverter output voltage during the burst-off period by changing the switching pattern of the inverter. Consequently, the lamp can be turned OFF, while the filaments of lamp are kept preheated without adding an inverter for preheating. Once the lamp is turned OFF, *N*-times resonant mode (where *N* means a natural number) occurs because the characteristic of the resonant circuit (which depends on lamp impedance) changes drastically. This mode keeps the root mean square of filament currents large enough to ensure long lamp life. Moreover, the inverter operates in zero-voltage-switching resonant mode during both the burst-on and burst-off periods. Experimental results showed that stable burst dimming and preheating characteristics were attained. The proposed method thus contributes to achieving long lifetime, small size, and low cost of lighting system for HCFLs.**

***Index Terms*—Dimming control, electronic ballast, fixed switching frequency operation, fluorescent lamp, resonant inverter, three-times resonant mode.**

I. Introduction

As standard and efficient light source, hot cathode fluorescent lamps (HCFLs) have been applied in various kinds of lighting equipment. For some lighting equipments, HCFLs are still more efficient and lower cost than light-emitting diodes (LEDs), which are receiving attention as new lighting devices. Accordingly, HCFLs seem to coexist with LEDs for the time being, and it is important to improve electronic ballasts for HCFLs in terms of efficiency, size, lifetime, and cost [1].

Resonant inverters have generally been used as the electronic ballasts for HCFLs [2], [3]. A circuit shown in Fig. 1 is one example of the resonant inverters which is called a series-resonant parallel-loaded full-bridge inverter. It realizes high-efficiency operation in zero-volt-switching (ZVS) resonant mode, which can reduce switching losses and noise. In the inverter shown in Fig. 1, a resonant inductor L_r has two auxiliary windings (W_{f1} and W_{f2}) connected to two lamp filaments (R_{f1} and R_{f2}) through two capacitors (C_{f1} and C_{f2}). These components make up simple preheating circuits which supply filaments with preheating currents (i_{f1} and i_{f2}). These currents are necessary to keep the temperature of each filament high enough to ensure long lamp life.

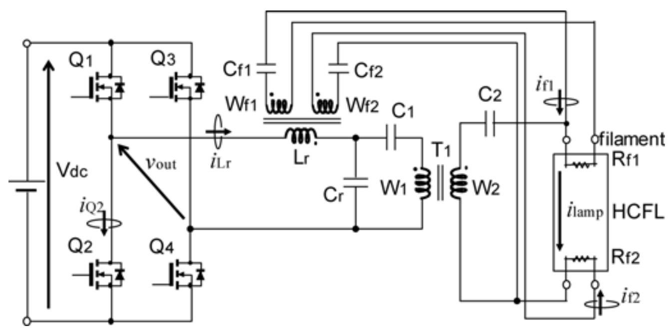

Fig. 1. Circuit configuration of resonant inverter for HCFL.

In a general dimming method for the inverter shown in Fig. 1, lamp current i_{lamp} is controlled by varying the switching frequency of the inverter, which utilizes the characteristic of a resonant load circuit including L_r, a resonant capacitor C_r, and the lamp [4], [5]. As the switching frequency becomes higher, the impedance of resonant load circuit (L_r in particular) increases and the lamp current decreases. Meanwhile, the root mean square (RMS) values of filament currents (i_{f1} and i_{f2}) do not decrease, because the impedances of capacitors C_{f1} and C_{f2} decrease. Consequently, this method keeps filament currents approximately constant over most dimming range, thereby maintaining long lamp life.

To avoid interference between the switching frequency and the operating frequency of other electronic equipment, however, it is sometimes required to fix the switching frequency or to use a much narrower frequency band. For example, when HCFLs are used for the backlight of a large-scale liquid crystal display (LCD), the dimming control system should be designed so that the switching frequency and scanning frequency of the LCD do not interfere with each other. Fixed switching frequency dimming is also effective to further reduce switching losses and noise and to realize a simple control circuit. However, in the case that the switching frequency should be fixed, it becomes impossible to use the dimming method described above.

Several dimming methods with fixed switching frequency, which vary the dc-link voltage or switches duty cycle of the inverter, have been proposed [6]–[9]. These methods, however,

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may have a negative effect on lamp life when they are applied to the inverter shown in Fig. 1 because not only lamp current but also filament currents decrease by dimming. Moreover, not all lighting systems actually allow the dc-link voltage or the switches duty cycle to be varied widely.

Another possible method is called burst dimming, which has been applied to the dimming of cold cathode fluorescent lamps [10], [11]. Burst dimming turns the lamp ON and OFF in the range of approximately 100–1000 Hz, and the ratio of duration where the lamp is ON (burst duty) determines average lamp current. However, using burst dimming for HCFLs requires another inverter to maintain the supply of filament currents during the burst-off period. This addition causes complexity, high cost, and large size of the lighting system.

This paper describes a novel fixed-frequency dimming method which is based on burst dimming. The proposed method does not require an additional inverter for preheating, but it still keeps filament currents above a certain level during the burst-off period. It is effective for cutting cost and size of the lighting system while retaining long lamp life.

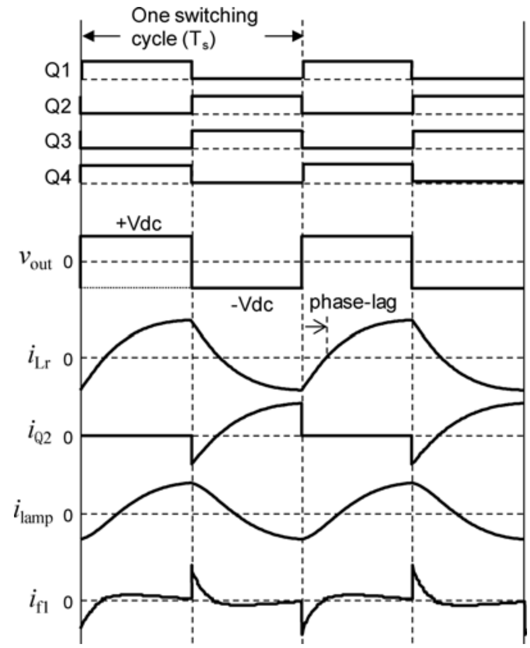

Fig. 2. Expected waveforms of inverter in burst-on period.

