A Highly Efficient AC-PDP Driver Featuring an Energy Recovery Function in Sustaining Mode Operation

Feel-Soon Kang, Sung-Jun Park and Cheul-U Kim

Abstract - A simple sustain driver employing an energy recovery function is proposed as a highly efficient driver of a plasma display panel. The proposed driver uses dual resonance in the sustaining mode operation: a main resonance between an inductor and an external capacitor to produce alternative pulses and a sub-resonance between an inductor and a panel to recover the energy consumption by the capacitance displacement current of the PDP. The operational principle and design procedure of the proposed circuit are presented with theoretical analysis. The operation of the proposed sustain driver is verified through simulation and experiments based on a 7.5-inch-diagonal panel with a 200 kHz operating frequency.

Key words - plasma display panel, sustain driver, energy recovery

1. Introduction

In the display industry, a PDP is considered to be best for manufacturing a wide, flat HDTV. Its advantages include such as ease of producing large panels, rapid response, long lifetime, thinness, wide viewing angle, enhanced memory capability, brightness, and luminous efficiency. PDPs can also retain pixels in the on state without continuous refresh signals, which means that increased brightness can be obtained for the same power and driving circuitry. This advantage also allows for excellent contrast ratios in high ambient illumination. Thanks to these attracting merits, the PDP will likely soon become consumer affordable wall-hanging color TVs with large diagonals [1]-[5].

As shown in Fig. 1, the PDP generally consists of front and rear glass plates with chemically stable rare gases between them. The inner space of the PDP is divided into numerous local cells by the opaque electrode grid lines encrust on the inner surfaces of glass plates. Like that of fluorescent lamps, the operating principle for each cell is to make use of a gas-discharging-generated ultraviolet ray to excite a visible ray emitting phosphor. However, power consumption is increased due to the low efficiency of the UV generation process. Compared to the well-known discharge lamps with a high lumen efficacy, the loss due to wall recombination of the electrons and ions in a small cell makes the discharge less efficient.

In PDP drivers, frequent discharges occur by alternatively charging each side of the panel to a critical voltage, which causes repeated gas discharges. By means of an address driver, if a pixel has been in the controlled ON state, the sustain driver will maintain the ON condition of that pixel by repeatedly discharging. On the other hand, if a pixel has been driven to OFF state, voltage across the cell is never high enough to cause a discharge and the cell remains OFF. Because the address electrodes are only used during the writing or erasing periods and are normally connected to ground during a sustain mode, the capacitance $C_p$ can be replaced by the equivalent circuit of the PDP as shown in Fig. 2 [5]-[8].

![Fig. 1 Illustration of the lighting mechanism for one individual cell of AC-PDP](image1)

![Fig. 2 Equivalent circuit of PDP with its simple driver and waveforms](image2)
During charging and discharging transients, if an inductor is placed in series or parallel with the panel, then $C_p$ can be charged and discharged by means of the inductor. Ideally, there is no power consumption since the inductor would store all of the energy otherwise lost in the non-ideal resistance and transfer it to or from $C_p$. However, to control the energy flow to and from the inductor when $C_p$ is charged and discharged, switching devices are essential. In this case, the drive circuit can probably be replaced by a resistive factor, and therefore, is comprised of an $RC$ series circuit. When $V_s$ is supplied, the circuit equation can be expressed as

$$V_s = R \cdot i(t) + \frac{1}{C_p} \int i(t) \cdot dt$$

(1)

where the initial condition $V_{cp}(t = 0) = 0$ and where $V_s$ is the supply voltage; $R$ is total resistance in the circuit, i.e., wire and electrodes resistance, on-resistance of switches, etc.; and $C_p$ is the total capacitive in the PDP.

Rewriting Eq. (1),

$$\frac{di(t)}{dt} = \frac{i(t)}{RC_p}$$

(2)

From Eq. (2) with the initial condition, the current equation can be obtained as

$$i(t) = \frac{V_s}{R} \exp\left(-\frac{1}{RC_p} \cdot t\right)$$

(3)

Therefore, power consumption ($P_{loss}$) in the circuit can be calculated as

$$P_{loss} = R \cdot i(t)^2 = \frac{V_s^2}{R} \exp\left(-\frac{2}{RC_p} \cdot t\right)$$

(4)

Assuming time constant is sufficiently smaller than unit pulse period, power consumption in a resistive factor can be expressed as

$$\int_0^\infty R \cdot i(t)^2 \cdot dt = \frac{1}{2} C_p V_s^2$$

(5)

From Eq. (5), during charging and discharging transients, when the waveform (a) in Fig. 2 is applied to the PDP, power consumption is $2f C_p V_s^2$ for each cycle. In the case of waveform (b), $4f C_p V_s^2$ is consumed for a complete sustain cycle. It is, moreover, proportional to the operating frequency. In usual driver circuits, the energy is almost dissipated in the non-ideal resistance of the wire and electrode and in the on-resistance of the power MOSFETs.

