Electrical feedback control for driving mercury-free flat fluorescent lamp

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Abstract — Recently, a mercury-free flat fluorescent lamp has been developed for LCD backlight application, utilizing a glow-discharge mode instead of a discharge contraction. This paper proposes a lamp-driving system with a feedback loop which prevents discharge contraction and stabilizes the operation of the lamp ignition and radiation. By measuring the current that flows through the lamp, the loop can adjust the current level to a normal operational level and suppress the long-term excitation that causes discharge contraction. The proposed method has been verified by hardware experiments which are compared to that of a conventional open-loop circuit by discharge contraction time and a change in luminance.

Keywords — Mercury-free, flat lamp, feedback control, glow discharge.

1 Introduction

Recently, LCD-backlighting technology has been progressing along with the advancement of applications in the LCD industry. As the front-panel size increases, the spatial and angular uniformity as well as the lighting efficiency becomes a more critical factor in the performance standards of display quality. For the performance requirement, backlighting system research has begun to focus on the transfer from spot lighting sources (none dimensional) or tubular lighting sources (one dimensional) to planar light sources (two dimensional). This planar light source technology will satisfy requirements such as high-quality opto-electronic characteristics and cost competitiveness.1–8 The cost competitiveness can be achieved through the use of a simple assembly process and the high uniformity of its own lamp characteristics attenuating the demand of additional optical auxiliary devices such as diffusion plates, reflectors, and bright enhancement films (BEF).

Recently, a mercury-free flat fluorescent lamp (MFFL) presented by Shiga and Mikoshiba has been developed as a next-generation planar light source, utilizing long-gap glow discharge driven by pulse driving instead of discharge contraction.1,2 Figure 1 shows the simple dielectric barrier discharge (DBD) panel with two soda-lime glasses. Sustaining electrodes insulated by 80-μm-thick dielectric layer are separated 70 mm apart. And white phosphor layers are placed both on the front and rear plates. The total pressure of the Ne–Xe mixture was varied from 10 to 110 Torr with 2–7% Xe concentration.2 This panel is 10 mm thick and is suitable for flat-panel-display applications and is mercury-free through green-device technology. For the next-generation backlighting industry, areal (local) dimming has been researched as another performance-improvement factor of future LCDs through contrast and efficiency enhancement. The luminance of the long-gap discharge lamp reaches 6000 cd/m² and the luminous efficacy is enhanced up to 45 lm/W.1

2 Discharge characteristics

Because MFFL is expanded through the use of a multi-cell structure, areal dimming can be conveniently achieved by cell-by-cell operation. However, this light source requires new driving waveforms with a very narrow switching pulse of from several to several-tens kHz frequency. Figure 2 shows the major driving waveforms in pulsation operating...
mode previously mentioned. When the driving voltage arrives at the gas breakdown voltage, the discharge of the flat light source begins to occur. This locally ignited glow discharge expands throughout the entire panel as an increased voltage is applied. Within a normal voltage margin, the diffused glow discharge occurs and accomplishes uniform luminance. Usually, the normal operating region of the diffused glow discharge is influenced by a few factors such as input power, gas conditions, discharge volume geometry, etc.

However, excessive external disturbances change the diffused glow discharge into a contracted radiation state and restricts the stable and uniform emissions. Figure 3(a) shows the entire panel stable illumination of MFFL in the glow-discharge mode. However, for long-term operation, due to the opto-electronic variations in the lamp and electro-thermal variations in the driving circuit, the operational mode transfers the discharge contraction as shown in Fig. 3(b). Sometimes, the discharge contraction occurs even at ignition.