II. Proposed Dimming Method

A. Circuit Configuration of Resonant Inverter

The proposed fixed-frequency dimming method, which is based on burst dimming, uses the inverter shown in Fig. 1. Note that it does not involve adding an inverter for preheating the filaments.

The MOSFET switches (Q_1–Q_4) make up a full-bridge inverter, which is fed by a dc-voltage source. The resonant load circuit is connected between the output terminals of the inverter. The main components of the resonant load are resonant inductor L_r, resonant capacitor C_r, and the HCFL (lamp). The lamp and C_r are connected in parallel via boost transformer T_1 and dc-cut filter capacitors (C_1 and C_2). T_1 is used to supply the lamp with high voltage, even if the dc-link voltage is low. T_1 and one of the dc-cut filter capacitors (C_1 or C_2) can be eliminated, depending on the dc-link voltage.

As mentioned above, L_r has two auxiliary windings (W_{f1} and W_{f2}) that compose the filament preheating circuits. Capacitors C_{f1} and C_{f2} regulate the filament currents (i_{f1} and i_{f2}) and reduce their dc components.

B. Full-Bridge Operation During Burst-On Period

As mentioned above, in burst dimming control, the controller turns the lamp ON and OFF periodically at a certain frequency, which is called burst frequency, $f_{\rm burst}$, hereafter. One cycle of burst dimming is divided into burst-on and burst-off periods. During the burst-on period, the inverter supplies the lamp with rated power and keeps lamp current $i_{\rm lamp}$ at a rated value. On the other hand, during the burst-off period, the inverter stops supplying the power and decreases $i_{\rm lamp}$ to almost zero. The ratio of the burst-on period (burst duty) determines average lamp current, that is, dimming level.

During the burst-on period, the full-bridge inverter operates normally. All switches (Q_1–Q_4) are in switching operation at fixed frequency f_s, and the duty cycle of each switch is approximately 0.5. The expected waveforms of circuit voltages and currents over two switching cycles in the burst-on period are shown in Fig. 2. Here, $i_{\rm Q2}$, $V_{\rm dc}$, and T_s $(=1/f_s)$ mean the current through Q_2, dc-link voltage, and inverter switching cycle, respectively. The switching operations of Q_1–Q_4 generate inverter output voltage $v_{\rm out}$ with a square waveform. This voltage gives resonant current i_{Lr} and $i_{\rm lamp}$. The frequency of i_{Lr} becomes the same as that of $v_{\rm out}$. Meanwhile, filament currents i_{f1} and i_{f2} flow by induced voltages across auxiliary windings W_{f1} and W_{f2}.

The inverter operates in ZVS resonant mode if the circuit parameters and switching frequency are designed properly. As shown by the $i_{\rm Q2}$ waveform in Fig. 2, $i_{\rm Q2}$ has a negative value at the instant when Q_2 is turned ON. This indicates that resonant current i_{Lr} flows through the body diode of Q_2 and that the voltage across Q_2 should be almost zero at this instant. Every switch is turned ON under the zero-voltage condition by the same mechanism. In ZVS resonant mode, resonant current i_{Lr} lags inverter output voltage $v_{\rm out}$, as shown in Fig. 2. ZVS resonant mode is, therefore, also called "phase-lag mode." This mode effectively reduces switching losses and noise.

C. Approximate Analysis of the Inverter Operation During Burst-On Period

The equivalent circuit of inverter during the burst-on period is shown in Fig. 3 for approximate analysis. The full-bridge inverter and the lamp are replaced by an ac voltage source and a resistance, respectively. Some of the circuit components in Fig. 1 such as auxiliary windings of L_r (W_{f1} and W_{f2}) can be omitted in this analysis as shown in Fig. 3. In Fig. 3, the voltage $V_{\rm out1}$ represents the RMS value of fundamental component of

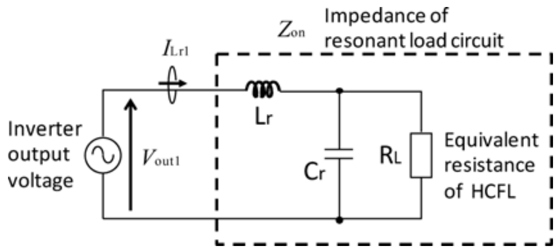

Fig. 3. Equivalent circuit of resonant inverter during burst-on period.

inverter output voltage $v_{\rm out}$, which is given by

$$V_{\rm out1} = \frac{2\sqrt{2}}{\pi} V_{\rm dc} \tag{1}$$

and the resistance R_L is

$$R_L = N_{T1}^2 R_{\rm lamp} \tag{2}$$

where N_{T1} is the turns ratio of boost transformer T_1 (W_1/W_2) and $R_{\rm lamp}$ is the equivalent resistance of lamp which can be gained by the rated lamp current and voltage. The complex impedance of resonant circuit is

$$\begin{aligned} Z_{\rm on}(f) &= j\,2\pi f\,L_r + \left(\frac{1}{R_L} + j\,2\pi f\,C_r\right)^{-1} \\ &= j\,2\pi f\,L_r + \left(\frac{1}{N_{T1}^2 R_{\rm lamp}} + j\,2\pi f\,C_r\right)^{-1} \end{aligned} \tag{3}$$

where *f* means frequency. The current I_{Lr1} in Fig. 3 represents the RMS value of the fundamental component of resonant current, which is given by

$$I_{\rm Lr1} = \frac{V_{\rm out1}}{|Z_{\rm on}|}. \tag{4}$$

The necessary condition for ZVS resonant mode mentioned above is that the inverter switching frequency f_s is higher than the resonant frequency. When the lamp is ON, the resonant frequency mainly depends on L_r, C_r, N_{T1}, and $R_{\rm lamp}$. Hereafter, this frequency is called "on-state resonant frequency," $f_{\rm ron}$. The frequency $f_{\rm ron}$ should be much lower than corner frequency f_{rc}, which is given by

$$f_{rc} = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{5}$$

and should make the argument of impedance $Z_{\rm on}$ zero. However, it is not impossible but complex to formulate the relation between $f_{\rm ron}$ and circuit parameters exactly.