Recently, to solve the power consumption problem, several AC-PDP sustain drivers employing an energy recovery function have been proposed [7]-[10]. Among them, three prior approaches are investigated and compared with the proposed driver. First, a conventional sustain driver was proposed in [7] and is shown in Fig. 7(a) with its control signals for simulation. This circuit basically utilizes the resonance between an external inductor and capacitance of the panel. Although this circuit can save a large amount of energy, it has a complex configuration that results in a high cost. Secondly, a regenerative circuit based on the full-bridge converter has been presented in [8]. Its configuration with its control signals is illustrated in Fig. 7(b). A remarkable point of this driver is a simpler structure than conventional drivers. During charging and discharging transients, this sustain driver directly recovers the energy from the panel via external inductors, and hence it saves a large amount of energy due to soft-transition of switches and diodes. Nevertheless, to form a zero level, current might be continuously flowed through the inductor and power MOSFETs during the reset or address periods. The continuously flowing current via power MOSFETs causes an increase in the energy loss because of their on-resistance; therefore, no energy is saved during those periods. Finally, as shown in Fig. 7(c), a novel energy recovery sustain driver using the parallel resonance is presented [9]. The parallel resonance between the inductor and the intrinsic capacitance of the panel can recover the energy lost by the capacitive displacement current of the PDP. Even though the parallel resonance saves a large amount of energy thanks to zero-voltage switching of switches and diodes, it is still complex, moreover, a complete soft-transition is uncertainly to overall periods because the total capacitance of panel is always changing according to the pixel conditions.

In this paper, an effective sustain driver for an AC-PDP is presented and compared with the conventional circuit. It has a simple structure compared with the conventional approaches. The most outstanding characteristic of proposed driver is its use of dual resonance, which results in high recovery efficiency. The operational principle and design procedure of proposed circuit are explained with theoretical analysis. Then, the validity of the proposed sustain driver is verified through the simulated and experimental results based on a 7.5-inch-diagonal panel with a 200 kHz operating frequency.

2. Proposed sustain driver

2.1 Circuit Configuration

Fig. 3 shows the configuration of the proposed sustain circuit for driving the AC-PDP. It consists of one inductor paralleled with a panel, the diode $D_4$ to form a main resonant path, and four switches equipped with their internal diodes ($S_2, S_3$) and without others ($S_t, S_{1b}, S_{1d}$), respectively. The inductor paralleled with the panel resonates with the external capacitor. In a full-bridge structure, a sufficient dead time must be given to protect pole-switches from an arm-short. This time is used for the sub-resonance of the proposed sustain driver, i.e., during a dead-time the stored energy in
the inductor is transferred to the parallel connected panel in a resonant manner, changing the voltage polarity. As a result, the displacement and discharging current of the panel is directly recovered to the inductor, and then the recovered energy in the inductor is retransferred to the external capacitor through the diode D1 or D2 in resonantly when switches are turned on again, i.e., the main resonance. Main resonance occurs prior to sub-resonance in order to change the polarity of voltage across the panel repeatedly. It produces alternative pulses for charging and discharging the equivalent capacitance of the panel.

\[ i_L(t) = V_{Com} \cdot \sqrt{\frac{C_s}{L}} \cdot \sin \omega_m (t - t_0) \]  

where \( \omega_m = \frac{1}{\sqrt{LC_s}} \), \( i_s(0) = 0 \), and \( V_C(0) = V_{Com} \).

Voltage across the external capacitor can be derived as

\[ V_C(t) = V_{Com} [1 - \cos \omega_m (t - t_0)] \]  

**Mode 2** \((t_1 \rightarrow t_2)\): Before \( t_1 \), voltage across the panel is maintained as \( V_s \) by means of \( S_4 \) conducting and the external capacitor voltage becomes \( V_S \) with the complete resonance. At \( t_1 \), \( S_1 \) and \( S_2 \) are turned off at the same time, resulting in the instantaneous blocking of the main resonant path. Consequently, the inductor current will flow through the panel resonantly as shown in Fig. 5(b). With initial condition, the circuit equation can be expressed as

\[ i_L(t) = V_s \cdot \sqrt{\frac{C_s}{L}} \cdot \sin \omega_s (t - t_1) + I_{M1} \left[ \omega_s + \frac{1}{\omega_m} \right] \cos \omega_m (t - t_1) \]  

where \( \omega_s = \frac{1}{\sqrt{LC_P}} \), \( V_C(0) = V_{Com} \) and \( i_s(0) = I_{M1} \).

