Capacitor ballast for a compact fluorescent lamp

Yoshio WATANABE*

A capacitor ballast that provides stable operation for a special kind of compact lamp with a short discharge channel is described. Three capacitor ballasts modified to improve operating performance are studied. They are: a capacitor ballast with an additional discharge circuit, a capacitor ballast with a variable capacitor, and a capacitor ballast with small series inductance.

Efficacy of the lamp using the modified capacitor ballasts is about 3 to 10% lower than the efficacy with a choke ballast. However, system efficacy for the modified capacitor ballast is nearly equal, or 14% higher than, the efficacy with a choke ballast due to low power dissipation in the capacitor ballast. Furthermore, the weight of the capacitor ballast is one sixth that of a choke ballast. A rapid starting circuit is also developed for the capacitor ballast.

1. Introduction

Up to now, various kinds of compact discharge lamps for the incandescent lamp sockets have been presented. A ballast for regulation of discharge current is necessary to operate such a discharge lamp, since both the lamp and commercial power sources have constant voltage characteristics.

A choke coil is commonly used as a ballast. However, it has the drawbacks of heavy weight and excessive power dissipation. These will be especially serious when the choke ballast is used with a compact lamp.

A capacitor might be suitable for use as a compact discharge lamp ballast, since it is light weight and has low power dissipation. However capacitors have not been used independently as ballasts for conventional fluorescent lamps because they can not establish stable discharge.

The present report describes on a capacitor ballast that provides stable operation for a special compact lamp. Several methods to further improve the operating performance of the capacitor ballast and a starter are also described.

2. Formation of stable discharge by a capacitor ballast

Typical discharge voltage and current waveforms for a conventional fluorescent lamp operated with a capacitor ballast are shown in Fig. 1. The lamp was 32 mm in diameter, 510 mm in length and filled with argon at 2.7 torr (360 Pa). Power source voltage was 100 V and capacitance was 10 μ F.

Luminous flux flickered strongly due to the difference between positive and negative waveforms. Discharge current waveforms show a remarkable pulsed shape and a very high peak value. The

negative waveform of the discharge voltage takes a remarkable low value when current is flowing. The efficacy of the lamp under this condition was very low, since most of the input power dissipated at the electrodes.

Fig. 1 Typical discharge voltage and current waveforms for a conventional fluorescent lamp operated with a capacitor ballast. The lamp is 32 mm in diameter, 510 mm in discharge length and is filled with argon at 2.7 torr. Power source voltage is 100 V and capacitance is 10 μ F. Discharge current is 510 mA: 50 V/div., 1 A/div., 2 ms/div.

A capacitor ballast was then applied to the compact fluorescent lamp shown in Fig. 2¹⁾. The lamp consists of an inner and outer tube in a coaxial configuration. The inner tube is 32 mm in diameter and 100 mm in length. The outer tube is 70 mm in diameter and 140 mm in length. One hot cathode is located in the inner tube. Two rod anodes are symmetrically located in the space between the outer and inner tubes. Neon at 6 torr (800 Pa) or argon at 2.7 torr (360 Pa) plus a small quantity of mercury fill this lamp. This compact lamp is, hereafter, called as "MA lamp". This MA lamp operates on direct current and its discharge channel length is nearly 200 mm.

The voltage and current waveforms for a MA

* Central Research Laboratory, Hitachi Ltd. 282, Higashi Koigakubo 1-chome, Kokubunji, Tokyo 185, Japan.

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Fig. 2 Construction of a "MA lamp" with two anodes. It is filled with neon at 6 torr or argon at 2.7 torr.

Fig. 3 Discharge voltage and current waveforms when a MA lamp filled with neon is operated with a capacitor ballast. The same operating circuit as the one at Fig. 1 was employed. The capacitance is $15 \mu\text{F}$. Discharge current is 395 mA: 20 V/div., 0.5 A/div., 2 ms/div.