If N_{T1} is small enough that the impedance of C_r can be neglected compared to R_L, the impedance $Z_{\rm on}$ is inductive and able to be approximated as

$$Z_{\rm on} \cong j\,2\pi f\,L_r + R_L = j\,2\pi f\,L_r + N_{T1}^2 R_{\rm lamp}. \tag{6}$$

In this case, the frequency $f_{\rm ron}$ is almost zero and the resonant current lags inverter output voltage. The condition for ZVS resonant mode is, therefore, met regardless of f_s. The approximate RMS value of fundamental component of lamp current during the burst-on period can be calculated easily as ($I_{\rm Lr1}/N_{T1}$) and adjusted only by L_r and N_{T1}.

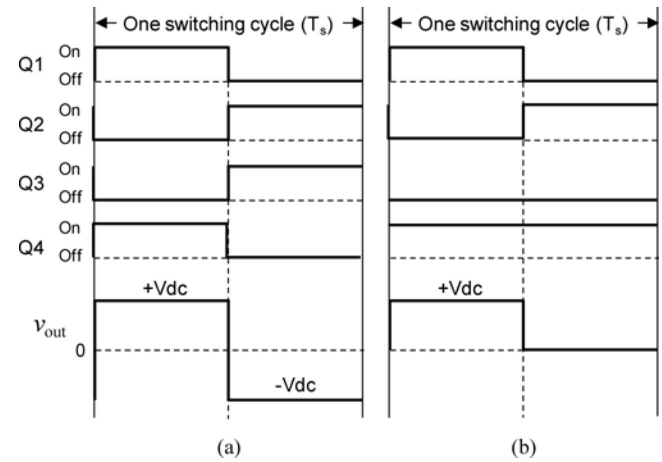

Fig. 4. Inverter switching patterns and inverter output voltages in(a) burst-on and (b) burst-off periods.

D. Single-Ended Push–Pull Operation During Burst-Off Period and Problem Concerning Phase-Lead Mode

During the burst-off period, the proposed method decreases the RMS value of inverter output voltage $v_{\rm out}$ by changing the inverter switching pattern, instead of stopping the switching operation of all switches (Q_1–Q_4). Examples of the switching patterns and inverter output voltages over one switching cycle in the burst-on and burst-off periods are shown in Fig. 4. As shown in the figure, during the burst-off period, only Q_1 and Q_2 (switches in one leg of the full-bridge inverter) keep switching at the fixed frequency, while Q_3 and Q_4 (switches in the other leg) maintain off-state and on-state, respectively. This switching pattern in the burst-off period shown in Fig. 4(b) makes the inverter operate as a single-ended push–pull (SEPP) inverter and decreases inverter output voltage $v_{\rm out}$ by half. The lamp becomes less able to remain on-state, and lamp current decreases to almost zero because of drastic decrease of $v_{\rm out}$. However, filament currents i_{f1} and i_{f2} keep flowing because the inverter keeps operating and $v_{\rm out}$ is not zero. Changing the switching pattern in this manner enables dimming control without need for an additional inverter.

There is, however, a difficulty in operating the inverter even in the burst-off period. That is, when the lamp is turned off, lamp impedance increases drastically and reaches an almost infinite value. Resonant frequency then becomes higher than $f_{\rm ron}$ and gets closer to corner frequency f_{rc}. The resonant frequency under the condition that the lamp is off is hereafter called "off-state resonant frequency," $f_{\rm roff}$, which mainly depends on L_r, C_r, C_{f1}, C_{f2}, and impedances of the lamp filaments. If $f_{\rm roff}$ is higher than the inverter switching frequency f_s and the necessary condition for phase-lag mode described above is not met, the inverter may operate in phase-lead mode. Expected waveforms over two switching cycles in the burst-off period and in the case that the circuit parameters are not properly designed (so

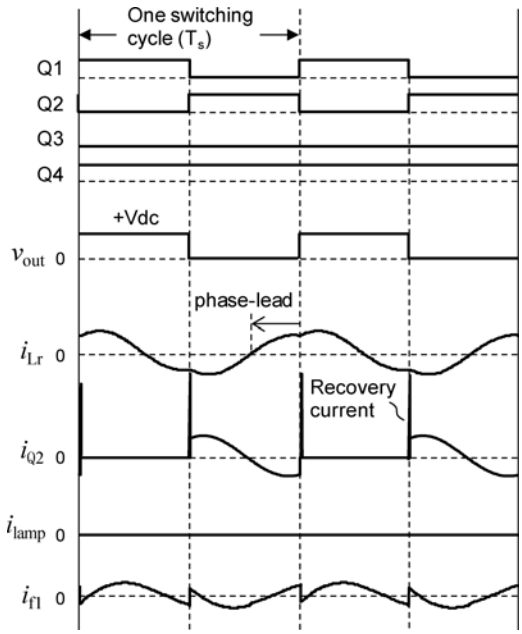

Fig. 5. Expected waveforms of inverter in burst-off period and phase-lead mode.