Recently, in order to extend the operating voltage margin and dimming capability, an improved flat-panel technique which adds an extra auxiliary electrode enhancing the stable operation has been reported. Figure 4 shows the operational margin curves according to the input voltage and pulse-width variations. From Fig. 4, it can be seen that sufficient operating (starting) margin to maintain the glow discharge between ignition \(V_{\text{minimum}}\) and contraction \(V_{\text{contraction}}\) are secured. The driving margin also guarantees a more-extended luminance variation range. The relationship between them is shown in Fig. 5(a). It shows that the lighting system can adjust the luminance down up to 14% of maximum with maintaining the entire surface discharge by controlling the driving voltage \(V_{\text{driving}}\). As shown in Figs. 5(b) and 5(c), the frequency and pulse width also have similar relationships as that of the driving voltage. This experimental data means that the opto-electronic characteristic of the improved panel enhances the dimming capability as well as the probability of successful ignition and driving operation using extra auxiliary electrodes. From the figure, however, the higher the input voltage of the lamp, the narrower the glow-discharge operational region becomes. Furthermore, for long-term operation, the possibility of discharge contraction increases because of the change in lamp parameters such as temperature, lamp voltage, lamp currents, etc. For these reasons, the time needed to maintain the glow discharge is generally reduced as the driving voltage or the current increases. From the figures, it can be seen that the current/voltage of the lamp should be regulated in a desirable region for stable operation.

One of the best ways is to control the capacitance of the DBD. The capacitances of a DBD can affect the threshold current or power for contraction, and the danger of contraction can largely be reduced by adjusting the capacitances. However, the tuning technique is quite dependent on the device tolerance and sensitivity, which is undesirable in perspective of mass production. As another option, an electrical feedback control technique is suggested for reducing the parameter sensitivity. By observation of the lamp conditions and adjustment of the driving condition, the occurrence of discharge contraction can be prevented. However, there have been few research achievements focusing on the MFFL feedback control method, so far. In this paper, the feedback control for stable MFFL driving is proposed. The proposed system consists of a sensing part for feedback information and a control part for appropriate regulation of
the lamp driving circuit. To verify the proposed method, hardware experiments measuring the discharge contraction transfer time in both closed-loop and open-loop systems are performed and compared.

3 Operational principles of the current feedback system

3.1 Operating condition detection

In order to control the illuminating mode by driving-condition feedback, the opto-electronic relationship between the luminous characteristics and electrical condition is important. Because the purpose of the proposed MFFL feedback is to prevent the lamp from discharge contraction, the symptoms of discharge contraction should be considered first. To detect the symptom, lamp current (or voltage) is under observation as a critical indicator. The indicator can be one or two of the several parameters such as lamp peak current, average lamp current, pulse width, etc. In this paper, the negative current peak, one of the most sensitive parameters in the panel excitation is examined. Figure 6 shows the key waveforms of MFFL employed in the lighting system hardware. Figure 6(a) shows the current and voltage waveforms of the lamp in stable operation. In Fig. 6(b), the lamp current waveform of the initial glow discharge is presented with a small negative peak. As the operating time flows, lamp current slowly increases as well as shown in Fig. 6(c). As shown in the figure, after the lamp is ignited, the lamp current increases with a change in the discharge state due to changes of temperature, humidity, other driving conditions, etc. Finally, the lamp current becomes discharge contraction with a sudden in-rush current due to the local heating from unbalanced particle-charge distribution in the dis-

FIGURE 6 — MFLL key waveforms. (a) Lamp voltage and current waveforms in glow discharge (Ref. 1). (b) Glow discharge in early excitation. (c) Long-term excitation. (d) Discharge contraction. (e) The contraction current in full shot.
charge space. Figures 6(d) and 6(e) show the contraction current with highly increased negative peaking.

From the index parameter of the discharge mode inside the panel, sensing the electric characteristic of the lamp can be a reasonable solution for stable operation by maintaining the glow discharge through the control of the driving circuit. This paper suggests a feedback control method for guaranteeing the stable operation of MFFL against any external disturbance.