Fig. 4 Discharge voltage and current waveforms when a short discharge-length tube is operated with a capacitor ballast. The channel length is 200 mm, diameter is 32 mm and the filler was argon at 2.5 torr. Stable waveforms similar to those in Fig. 3 are obtained, even though anode oscillation is not found during the negative period. Discharge current is 466 mA: 20 V/div., 0.5 A/div., 2 ms/div.

lamp filled with neon and operated with a capacitor ballast are shown in Fig. 3. A capacitance of $15 \mu\text{F}$ and a source voltage of 100 V were employed. Stable discharge was established and no flicker in luminosity was noticed. There was little difference in the waveforms of each half cycle. The peak value of the discharge current decreased and luminous efficacy was greatly improved compared with the case shown in Fig. 1.

The reason the MA lamp could succeed in stable operation with a capacitor ballast was investigated. It was found that the short discharge channel which the MA lamp had was effective in establishing stable discharge with the capacitor ballast.

The discharge voltage and current waveforms for a short length tube filled with argon at 2.5 torr (333 Pa) are shown in Fig. 4. The channel length was 200 mm, and the tube diameter was 32 mm. Stable waveforms similar to those in Fig. 3 were obtained, even though anode oscillation did not take place during the positive period. This shows that a capacitor ballast can stably operate a lamp with a short discharge channel, such as the MA lamp.

3. Analysis of operating characteristics of a MA lamp with a capacitor ballast

The principle circuit diagram and voltage waveforms for a capacitor ballast are illustrated in Fig. 5. The following equation describes this circuit:

Fig. 5 Principle circuit diagram and voltage waveforms for a capacitor ballast.

$$V_1 \sin \omega t = V_C + V_L, \dots\dots\dots(1)$$

where $V_1 \sin \omega t$ is the source voltage, V_C is the voltage at capacitance C and V_L is the lamp voltage. When equation (1) is differentiated and multiplied by C discharge current i is represented as follows:

$$i = C \frac{d}{dt} V_C = \omega C V_1 \cos \omega t - C \frac{d}{dt} V_L, \dots\dots\dots(2)$$

The term, $\omega CV_1 \cos \omega t$, presents the sinewave current. The term, $\frac{d}{dt} V_L$, is nearly zero after reignition. However $|\frac{d}{dt} V_L|$ takes a large value at reignition. As a result, current flow is pulsed.

If equation (2) is multiplied by V_L , integrated during the current flow period and averaged, discharge power, W_L , is obtained as following:

$$W_L = 2fCV_1 \int_{\alpha}^{\pi/2} V_L \cos x dx - 2fC \int_{V_{RS}}^{V_{Le}} V_L dV_L, \dots\dots\dots(3)$$

where $f = \frac{\omega}{2\pi}$, $x = \omega t$, and α is the reignition phase

angle. Current i goes to zero close to $\pi/2$, since a capacitor can not be charged further after the source voltage reaches its maximum value at $\pi/2$. V_{Le} is the discharge maintaining voltage when current ceases. V_{RS} is the reignition voltage. These parameters are indicated in Fig. 5.

Since the value of V_L in the first term on the right side of equation (3) is regarded as a constant, equation (4) can be rewritten as follows:

$$W_L = 2fCV_1 V_L (1 - \sin \alpha) - fC(V_{Le}^2 - V_{RS}^2). \dots\dots(4)$$

Since the charge voltage at capacitance C at $\pi/2$ is given by $V_1 - V_{Le}$,

$$V_1(1 + \sin \alpha) V_{RS} + V_{Le}. \dots\dots\dots(5)$$

Rewriting equation (4) using equation (5),

$$W_L = 2fC \left\{ 2V_L V_1 - V_L(V_{RS} + V_{Le}) + \frac{1}{2}(V_{RS}^2 - V_{Le}^2) \right\} \dots\dots\dots(6)$$

The inverse of capacitance, $1/C$, and the peak and r.m.s. values of the current were measured as a function of the source voltage (rms), V_{10} , while the discharge power was kept constant. The results for two types of lamp are shown in Fig. 6. The lamp filled with neon at 6 torr (800 Pa) was operated at 22 W and the discharge voltage for it was about 56 V. The lamp filled with argon at 2.7 torr (360 Pa) was operated at 20 W and the discharge voltage was about 36 V.