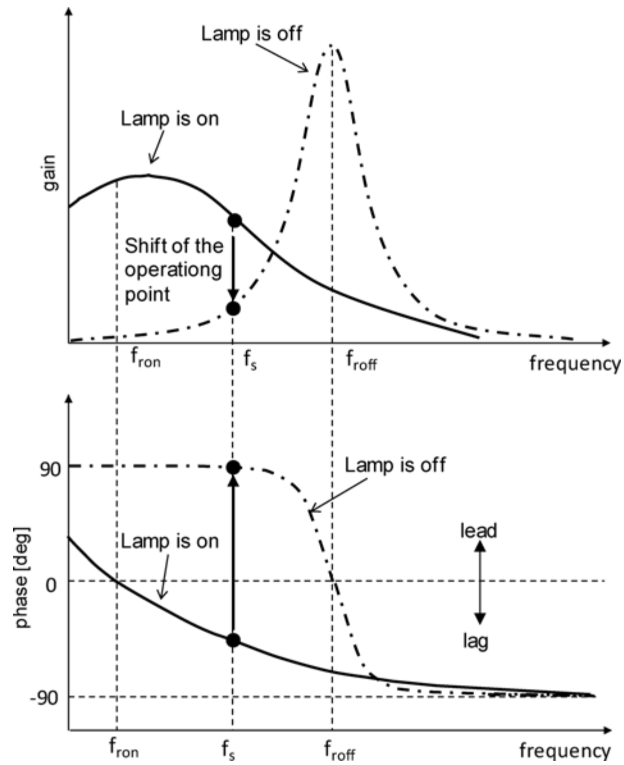

Fig. 6. Image of frequency transfer characteristics of resonant load circuit in the case that phase-lead mode occurs.

the inverter operates in phase-lead mode) are shown in Fig. 5. As mentioned above, only Q_1 and Q_2 are in switching operation, and Q_3 and Q_4 are kept OFF and ON, respectively. In phase-lead mode, resonant current i_{Lr} leads inverter output voltage v_{out}. At the instance when switch Q_2 turns ON, a large current (which results from the recovery of Q_1's body-diode) flows through Q_1 and Q_2, thereby increasing switching losses seriously. This mode should, therefore, be avoided.

The image of frequency transfer characteristics of the resonant load circuit is shown in Fig. 6. In this figure, the input and output of the resonant load circuit are considered to be inverter output voltage v_{out} and resonant current i_{Lr}, respectively. The solid line and dashed line represent the characteristics in the cases that the lamp is ON and OFF, respectively. The arrows in Fig. 6 indicate the shift of the operating point when the lamp is turned OFF. It is clear that the operating point of the inverter moves into the phase-lead mode region when the lamp is turned OFF.

E. N-Times Resonant Mode for Maintaining ZVS Operation During Lamp-Off Period

A proper design of circuit parameters, especially C_r, is effective to overcome the problem concerning phase-lead mode mentioned above. The expected waveforms in the case that the lamp is OFF and off-state resonant frequency f_{roff} is designed to be higher than the value that results in phase-lead mode are shown in Fig. 7. According to the figure, frequency of the resonant current i_{Lr} is three times higher than inverter switching frequency. This operation mode is, thus, called "three-times resonant mode," which is a kind of *N*-times resonant mode or *N*th-order resonant mode (where *N* is a natural number) [12]. The waveforms in the figure also indicate that the inverter operates in ZVS resonant mode because i_{Q2} has a negative value at the instant when Q_2 is turned ON.

The image of frequency transfer characteristics of the resonant load circuit in the case that three-times resonant mode emerges is shown in Fig. 8. This figure indicates the reason that this mode occurs as follows. The square waveform of inverter output voltage v_{out} contains not only the fundamental component (whose frequency is equal to inverter switching frequency f_s) but also a third-harmonic component (whose frequency is $3f_s$), which is the source that generates three-times resonant mode. These two components are input to the resonant load circuit and result in two frequency components of resonant current i_{Lr}. As shown in the gain characteristic plotted in the upper graph of Fig. 8, gain at f_s is by far smaller than that at $3f_s$. The f_s component of resonant current i_{Lr} is, therefore, decreased drastically and only the $3f_s$ component appears as clearly as shown in Fig. 7. The phase characteristic plotted in the lower graph of Fig. 8 shows that the $3f_s$ component of i_{Lr} lags inverter output voltage v_{out}. These characteristics of the $3f_s$ component keep the inverter operation in ZVS resonant mode. When the lamp is turned OFF, the imaginary operating point is moved as shown by the arrows in Fig. 8 even though the inverter switching frequency is exactly fixed at f_s.

There is another advantage of three-times resonant mode. Because the impedances of capacitors in preheating circuits (C_{f1} and C_{f2}) become 1/3 smaller, the RMS values of filament currents can be kept at a sufficient value for preheating even though the inverter output voltage v_{out} decreases by half.

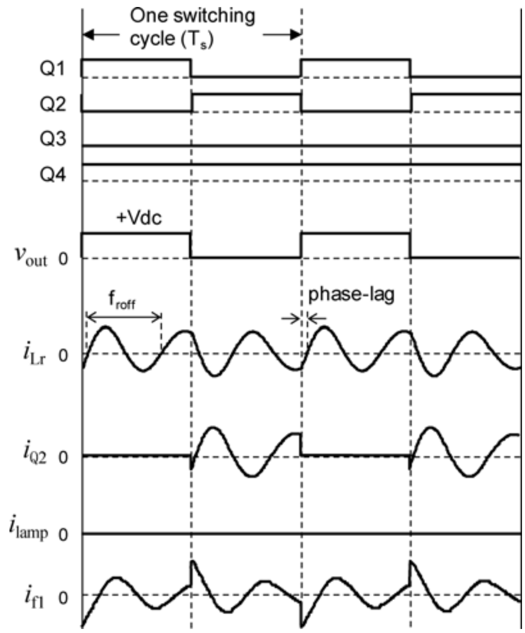

Fig. 7. Expected waveforms of inverter in burst-off period and three-times resonant mode.