### 3.2 Lamp control

Following the measurement, lamp control is presented for maintaining glow discharge. Figure 7 shows the overall MFFL system configuration with the proposed feedback method, especially based on the principles of current feedback. The feedback loop (current loop) of the proposed system regulates the lamp current by adjusting the lamp driver's frequency, voltage, and/or the pulse width. The detection network in the figure provides pulse-current (or voltage) detection information for the lamp driver (controller).

Figure 8 shows an example of the proposed feedback system controlling the lamp current by adjusting the dc-link ($V_{\text{link}}$) voltage. The figure has a current-loop feedback controller in the dot-closed box processing the sensed current signal. For the regulation of $V_{\text{link}}$, the voltage reference ($V_{\text{ref}}$) of the inner loop is given by the outer current-sensing loop. If the lamp current starts to increase over a desirable level by external/internal variations, the current controller decreases $V_{\text{ref}}$, then the dc-link voltage decreases and the lamp current returns to the desirable level. This negative-feedback action performs the stabilization of lamp operation in the glow-discharge mode. On the other hand, since the conventional system has an open-loop controller without monitoring the lamp conditions, the dc-link voltage of the lamp driver is always constant. Therefore, the response action to the lamp's abnormal operation is absent.

Figure 9 shows a long-term lamp-state trajectory comparison between a conventionally fixed dc-link lamp driving method (w/o feedback loop) and the proposed one. The X-axis is radiation time and Y-axis is applied power to MFFL Lamps. There is a discharge contraction region when the power is too high. When using an open-loop driving circuit, when the conventional method has a constant dc-link voltage, there is a tendency for the lamp power consumption to increase according to radiation time. Because of this feature, it has the possibility of a normal glow-discharge failure or a reduction in the normal operating time.

On the other hand, the proposed feedback system drives the lamp power to stay in the glow discharge region (safety operation area) by adjusting the dc-link voltage and guarantees normal operation during the long-term radiation.
4 Feedback circuit configuration

This section considers the realization of the proposed lamp driver. Figure 10 shows the detailed circuit diagram of the power and control stages. The power stage is composed of an ac/dc converter, dc/dc pre-regulator, and dc-to-pulse lamp inverter. The control stage is divided by the sensing and control parts. A detailed description of each part is given in following sections.

4.1 Power stage

The power stage of the lamp system dominantly determines system size, energy efficiency, the cost, etc. ac/dc and dc/dc converters perform the regulation of input voltage of the lamp driver, and the lamp driver converts the dc input into a bipolar (unipolar) power-amplified pulse signal. For high efficiency, the driver includes energy-recovery functions to prevent the lamp from dissipating the panel-charging energy (the flat panel is nearly capacitive during the voltage transition mode such as a plasma display panel). Also, the driver circuit employs a soft-switching technique for loss minimization in the power stage. For high-voltage driving, the driver enhances the pulse signal into the kV level by using an isolation transformer. The driver-circuit diagram and the key waveforms are shown in Ref. 1. The dc/dc pre-regulator is composed of a step-down buck converter and regulates dc-link voltage by PWM control. A buck converter is given the voltage reference by the current feedback controller and adjusts the link voltage through the dc-link voltage feedback loop inside the converter. The system efficiency was measured at 2500 cd/m² luminance with six-cell panels, and the efficiency reaches 36 lm/W.

4.2 Control stage

The control stage of the lamp consists of both the output-sensing part and in the controller part.

The sensing part can be realized by several circuit versions according to the sensing position and sensing method. The transition symptom of discharge contraction can be observed at several positions on the board, such as the input current, primary-winding current, secondary-winding current, etc.

The sensed current is compared with the current reference, regulating the limitation of a normal operation region. This sensed current is given to the input of the lamp-current controller. The output of the lamp-current controller can be used for the control of the driver's input voltage. By adjusting the dc-link voltage, the glow-discharge state is maintained. Also, the driving frequency and pulse width of the inverter can be used for maintaining a glow discharge.