The two solid lines in the top figure represent the calculated results of capacitance from equation (6), using the measured values of V_{RS} and V_{Le} , which were nearly constant against V_{10} . The calculations and measurements agree quite well. Thus, the output characteristics of a capacitor ballast can be calculated using the above equations.

Though, inductance and resistance were neglected in the above equations, there were a small inductance and resistance in series with the capacitor in the measurement circuit. Their values were indicated in Fig. 6. A small series impedance affected the peak and rms current values, but did not affect the output power characteristics. The small impedance is effective only during pulsed cur-

Fig. 6 Inverse of capacitance, $1/C$, and peak and rms values of current as a function of source voltage. A tube filled with neon was operated at 22 W and the discharge voltage was about 56 V. A tube filled with argon at 2.7 torr was operated at 20 W and the discharge voltage was about 36 V. The two solid lines in the top figure present calculated results from equation 6. The inductance and resistance are from the measurement circuit in series with the capacitor. Dotted line: 5.7 mH and 6.17 Ω . Solid line: 12.3 mH and 24.35 Ω .

rent flow. Power dissipation during that short period is small compared with the power dissipation for the entire period.

4. Modified circuits for capacitor ballast

Although a capacitor ballast was found to be usable with the MA lamp, the peak value of the discharge current in Fig. 3 is still high and luminance efficacy is low, compared with the values obtained using a choke ballast. It is necessary to reduce the peak value of the current to improve the performance of the capacitor ballast, since high peak current causes low efficacy and short electrode life. Three methods of improvement are examined in the following sections.

4.1 Capacitor ballast with additional discharge circuit

One method of reducing peak current is to decrease the value of dV_L/dt in equation (2). This can be accomplished by reducing the reignition voltage. When a discharge lamp is operated on a capacitor ballast, the period called "off-time", when current does not flow, inherently exists, since the voltage on a capacitor can not change abruptly to cause reignition. Ions and electrons rapidly recombine during this period to increase reignition voltage. High reignition voltage causes a sharp voltage drop after reignition.

Therefore, one effective way to decrease dV_L/dt is to reduce the off-time. The test circuit shown in Fig. 7 was employed to do this. The main discharge current was supplied from an ac power source through the capacitor ballast. A small dc current that flowed during the entire period was superimposed on the main current.

Measured results are shown in Fig. 8. Reig-

Fig. 7 Test circuit to study the effect of small current superimposition.

Fig. 8 Input lamp power from an ac source, reignition voltage and peak current values as a function of superimposed dc current for the circuit in Fig. 7. A lamp filled with neon was used. The capacitances employed here were: $7.0 \mu F$ for 220 V, $16 \mu F$ for 115 V, $18.2 \mu F$ for 100 V.

nition voltage, hence the peak value of the current, decreases as dc current increases. Input power from the ac source decreases as dc current increases due to the decrease in V_{rs} in equation (6).

An interesting ballast circuit for a operating dc lamp from an ac source was drawn up by Farrow in the U.S. (Pat. 3,787,751)²⁾. The ballast consists of a capacitor, an inductor and rectifiers. The capacitor and the inductor operate independently as ballasts using the rectifiers.

Fig. 9 Circuit diagram of a capacitor ballast with an additional discharge circuit.

A modified circuit in which resistor R replaces the inductor in Farrows' circuit is shown in Fig. 9. C_0 is a ballast capacitor, rectifiers D_1 - D_4 constitute a fullwave rectifier and rectifiers D_5 and D_6 and resistor R constitute the operating circuit that supplies the small current during the entire period.