Due to the resonance between the inductor and the panel, the voltage polarity of the panel is changed from positive \( V_S \) to negative \( V_S \) at the end of resonance. This mode is in the sub-resonance to recover the energy consumption by the capacitive displacement current of the PDP and to change the polarity of the voltage across the panel.

**Mode 3** \((t_2 \rightarrow t_3)\): At \( t_2 \), voltage across the panel becomes negative \( V_S \), and current flowing through the panel is null. \( S_1 \) and \( S_4 \), the terminal of mode 2, are turned on simultaneously to sustain the voltage across the panel negative \( V_S \). Then the main resonant path between the inductor and the external capacitor is reformed by \( D_1 \) and \( D_2 \), as indicated in Fig. 5(c); therefore, the stored energy in the inductor is transferred to the external capacitor. During this mode, the circuit equation can be derived as

\[ i_L(t) = V_s \cdot \sqrt{\frac{C_s}{L}} \cdot \sin \omega_m (t - t_2) - I_{M2} \left[ \omega_m + \frac{1}{\omega_m} \right] \cos \omega_m (t - t_2) \]  

where \( \omega_m = \frac{1}{\sqrt{LC_s}} \), \( V_C(0) = V_S \), and \( i_s(0) = I_{M2} \).

During the prior mode, if the resonance was complete, or
voltage across the panel became negative $V_S$ exactly, the input current supplied from the power supply through $S_4$ will be zero. However, it is somewhat difficult because of electrode resistance, on-resistance of the power MOSFETs, and other non-ideal factors. A complete resonance during the prior mode can guarantee that voltage across the panel sufficiently became negative $V_S$. It is important in the viewpoint of recovery efficiency because voltage across the panel is sufficiently increased by the resonance during the mode 2, a lower input current will be needed to sustain a constant panel voltage.

### 2.3 Design Considerations

According to the characteristics of the PDP, the operating frequency is determined. In practical applications, the PDP is usually operated from 80 to 200 kHz. Under the fixed operating frequency, the following design procedure indicates how to calculate the proper values of the inductor and external capacitor to achieve a complete dual resonance. Generally, when series connected switches are used, a sufficient dead-time should be set to protect pole-switches from an arm short. To obtain a high contrast ratio, the sustain period that is clamped by $V_S$ is generally set to about 1-1.2 $\mu$s in the 200 kHz operating frequency. As a result, half of the balance can be used for sub-resonance time and is determined by

$$t_2 - t_1 = t_5 - t_4 \geq \frac{\pi}{2} \sqrt{L \cdot C_p}.$$

Because the panel capacitance $C_p$ is usually determined by the panel size, inductor value can be obtained from Equation (10). Main resonance occurs prior to sub resonance in order to repeatedly change the polarity of voltage across the panel and should happen twice in a complete cycle. Therefore, the frequency of main resonance between the inductor and the external capacitor should be equal to the operating frequency. Hence, the value of the external capacitor can be calculated as

$$f_S = \frac{1}{2\pi \sqrt{L \cdot C_s}}$$

where $f_S$ is the operating frequency of the PDP. For practical purposes, obtaining the exact value of elements is very difficult due to non-ideal components, such as stray capacitance, inductance, and other unexpected factors; moreover, the total capacitance of the panel is always changing according to the condition of the pixels. Therefore, the optimal values might be obtained by trial-and-error through simulation or experimentation considering the panel condition.

### 2.4 Relationship Between the Wall-Voltage and the Applied Voltage

In general, the AC-PDP driver utilizes its inherent memory characteristic via the accumulated wall charge in a discharge space.

Fig. 6 illustrates the relationship between the wall voltage $V_W$ and the applied voltage $V_S$ in the discharge space. Fig. 6 also shows the relative conditions of ions and electrons that depend upon the voltage variation of the discharge space. In this figure, $V_G$ means the voltage across the discharge space. To simplify its explanation, we ignored the address electrode and it was regarded as simple electrodes.