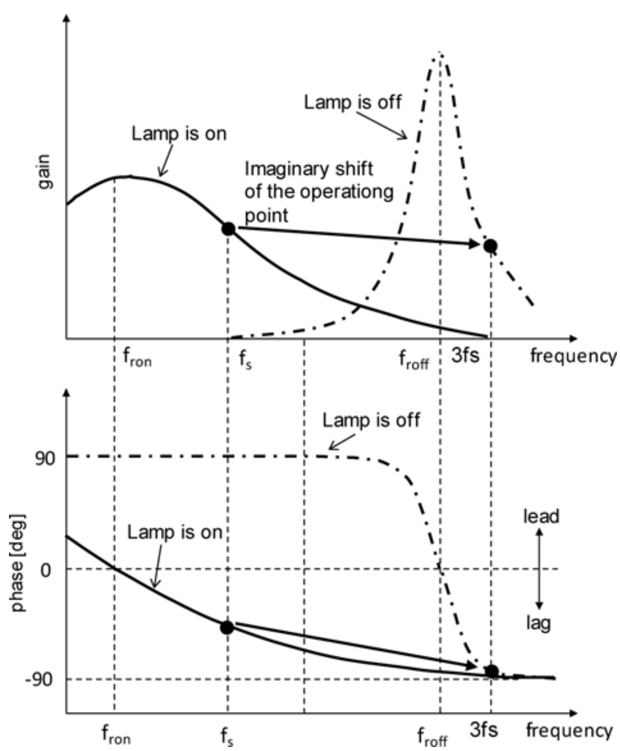

Fig. 8. Image of frequency transfer characteristics of resonant load circuit in the case that three-times resonant mode emerges.

The waveform of i_{Lr} in Fig. 8 indicates that the condition for three-times resonant mode depends on the relation between f_s and f_{roff}, which is given by

$$\frac{f_{\mathrm{roff}}}{3} < f_s < \frac{f_{\mathrm{roff}}}{2}. \tag{7}$$

TABLE I
PARAMETERS OF CIRCUIT AND CONTROLLER

Item (Symbol)		Value
DC-link voltage (V_{dc})		24 V
Burst dimming frequency (f_{burst})		120 Hz
Inverter switching frequency (f_s)		58 kHz
Resonanat inductor (with air-gap of core)	Inductance of primary winding (L_r) *	26 μH
	Inductance of auxiliary windings (W_{f1},W_{f2}) *	2.5 μH
	Coupling coefficient	0.86
Resonanat Capacitor (C_r)		22 nF
Boost transformer (T1)	Turns ratio ($N_{T1} = W_1/W_2$)	1/12 (=0.0833)
	Inductance of primary winding *	290 μH
DC-cut filter capacitor at primary side (C_1)		1 μF
DC-cut filter capacitor at secondary side (C_2)		0.22 μF
Capacitors for preheating circuit (C_{f1},C_{f2})		20 nF

*Inductance values are measured under the condition where the frequency is 10 kHz.

If the impedances of filament preheating circuits are much higher than that of resonant inductor L_r and can be neglected, f_{roff} is almost equal to the corner frequency f_{rc}. The capacitance C_r is useful to adjust f_{roff} and attain the three-times resonant operation. The capacitance C_r can vary f_{roff} without affecting the RMS value of the lamp current during the burst-on period as analyzed above. It is difficult and complex to calculate f_{roff} and desirable C_r for the three-times resonant mode theoretically. C_r was actually adjusted through a process of trial-and-error in the experimental verification mentioned in the following section.

III. Implementation and Experimental Verification

A. *Designing Inverter System and Circuit Parameter*

The proposed dimming method was applied to a lighting system for a 20-W-T5 prototype lamp. The rated lamp current and voltage of that lamp were about 200 mA and 100 V, respectively. The rated filament current of the prototype lamp was about 80 mA. Table I lists the parameters of the inverter circuit and controller used in this experiment. A stable dc power supply was used to generate dc-link voltage V_{dc}, which was set to 24 V. This voltage reflects application of the proposed method to the LCD back-lighting system, which has a front-end power supply. Burst frequency f_{burst} was set to 120 Hz, considering that flickering of the lamp should not appear and that a practical dimming range could be obtained. Too high f_{burst} causes a narrow dimming range actually because the lamp current gradually decreases after transition from burst-on to burst-off period. The inverter switching frequency f_s was fixed at 58 kHz considering the sizes and losses of circuit components such as MOSFET switches (Q_1–Q_4), the resonant inductor L_r, and the boost transformer T_1.

Resonant parameters L_r and C_r were designed based on the analysis of the inverter in the previous section and through the trial-and-error. The inductance L_r was, at first, set to 26 μH considering that the RMS value of the lamp current during the burst-on period should be about 200 mA. As shown in Table I, the transformer T_1 required relatively small turns ratio ($N_{T1} = 1/12$) in order to start up the lamp because of the low dc-link

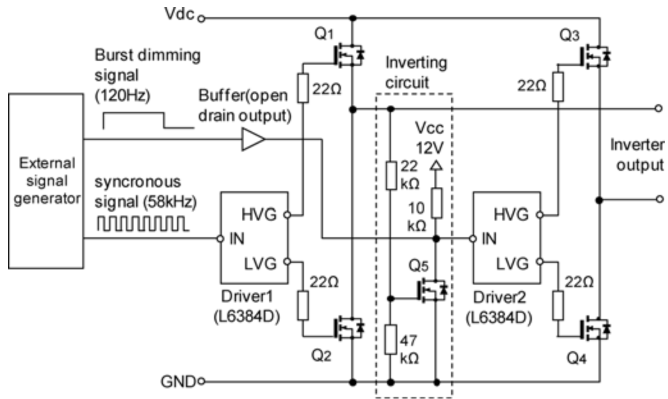

Fig. 9. Circuit configuration of a dimming controller.

voltage ($V_{\rm dc} = 24$ V). Therefore, the impedance of C_r could be neglected and the RMS value of the lamp current mainly depended on L_r as mentioned in the previous section. Next, C_r was set to 22 nF in order to attain the three-times resonant operation during the burst-off period. C_r was designed based on (7), measuring the off-state resonant frequency $f_{\rm roff}$ appeared in the waveform of resonant current i_{Lr} during the burst-off period by an oscilloscope. Finally, the RMS values of filament currents were adjusted by the inductances of auxiliary windings ($W_{f1} = W_{f2} = 2.5$ μH), that was, turns ratio of resonant inductor and capacitances ($C_{f1} = C_{f2} = 20$ nF).