The main discharge current flows through V_1 - C_0 - D_1 -Lamp- D_4 - V_1 or V_1 - D_2 -Lamp- D_3 - C_0 - V_1 . C_0 charges up as the source voltage reaches the peak value. Then the main current ceases. The small current, limited by R , flows through V_1 - R - D_5 -Lamp- D_4 - V_1 or V_1 - D_2 -Lamp- D_6 - R - V_1 while the source voltage remains greater than the charge on C_0 . When the source voltage decreases below the charge on C_0 , the current, still limited by R , flows through C_0 - R - D_5 -Lamp- D_3 - C_0 or C_0 - D_1 -Lamp- D_6 - R - C_0 . As a result, this small current remains during off-time. The voltage and current waveforms are illustrated in Fig. 10.

Fig. 10 Voltage and current waveforms for each part of the circuit in Fig. 9: 50 V/div., 0.5 A/div., 2 ms/div.

The reignition voltage and input power from the ac source are shown in Fig. 11 as a function of the current, I_R , which flows through R . The characteristics are the same as those in Fig. 8 except that lamp power reaches a minimum point against I_R . The decrement on the left side of the minimum point is due to the decrement in V_{RS} described above. The increment to the right is due to power dissipation at R . This circuit operates an MA lamp quite well, although there is a little power dissipation at R .

Fig. 11 Input power from an ac source and reignition voltage as a function of the current, I_R , which flows through resistance R . The capacitance for the lamp filled with neon was $16 \mu\text{F}$, that for the lamp filled with argon $18.2 \mu\text{F}$. Source voltage was 100 V.

4.2 Capacitor ballast with variable capacitor

Equation (2) indicates that discharge current i is proportional to capacitance C . If the capacitance is kept small during the reignition phase and becomes large after reignition, the peak value of the current at reignition will be reduced.

A circuit to realize this method is shown in Fig.

Fig. 12 Circuit diagram of a capacitor ballast with a variable capacitor.

12. Capacitor C_0 is the ballast capacitor and C_1 and C_2 are additional capacitors smaller than C_0 . Rectifiers D_1 - D_4 constitute a full-wave rectifier.

When the source voltage reaches its peak value, V_1 , the charge voltage on C_0 is $V_1 - V_L$, while the charge voltage on C_2 is V_1 . Therefore, the charge voltage on C_2 is greater by V_L than that on C_0 . When the source voltage decreases, the voltage difference between the charge voltage on C_2 and the source voltage appears across the lamp. When the lamp reignites, the discharge current is limited by the smaller capacitor, C_2 . When the charge voltage on C_2 decreases and reaches a value equal to the charge voltage on C_0 , the large discharge current flows through both C_2 and C_0 .

The voltage and current waveforms for the lamp filled with neon are shown in Fig. 13, where $C_0 = 16 \mu\text{F}$, C_1 and $C_2 = 2.2 \mu\text{F}$, and the source voltage is 100 V rms. The pulsed current at reignition has disappeared. The reason the discharge voltage did not reduce to zero during off time is the existence of the charge on C_1 and C_2 , which are connected in parallel to the lamp. The high frequency component of the current flowing through C_1 or C_2 is due to anode oscillation.

Fig. 13 Discharge voltage and current waveforms for a capacitor ballast with a variable capacitor. A lamp filled with neon was operated at 20.2 W. Source voltage was 100 V. $C_0 = 16 \mu\text{F}$, $C_1 = C_2 = 2.2 \mu\text{F}$: 20 V/div., 2 ms/div.

4.3 Capacitor ballast with a small series inductance

As has already been pointed out, a small inductance is effective in reducing the peak value of the current at reignition. When a capacitor is used as a ballast for a conventional fluorescent lamp, an inductor is usually connected in series with the capacitor to eliminate pulsed current. In that case, a large inductance is necessary to stabilize discharge. However, a very small inductance is enough to effectively stabilize the discharge in an MA lamp. In fact, a small inductance in series with the ballast capacitor is necessary to suppress rush current when the starting circuit is turned on and to prevent radio interference due to anode oscillation.

The capacitance of the ballast capacitor, and the rms and peak values of the discharge current at constant lamp power were measured as a function of series inductance, L . The lamp filled with neon was operated at 22 W. The results at source voltages of 220 V and 100 V are shown in Fig. 14. Interestingly, all curves took minimum and maximum values at nearly the same values of series inductance.

