Regenerative Power Electronics Driver for Plasma Display Panel in Sustain-Mode Operation

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Abstract—A regenerative power electronic circuit is proposed to drive a plasma display panel (PDP) in sustain-mode operation. This driver utilizes inductors to resonate with the equivalent intrinsic capacitance of the PDP to avoid the abrupt charging/discharging operation. The energy losses due to conventional hard-switching driving and the displacement current of the PDP are mainly recovered. Compared with prior approaches, this driving circuit has a quite simple structure and is suitable for asymmetrical operation.

Index Terms—Driver, energy recovery, plasma display panel, sustain mode.

I. INTRODUCTION

PLASMA DISPLAY panels (PDPs), invented at the University of Illinois in 1946 by Prof. Bitzer and Prof. Slottow, have advantages over conventional display technologies due to their screen size, thinness, long lifetime, and wide viewing angle. It is likely that PDPs will soon become consumer-affordable wall-hanging color TVs with large diagonal measurements. Fig. 1 shows the simplified structure of a three-electrode-type surface-discharge ac PDP. It comprises transparent X and Y sustain electrodes covered by a dielectric layer on the face plate, address electrodes perpendicular to the sustain electrodes on the back plate, barrier ribs for securing discharging gas space filled with discharging gas such as helium (He) or xenon (Xe), phosphor layers over the back plate to convert the ultraviolet radiation into visible light, and a protective layer of magnesium oxide (MgO) for protecting the dielectric layer from the discharging. By providing the phosphor layers with red, blue, and green for each pixel, a full-color plasma display can be obtained.

Like fluorescent lamps operation, the PDP utilizes the ultraviolet ray generated by gas discharge to excite phosphors encrusted on the address electrodes to emit the visible light. Applying an external electric field between the x electrode and y electrode will cause the filled gas to ionize. The ionized charges will be accelerated by the applied electric field. Some gas atoms

Fig. 1. Simplified structure of a three-electrode-type ac PDP.

Fig. 2. Equivalent circuit of PDP with its simplest driver.

will be excited by the free electrons with enough kinetic energy. When the excited atoms return to the ground state, the ultraviolet rays are emitted and visible light is emitted after ultraviolet rays hit the phosphors.

Due to the existence of the dielectric layer, the PDP exhibits capacitive characteristic during voltage transient despite the gas discharge interval [1]. The equivalent circuit of the PDP with the simplest panel driver to generate the sustain pulse for the PDP is shown in Fig. 2 [2]. The current source I_d is used to represent the gas discharge current. Typical values of C_{xy} , C_{ax} , and C_{ay} are about 1 nF for an 8-inch-diagonal PDP and increase with the panel size. The values of C_{xy} , C_{ax} , and C_{ay} may be slightly affected by wall charge [1]. In this paper, however, we neglect the

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Fig. 3. Driving Circuits for PDP. (a) Prior approach. (b) Proposed driving circuit.

effect of discharge current and assume that the values of C_{xy} , C_{ax} , and C_{ay} are constant to simplify the circuit analysis. Referring to Fig. 2, the address electrodes are normally connected to ground during the sustain period and are only available during the writing or erasing operation [3], [4]. Therefore, we can replace the equivalent circuit of the PDP by a capacitor C_p . In this case, when applying a sustaining pulse to the electrodes, the energy W supplied from a power source is

$$W = C_p(V_{dc})^2 \quad (1)$$

where V_{dc} is the supplied voltage [5]. In the usual driver circuit, the energy W is almost dissipated in the nonideal resistance of the wire and switching elements. For driving a large-size panel with large panel capacitance C_p in a high-frequency high-voltage application, the energy loss will increase and better thermal design is required. Further, the surge charging/discharging current will cause a large amount of electromagnetic interference (EMI) noise, which will degrade the circuit performance.

In this paper, a regenerative driver is presented to achieve soft transient, recover capacitive energy, and reduce circuit complexity.

II. PRIOR APPROACH

One example of prior approaches [6]–[8] used to overcome the aforementioned problems is shown in Fig. 3(a). This circuit utilizes the resonance between the external inductor and

Fig. 4. Operation waveforms of the proposed driver.

Fig. 5. Circuit operation before t_0 .

the PDP to avoid abrupt charging/discharging current and, thus, saves a large amount of energy. The major disadvantage of this circuit is the circuit complexity, so that additional components and control circuits are needed. Furthermore, there will be more switching losses due to the additional switches.