B. Implementation of the Proposed Dimming Method

The dimming controller was designed to output gate drive signals for the MOSFET switches (Q_1–Q_4) according to a dimming control signal and a synchronous signal from an external signal generator. The high and low levels of the dimming control signal corresponded to burst-on and burst-off periods, respectively. The synchronous signal was used as the reference signal for driving switches (Q_1–Q_4), and the frequency and duty cycle of this signal were set at 58 kHz and 0.5, respectively. The dimming control signal and the synchronous signal were also used as trigger signals in measuring waveforms by the oscilloscope.

The circuit configuration of the dimming controller designed for this experiment is shown in Fig. 9. In the dimming controller, two half-bridge drivers were connected in cascade via an inverting logic circuit. Each of the drivers was L6384D model by ST Microelectronics. These two drivers configured a full-bridge driver although quite a short delay appeared between their operations. During the burst-off period only, the gate signals of Q_3 and Q_4 were kept OFF and ON forcibly, and the inverter operated in SEPP mode, as shown in Fig. 4(b).

C. Experimental Results

Burst dimming waveforms of the dimming control signal, inverter output voltage $v_{\rm out}$, lamp current $i_{\rm lamp}$, and filament current i_{f1} at different burst duties are shown in Fig. 10. Burst duty means the duty cycle of the dimming control signal, that is, the dimming level. Two sets of waveforms at different burst duty are shown in Fig. 10. The waveform of $v_{\rm out}$ showed the effect of the proposed control which decreased $v_{\rm out}$ in the burst-off period. The lamp current $i_{\rm lamp}$ flowed only in the burst-on period. The filament current i_{f1} flowed and kept preheating filament even in the burst-off period.

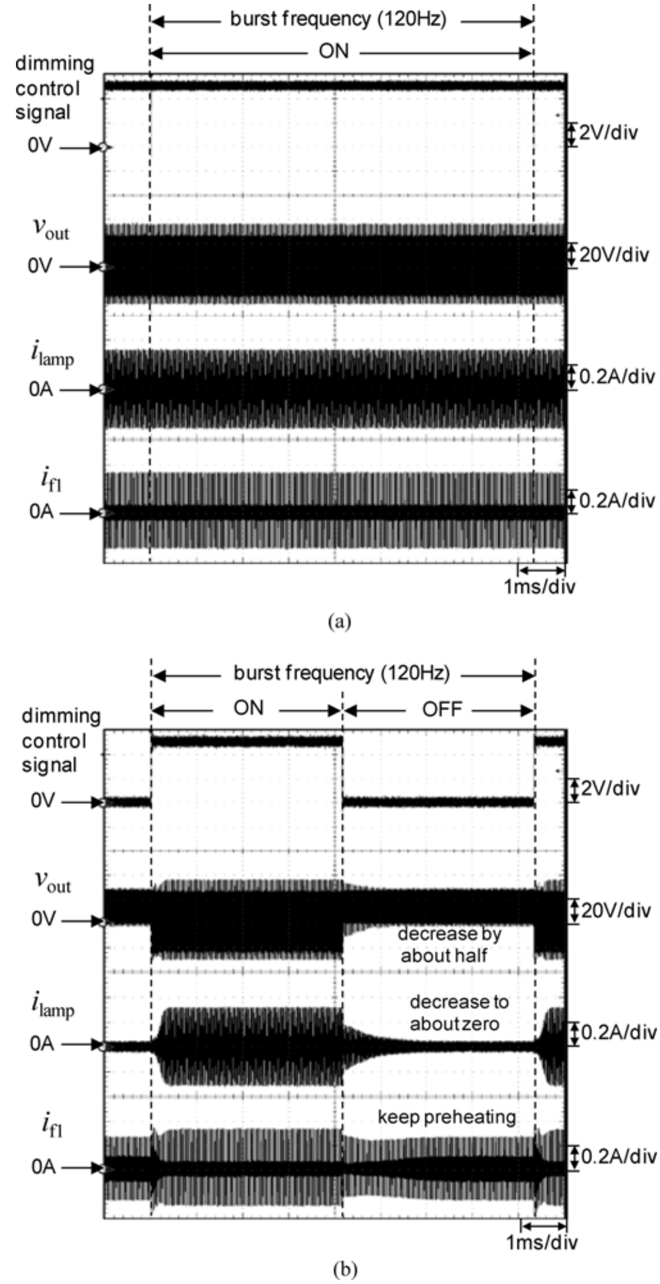

Fig. 10. Burst dimming waveforms of the proposed method. (a) burst duty 100%. (b) burst duty 50%.

Fig. 11 shows the relation between the burst duty and average lamp current over one burst cycle. The average lamp current decreased from 205.5 to 52.6 mA by varying the burst duty from 100% to 10%. The minimum value (52.6 mA) was less than 30% of the rated lamp current. Fig. 12 shows the relation between the burst duty and average filament current over one burst cycle.

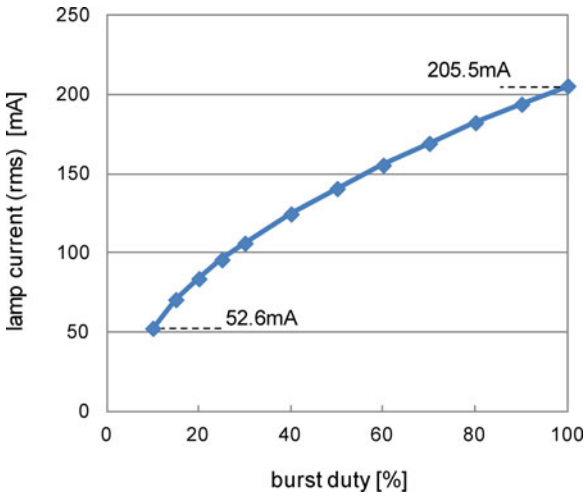

Fig. 11. Relation between burst duty and average lamp current.