Fig. 14 Capacitance for the ballast capacitor, and rms and peak values of the discharge current as a function of series inductance, L . A lamp filled with neon was operated at 22 W. Source voltage was 220 V or 100 V. The dotted line is the calculated result from equation (7).

The current and voltage waveforms at typical values of the series inductance for 220 V in Fig. 14 are shown in Fig. 15. Figure 15(a) was obtained at $L=260$ mH which was large enough to diminish off-time. Figure 15(b) was obtained at $L=73.6$ mH, where the curves reached maximum values. The current waveform showed a long off-time. Figure 15(c) was obtained at $L=53.1$ mH, where the curves reached minimum values. The current waveform showed two peaks during each half cycle. The two peak values of the current was smaller, and off-time was shorter, than those in Fig. 15(b).

This phenomenon was reported by J. Rottier in the U.S. (Pat. 3,986,076)³. However, he did not

Fig. 15 Discharge voltage and current waveforms at typical series inductance values. A lamp filled with neon was operated at 22 W. Source voltage was 220 V. (a) $L=260$ mH, inductance large enough to diminish off-time. (b) $L=73.6$ mH, curves take maximum point. (c) $L=53.1$ mH, curves take minimum point.

analyze it clearly. When the ballast consists of an inductor and a capacitor, and the lamp reignites in each half cycle after off-time, the discharge current is expressed as follows:

$$i = \frac{1}{\omega L} A \cos(\omega t + \phi) + \frac{1}{\beta L} B \exp(\kappa t) \sin(\beta t + \xi), \dots\dots\dots (7)$$

where A , B and k are numerical constants, ϕ and ξ are phase angles and β is transient angular velocity. These constants depend on circuit components, lamp and source voltages, and initial con-

ditions. The first term on the right side of equation (7) represents the steady state and the second term represents the transient state.

Calculated current waveforms for 200 V are illustrated in Fig. 16. When inductance is 150

Fig. 16 Calculated waveforms for discharge current as a function of series inductance. Discharge voltage is 55 V and source voltage is 220 V. Capacitance is $8 \mu F$.

or 100 mH, transient frequency is low, and the current waveform shows off-time and has one peak. When inductance is 66.7 or 44.4 mH, two peaks appear in the current waveform and off-time is a little shorter. The latter of the two peaks results from the transient term in equation (7). A calculated curve of capacitance to inductance for 100 V is also shown in Fig. 14.

The characteristics of the capacitor ballast with inductance for the lamp filled with neon at 220 V in Fig. 14 are shown in Table 1 for typical inductance values. The first line shows the characteristics when inductance is very small, the second line inductance giving the minimum point of the curves, the third line for the value of inductance at which the capacitance has the same value as that at the minimum point of the curve, and the last line inductance large enough to diminish off-time. The value of the series inductance at which the curve shows the minimum point seems to be most suitable for use with a capacitor ballast.

Table 1 Characteristics for several inductances in series. Lamp was filled with neon. Source voltage was 220 V. Lamp power was 22 W.

L (mH)	VA on L^* (%)	C (μF)	CV on C^{**} (%)	i (A)	i_{peak} (A)
13	25.9	7.6	103.8	0.55	1.32
54	100	6.9	100	0.53	1.06
44	215	6.9	111.3	0.59	1.1
260	419	5.5	93.4	0.049	0.795

* The product of voltage and current on L . This value is proportional to the cost of L .

** The product of voltage and capacitance on C . This value is proportional to the cost of C .

4.4 Efficacy of capacitor ballasts

The relative efficacy of the MA lamp when it is operated in the modified capacitor ballast circuits described above are shown in Table 2. The efficacy values were normalized by the value for operation using a choke ballast. When the lamp was operated in the principle capacitor ballast circuit, the efficacy was 74%. When it was operated with a modified capacitor ballast, the efficacy increased by 21~31%. These values are still 3~10% lower than the value obtained using a choke ballast. However, ballast loss are greatly decreased, so that total system efficacy, including ballast loss, is nearly equal to, or 14% higher than, the value when the choke ballast was employed. Another advantage of the capacitor ballast is that the ballast weight is about one-sixth that of a choke ballast.