As shown in Fig. 6, the wall-voltage generated by accumulated wall-charges affects the igniting of the panel. When the voltage of discharge space $V_G$ is lower than the discharge

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Fig. 5 Operational modes: (a) Mode 1, (b) Mode 2, (c) Mode 3
inception voltage $V_f$, no igniting occurs as described from A through C (or from F to H) in Fig. 6. During the period from B to C (or from G to H), the displacement current just flows through the panel due to the variation of $V_G$. On the other hand, $V_G$ becomes higher than $V_f$, the panel starts to ignite, and the discharging current flows through the panel as shown in case D (or I). At this moment, wall-charges are accumulated on the dielectric layers, decreasing the effective voltage of the discharge space. The igniting stops when $V_G$ becomes critically lower than $V_f$. The next discharge starts when the polarity of the applied pulse is reversed. Consequently, once the discharge is begun, it repeats again and again as long as the sustain voltage is alternatively supplied to the panel. Thanks to the memory characteristic of the panel, a sustain voltage lower than the discharge inception voltage $V_f$ can operate the AC-PDP, emitting visible light.

3. Simulated and Experimental Results

Fig. 7 shows the configurations of the three mentioned sustain drivers with their control signals. To assess the validity of proposed sustain driver, the three prior circuits, i.e., Weber's, Hsu's, and Liu's sustain drivers, are simulated with Pspice. The used components are listed in detail in Table I. Fig. 8 shows the simulated results of voltage across and of current flowing through the panel in each circuit at the sustain voltage $V_s = 180$ V; therefore, only displacement current flows through the panel. The simulated waveforms of voltage across the panel of Weber's and Hsu's sustain drivers are analogous to that of Fig. 2(a). On the other hand, the operational waveforms of the proposed circuit is very similar to that of Liu's driver.
Fig. 7 The prior sustain drivers and their gate signals for simulation at $V_s=180$ V: (a) Weber’s circuit, (b) Hsu’s circuit, (c) Liu’s circuit, (d) Gate signal of (a), (e) Gate signal of (b), (f) Gate signal of (c)

Table 1 Components list of each sustain driver for simulation

<table>
<thead>
<tr>
<th>Items</th>
<th>Weber’s</th>
<th>Hsu’s</th>
<th>Liu’s</th>
<th>Proposed</th>
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<td></td>
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<td>Value</td>
<td>Symbol</td>
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<td>IRF460</td>
<td>S1-S4</td>
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<td>Dx1, Dx2</td>
<td>mbr4040</td>
<td>D1-D4</td>
<td>internal</td>
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<tr>
<td></td>
<td>Dy1, Dy2</td>
<td></td>
<td>D5-D8</td>
<td>mbr4040</td>
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<td>inductor</td>
<td>Lx, Ly</td>
<td>20 μH</td>
<td>Lx, Ly</td>
<td>40 μH</td>
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<tr>
<td>external capacitor</td>
<td>Cxx, Csy</td>
<td>220 nF</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ESR of inductor/capacitor</td>
<td>0.02 / 0.01 ohm, respectively</td>
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<td></td>
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<tr>
<td>Panel</td>
<td>Before igniting = 1.5 nF, After igniting = 3 nF</td>
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Fig. 9 shows the simulated results of the proposed sustain driver employing an energy recovery function to verify the theoretical analysis at the supplied voltage $V_S = 180$ V. From the waveforms of $v_{CP}$, $i_{CP}$, $i_{Cn}$, and $i_T$, the dual resonant operation can be found: $i_{Cn} + i_{CP} = i_T$. One is the main resonance between the inductor and external capacitor, and the other is the instantaneous sub-resonance between the inductor and the panel.

Fig. 9 Simulated waveform of proposed circuit, $V_S = 180$V

Based on the simulated results, a prototype for the implementation was manufactured according to Table II. The prototype was equipped with a 7.5-inch-diagonal panel that has the maximum value of capacitance approximately 3 nF when all pixels of the PDP are igniting. The operating frequency is set to 200 kHz, and the control signals were generated by the ALTERA using the VHDL (Very High Speed Integrated Circuit Hardware Description Language). In the experiment, when voltage across the panel is higher than that of discharge inception, all the pixels of the panel are ignited displaying a white image, since no reset and address periods were considered.