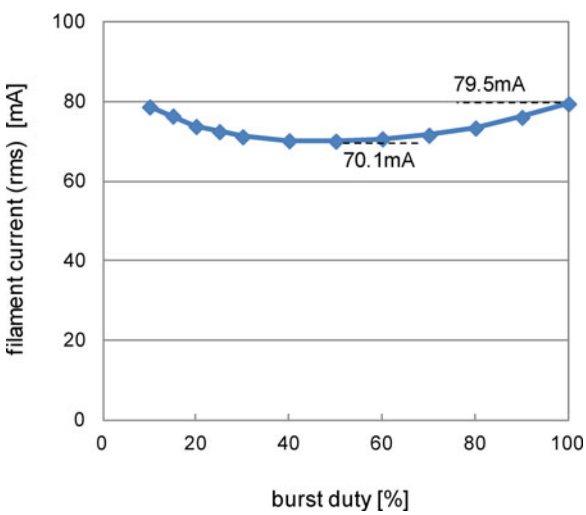

Fig. 12. Relation between burst duty and average filament current.

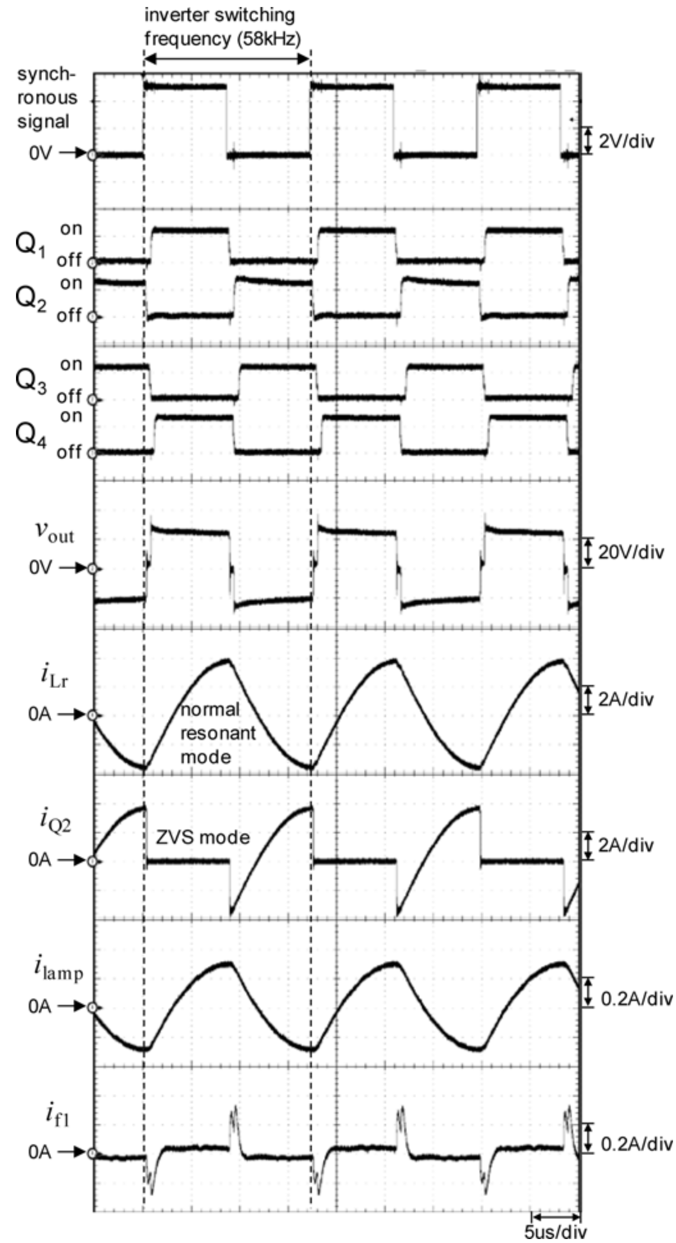

Fig. 13. Waveforms in burst-on period.

The average filament current was kept in the range from 70.1 to 79.5 mA and did not decrease in proportion to the burst duty.

Figs. 13 and 14 show the waveforms of the synchronous signal, ON–OFF states of switches Q_1–Q_4, v_{out}, i_{Lr}, the current flowing through the switch Q_2 (i_{Q2}), i_{lamp}, and i_{f1} in the burst-on and burst-off periods, respectively. Note that the "time/div" scales of these figures differ from that of Fig. 10. Figs. 13 and 14 verified the expected waveforms shown in Figs. 2 and 7, respectively. According to Fig. 14, in the burst-off period, the three-times resonant mode occurred and the frequency of i_{Lr} was three times higher than the inverter switching frequency. It was also shown that the inverter operated in ZVS resonant mode during both the burst-on and burst-off periods. It was verified from experimental results that the inverter was controlled properly by the proposed method and the stable dimming control and preheating filaments were obtained.

The waveform of i_{Lr} in Fig. 14 showed that the off-state resonant frequency f_{roff} was 162 kHz, which was used to design the inverter switching frequency $f_s = 58$ kHz. These frequencies met the condition for three-times resonant mode (7). f_{roff} was lower than the corner frequency f_{rc}, which was about 210 kHz calculated from (5) using the resonant parameters $L_r = 26$ μH and $C_r = 22$ nF. It was thought that the impedances of filament preheating circuits, the leakage inductance of L_r, and the parasitic capacitance of boost transformer T_1 might lower f_{roff}.