Table 2 Relative efficacy of a MA lamp with various capacitor ballast circuits. Lamp was filled with neon at 6 torr. Lamp power was 20 W.

Type of ballast	Source Voltage (V)	Ballast loss (W)	Efficacy (%)		Ballast Weight (g)
			Lamp	System	
Choke	100	4.9	100	100	320
Capacitor	100	1.0	74.4	88.2	50
Capacitor with additional dc	100	2.2	89.9	100.8	55
Capacitor with variable C	100	1.0	96.3	114.2	59
Capacitor with Series L	220	2.5	97.3	107.7	190

5. Starter circuit for a capacitor ballast

Another important point when a capacitor ballast is used is how to ignite the lamp. When a choke is used as the ballast, a high starting voltage is easily obtained by interrupting the current flowing through the choke. However, a capacitor can not produce a high voltage by current interruption. Thus, a conventional glow switch starter can not be used with a capacitor ballast. Therefore, a new starting circuit must be developed for use with capacitor ballasts.

A circuit diagram for one such starter is shown in Fig. 17. C_0 is the ballast capacitor, rectifiers D_1 - D_5 constitute a fullwave rectifier, and rectifiers D_6 and D_7 with semiconductor switching device (SSS) Q constitute a pre-heating circuit. Small capacitors C_1 and C_2 and rectifiers D_2 and D_3 make up the starting voltage generator. Switch Q has a self-breakdown voltage, V_b , which is chosen to be between the peak values of the source and discharge voltages. After self-breakdown, it remains closed until the current flowing through it ceases.

The operation of this circuit is as follows. Initially, the lamp has not been ignited, and the

Fig. 17 Circuit diagram of a starter for a capacitor ballast.

polarity of the source voltage is assumed to be as shown in Fig. 17. Capacitors C_1 and C_2 are charged to the source voltage through V_1 - D_2 C_1 - C_0 - V_1 or V_1 - D_2 - D_3 - C_2 - V_1 . When the source voltage reaches the self-breakdown voltage of Q , Q closes and pre-heating current flows through V_1 - D_7 - Q - Cathode- D_5 - C_0 - V_1 . When C_0 is fully charged, pre-heating current ceases. At that time, C_1 is charged to nearly the value of V_b , and C_2 is charged to the peak value of V_1 plus the charge on C_1 , through C_0 - C_1 - D_3 - C_2 - C_0 . When the source voltage decreases and the polarity reverses, the voltage difference between the charge on C_0 and the source

Fig. 18 Starting voltage and pre-heating current waveforms for the circuit in Fig. 9: 100 V/div., 1 A/div., 5 ms/div.

voltage appear at Q . Then, Q closes again to let pre-heating current flow through V_1 - C_0 - D_6 - Q - Cathode- D_4 - V_1 . The starting voltage, which is twice the peak value of the source voltage plus V_b , appears between the anode and the cathode through Cathode- D_4 - V_1 - C_2 - Anode. Starting voltage and pre-heating current waveforms are shown in Fig. 18. This starting circuit provides for rapid starting. The same starting circuit can be applied to any kind of capacitor ballast for MA lamps that operate on dc source.

6. Conclusion

A lamp with a short discharge channel usually has low efficacy, since the shorter discharge channel means relatively smaller power dissipation in the positive column. However, such a lamp can be successfully operated with a capacitor ballast in which weight and power dissipation are quite small. Particularly, when the source voltage is high, the capacitor ballast has an advantage in that a small capacitance can be used. On the other hand, a choke ballast will be larger due to the increase in the voltage and current product. Consequently, a capacitor ballast is favorable when the source voltage is high.

Another problem for a capacitor ballast is how to ignite the lamp. This problem has been resolved by development of a new rapid-start circuit for MA lamps.

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