The control part adjusts the lamp current by regulating the output of the buck converter. The voltage reference determining the dc-link voltage is given by the current-loop error amplifier. In order to stabilize and to regulate the lamp current, the current-loop error amplifier (compensator) is designed with a proportional integrator. The output of the compensator is used as the reference of the buck-converter inner loop. The system dynamic of the total (two-loop) loop gain is designed to a several Hz range, which is fast enough to control the electro-thermal variation of the lighting system. Figure 11 is the entire-system control flow chart demonstrating each stage of processing the MFFL feedback signal based on the lamp-current measurement. First, the driving power is injected and the lamp current is measured. Second, the sensed pulse current is converted into (an) index parameter(s) such as peak, average, and pulse-width value through standardization. Then, the standardized value is compared with a control reference (I_ref) which is the control output of the lamp-current feedback loop in the early excitation stage. Then, the controller checks the relationship between them with the following equation:

\[ |I - I_{\text{ref}}| < K, \]

where \( K \) is the allowable criterion for the control of the current. When the sensing current enters into the criterion, the symptom of contraction is examined by observation of the standardized parameter value or variation, and the controller decides whether the \( I_{\text{ref}} \) is relevant or not in order to

\[ \text{FIGURE 11 — Flow chart of the MFFL current-feedback method.} \]
prevent the contraction mode. If not, then the reference is changed and the algorithm process repeats.

5 Experimental results

In this research, a hardware verification of the proposed feedback system has been performed. For the experimental test, a hardware prototype with a $2 \times 3$ MFPL panel has been built. Both the open-loop and closed-loop lamp system were tested under the conditions of an inverter operating frequency of 12.5 kHz, a duty of 1.38%, and a transformer turn ratio of 11:132.

The brightness of the operating condition is set to the greatest level as far because the discharge contraction does not occur at the beginning. On that condition, even though the brightness is at the highest level, the possibility of discharge contraction is also very high. In order to compare the maintaining capability of glow discharge, the operating-time duration of glow discharge was measured both in the open loop and the closed loop. The current sensing level and luminance are also measured by noticing the illumination stability. The luminance was measured by a chromameter CS-200 (Konica-Minolta).

Figure 12 shows the lamp-current variation according to operation time. For a conventional system, the lamp current begins to increase during operation, and discharge contraction occurs in 5 minutes. It means that the MFPL system requires a monitoring system for long-term operation. In the case of the proposed system, normal glow discharge is maintained even for more than 100 minutes of radiation time.

Figure 13 shows the luminance variation according to operation time. For a conventional system, from the ignition, the luminance increases continuously due to circumstantial long-term factors, then the luminance drops immediately due to the local illumination of the panel, which indicates a failure in normal discharge. However, for the proposed system, the luminance is stabilized after a slight fluctuation. From the results, it is shown that the

![FIGURE 12](image1)

![FIGURE 13](image2)
feedback control method makes the system more reliable for long-term operation than the open-loop controller.

Figure 14 shows the result of an additional experimental test using a long-time tested lamp. When the aged lamp was operated without feedback, the lamp state was very unstable (rugged) and eventually entered into the discharge contraction mode in less than 25 minutes. However, for the proposed system, the aged lamp was maintained more stable over 25 minutes. This result shows that the feedback control method significantly reduces the sensitivity on the panel characteristics and makes the system more tolerable for the stable operation of various MFFL groups than the open-loop controller does.

6 Conclusions

In this paper, we propose an MFFL driving system with an electrical feedback loop. The opto-electronic relationship between discharge conditions and electrical characteristics has been considered and the solution to prevent the lamp from discharge contraction through the feedback control also has been presented. The feedback controller adjusts the dc-link voltage, inverter frequency, or the duty cycle to control the lamp current. The proposed systems are verified through a 3-cell MFFL with a dc/dc converter and a pulse-type inverter. The results show that the closed-loop system has very stable operation such that the glow discharge is maintained without the occurrence of the discharge contraction despite long-term radiation.

References


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