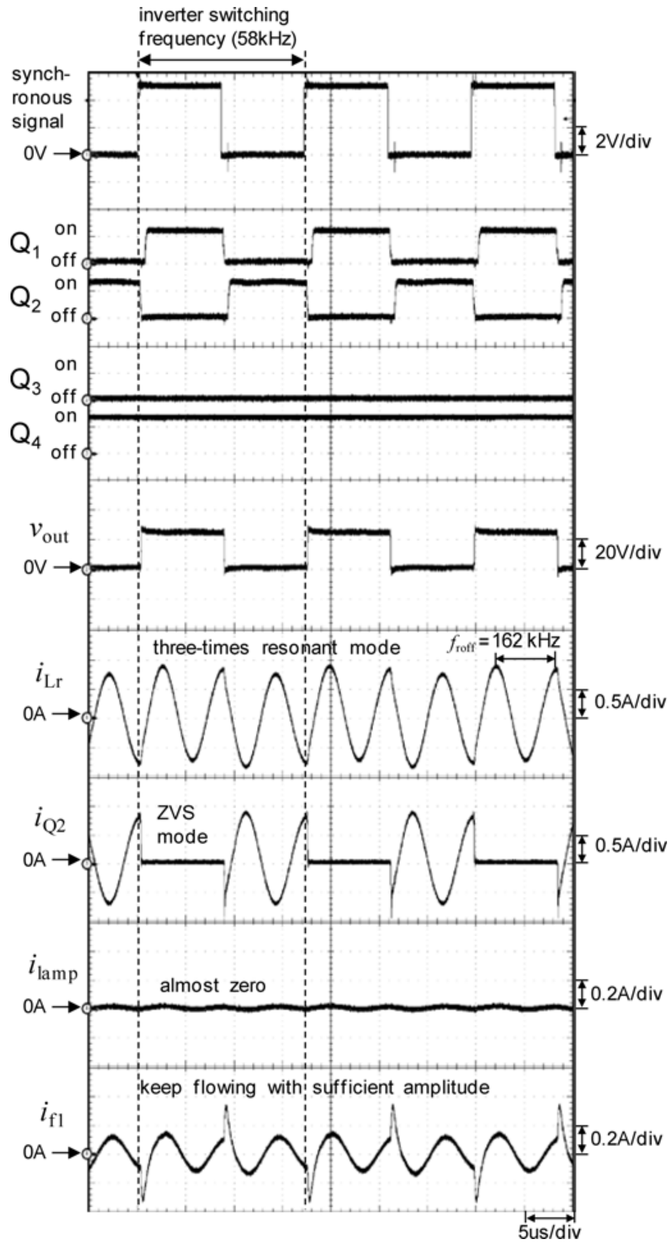

Fig. 14. Waveforms in burst-off period.

IV. Conclusion

This paper has described the dimming method for HCFL using the series-resonant inverter operating at fixed switching frequency. The proposed method, which is based on the burst dimming, decreases the inverter output voltage by changing the switching pattern in the burst-on and burst-off periods. When the HCFL is OFF in the burst-off period, the three-times resonant mode appears and enables the inverter to operate in ZVS resonant mode and supply sufficient filament currents. It was experimentally shown that the proposed method produces the specified dimming and preheating characteristics. The proposed method effectively reduces the cost and size of lighting system, while extending its lifetime and avoiding frequency interference with other equipments.

As for future work, the relation between resonant frequency and circuit parameters should be analyzed and formulated to obtain the theoretical design of the inverter, especially in the burst-off period. It should be verified as one of the future works if the ZVS operation of inverter is kept in transition between the burst-on and burst-off periods, particularly in a few switching cycles after transition.

References

[1] Fluorescent Lamp Operations Committee, "Now, look anew at the ability of fluorescent lamps," (in Japanese), *JELMA J.*, no. 523, 2011.

[2] E. E. Hammer and T. K. Mcgowan, "Characteristics of various F40 fluorescent systems at 60 Hz and high frequency," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 1, pp. 11–16, Jan. 1985.

[3] M. K. Kazimierczuk and D. Czarkowski, "Electronic ballast for fluorescent lamp," in *Resonant Power Converter*, 2nd ed. Hoboken, NJ, USA: Wiley, 2011.

[4] C. S. Moo, H. L. Cheng, H. N. Chen, and H. C. Yen, "Designing dimmable electronic ballast with frequency control," in *Proc. IEEE 14th Annu. Appl. Power Electron. Conf.*, 1999, pp. 727–733.

[5] "Electronic ballast with PFC using L6574 and L6561," ST Microelectronics, Geneva, Switzerland, Appl. Note AN993, 2009.

[6] C. S. Moo, H. L. Cheng, T. F. Lin, and H. C. Yen, "Designing a dimmable electronic ballast with voltage control for fluorescent lamp," in *Proc. IEEE Int. Symp. Ind. Electron.*, 1999, pp. 786–791.

[7] S. T. S. Lee, H. S.-H. Chung, and S. Y. Hui, "A novel electrode power profiler for dimmable ballasts using DC link voltage and switching frequency controls," *IEEE Trans. Power Electron.*, vol. 19, no. 3, pp. 847–853, May 2004.

[8] S. Y. R. Hui, L. M. Lee, H. Chung, and Y. K. Ho, "An electronic ballast with wide dimming range, high PF, and low EMI," *IEEE Trans. Power Electron.*, vol. 16, no. 4, pp. 465–472, Jul. 2001.

[9] S. Ben-Yaakov and M. Shvartsas, "An electronic ballast for fluorescent lamps with no series passive elements," in *Proc. IEEE 16th Annu. Appl. Power Electron. Conf.*, 2001, pp. 670–675.

[10] Y. N. Chang, C. C. Lin, S. Y. Chan, S. N. Lin, and J. C. Lin, "Development of lighting source with CCFL in T8-tube," in *Proc. IEEE Int. Power Electron. Conf.*, 2010, pp. 390–397.

[11] Y. T. Hong, T. J. Liang, H. K. Liao, and J. Y. Lee, "Study and implementation of hybrid dimming inverter for T5 fluorescent lamp," in *Proc. IEEE 5th Int. Conf. Ind. Electron. Appl.*, 2010, pp. 445–450.

[12] H. Fujita and H. Akagi, "A 2-MHz 2-kW voltage-source inverter for low-temperature plasma generators: Implementation of fast switching with a third-order resonant circuit," *IEEE Trans. Ind. Appl.*, vol. 35, no. 1, pp. 21–27, Jan./Feb. 1999.

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