Fig. 10 shows the experimental waveforms of the proposed sustain driver before and after igniting. Figs. 10(a) and (b) show the voltage across and the current flowing through the panel, inductor, and external capacitance when no light is emitted. During a dead-time, the mentioned sub-resonance between the inductor and panel can be verified from the experimental waveforms. In this case, only displacement current is flowing through the panel due to the variation of applied voltage. When voltage across the PDP is increased up to the discharging inception level, the panel will start to ignite the pixels, showing visible light. At this moment, the discharging current flows through the panel in addition to the displacement component. The discharging current appears in the tail of the current flowing through the panel as shown in Fig. 10(d), and we find that voltage across the panel is slightly affected by gas as shown in Fig. 10(c). Since we considered no driving voltages added from an address driver, which could influence the sustain voltage of the next display period, a higher voltage, i.e., over 200 V, is required to ignite the panel.

Fig. 8 Simulated waveforms of panel voltage and current in each sustain driver at $V_S = 180$ V: (a) Weber's circuit, (b) Hsu's circuit, (c) Liu's circuit, (d) Proposed circuit.
Table 2 Components of the proposed sustain driver

<table>
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<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value or Type</th>
<th>Manufacturer</th>
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<tr>
<td>Panel</td>
<td>C_p</td>
<td>7.5 μF DC PDF</td>
<td>LG Electronics Inc.</td>
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<tr>
<td>Power MOSFET</td>
<td>S1, S4</td>
<td>IRF7400</td>
<td>International Rectifier</td>
</tr>
<tr>
<td>Diode</td>
<td>D1, D3, D2A</td>
<td>FE4D</td>
<td>General Semiconductor</td>
</tr>
<tr>
<td>Inductor</td>
<td>L</td>
<td>157 μH / 1.5 kV</td>
<td></td>
</tr>
<tr>
<td>External capacitor</td>
<td>C_s</td>
<td>220 μF, Multilayer Polymer Film</td>
<td></td>
</tr>
<tr>
<td>Gate amp</td>
<td></td>
<td>TLP250 / Transfer Switch</td>
<td>Toshiba</td>
</tr>
<tr>
<td>Signal Generator</td>
<td></td>
<td>EPM704LC74, EPM705</td>
<td>ALTERA</td>
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</table>

This paper provides a new sustain driver that will recover the energy otherwise lost in charging and discharging the panel capacitance, C_p. The efficiency with which the sustain circuit recovers the energy, the recovery efficiency, is expressed by the input current from a power supply.

\[
E_R = \left( \frac{I_{w_d} - I_{w}}{I_{w}} \right) \times 100 = \left( 1 - \frac{I_{w_d}}{I_{w}} \right) \times 100 \%
\]

where \( I_{w_d} \) and \( I_{w} \) are the averaged input current without and with the energy recovery circuit, respectively. Notice that the recovery efficiency is not equivalent to conventional power efficiency, defined in terms of the power delivered to a load, since no power is delivered to the capacitor, C_p; it is simply charged and then discharged [7]. The recovery efficiency of each circuit according to the variation of applied voltage is shown in Fig. 11. The recovery efficiency was compared using the simulated results, and Table 1 details the simulation conditions. As shown in Fig. 11, a steep increase or decrease in the slope of the indicates that the cells start to discharge. In the case of proposed circuit, the recovery efficiency before igniting is to almost 95 percent regardless of the variation of sustain voltage. After igniting, the recovery efficiency decreases to 90 percent. The other circuit's recovery efficiency increases. This difference occurs because charging and discharging operations in the proposed circuit occurs during a dead-time period and it does not occur during such a period in the other circuits.

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**Fig. 10** Experimental waveforms of the proposed sustain driver employing the energy recovery faculty: (a) Before light emission, \( V_s = 180 \) V, (b) During light emitting, \( V_s = 240 \) V

**Fig. 11** Comparison of the recovery efficiency of each sustain driver
5. Conclusion

Based on dual resonance, a sustain driver employing the energy recovery function is proposed for an efficient drive of a plasma display panel in sustaining mode operation. The proposed driver has a simple structure compared with the conventional approaches. The most outstanding characteristic of proposed driver is use of dual resonance; the main resonance between the inductor and the external capacitor to generate alternative pulses and a sub-resonance between the inductor and the panel to recover the energy consumption by the capacitive displacement current of the PDP. Thus dual resonance results in a high recovery efficiency. The operational principle and design procedure of the proposed circuit are presented with theoretical analysis. The validity of proposed circuit is verified through simulation and experimental results based on a 7.5-inch-diagonal panel with a 200 kHz operating frequency.

References


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