III. PROPOSED CIRCUIT

Fig. 3(b) shows the proposed driver for the PDP. It consists of four MOSFET switches ($M1$ – $M4$) connected as a full-bridge configuration, four diodes ($D5$ – $D8$), and two inductors (L_1 and L_2). Diodes $D1$ – $D4$ and capacitors C_1 – C_4 are parasitic components of the four switches. The inductors are used to resonate with the PDP. The resonant current is utilized to charge/discharge the equivalent capacitance of the PDP and switches so that the abrupt charging/discharging operation is avoided and soft transient is achieved. The diodes are used to clamp the

Fig. 6. Circuit operation at t_0 – t_1 . (a) Before V_A becomes 0 V. (b) Equivalent resonant circuit of (a). (c) After V_A becomes 0 V.

voltage of the PDP electrodes and conduct the extra current of the inductors. Detailed circuit operations are depicted in the next section.

IV. CIRCUIT OPERATION

Fig. 4 shows the operation waveforms of the proposed driver. $G1$ – $G4$ are the respective driving signals of $M1$ – $M4$. The complete cycle is divided into two halves, t_0 – t_3 and t_4 – t_5 . Because the operating principles of the two half cycles are symmetric, we only explain that of the first half cycle.

A. Stage 0 (Before t_0)

As shown in Fig. 5, $M1$, $M4$, $D5$, and $D8$ are conductive before t_0 . The X -side voltage of the PDP (V_X) is equal to the dc-bus voltage (V_{dc}) and the Y -side voltage of the PDP (V_Y) is equal to zero. Therefore, the voltage across the PDP (V_{XY}) is equal to V_{dc} . At the same time, the voltages across L_1 and L_2 are zero so that the inductor current will keep constant. The inductor current of L_1 (I_{L1}) circulates through $D5$ and $M1$, and the inductor current of L_2 (I_{L2}) circulates through $M4$ and $D8$.

B. Stage 1 (t_0 – t_1)

At t_0 , $M1$ is turned off and I_{L1} starts to charge C_1 and discharge C_2 at the same time, as indicated in Fig. 6(a). Fig. 6(b) shows the equivalent resonant circuit. In general, we suppose

that C_1 and C_2 are equal. With initial condition $V_A(t_0) = V_{dc}$, we have

$$V_A(t) = V_{dc} - A_1 \sin\left(\frac{t - t_0}{\sqrt{2L_1C_1}}\right) \quad (2-a)$$

$$I_{L1}(t) = \frac{A_1\sqrt{2C_1}}{\sqrt{L_1}} \cos\left(\frac{t - t_0}{\sqrt{2L_1C_1}}\right) \quad (2-b)$$

where A_1 is a constant and will be discussed later.

After V_A drops to 0 V, $D2$ becomes conductive and I_{L1} will flow through $D2$ and $D5$, as indicated in Fig. 6(c). Now, the voltage across L_1 is $-V_{dc}$ so that I_{L1} begins to decrease linearly with slope V_{dc}/L_1 and the energy stored in L_1 is recovered back to the dc bus. Then, $D5$ and $D2$ will be turned off naturally without the problem of reverse recovery when I_{L1} becomes zero.

C. Stage 2 (t_1 – t_2)

After I_{L1} decreases to zero, $M2$ is turned on with zero-voltage transition (ZVT) at t_1 . Now, V_{XY} is equal to V_{dc} and C_p will resonate with L_1 through $M2$ and $D8$, as depicted in Fig. 7(a). The equivalent resonant circuit is shown in Fig. 7(b). With initial conditions $V_{XY}(t_1) = V_{dc}$ and $I_{L1}(t_1) = 0$, we can derive the following equations:

$$V_{XY}(t) = V_{dc} \cos[w(t - t_1)] \quad (3-a)$$

$$I_{L1}(t) = -\frac{V_{dc}\sqrt{C_p}}{\sqrt{L_1}} \sin[w(t - t_1)] \quad (3-b)$$

Fig. 7. Circuit operation at t_1 – t_2 . (a) Before V_{XY} becomes 0 V. (b) Equivalent resonant circuit of (a). (c) After V_{XY} becomes 0 V.

where

$$w = \frac{1}{\sqrt{C_p L_1}}.$$

When V_{XY} decreases to 0 V, $D6$ becomes conductive and V_x is clamped at 0 V, as indicated in Fig. 7(c). The voltage across L_1 is 0 V here, and I_{L1} will keep constant.

D. Stage 3 (t_2 – t_3)

At t_2 , $M4$ is turned off and I_{L2} starts to charge C_4 and discharge C_3 at the same time, as indicated in Fig. 8(a). The equivalent resonant circuit is shown in Fig. 8(b). With initial condition $V_B(t - t_2) = 0$, we have

$$V_B(t) = A_2 \sin\left(\frac{t - t_2}{\sqrt{2L_2 C_3}}\right) \quad (4-a)$$

$$I_{L2}(t) = \frac{A_2 \sqrt{2C_3}}{\sqrt{L_2}} \cos\left(\frac{t - t_2}{\sqrt{2L_2 C_3}}\right) \quad (4-b)$$

where A_2 is a constant and will be discussed later.

After the voltage of C_4 rises to V_{dc} , $D3$ becomes conductive and I_{L2} will flow through $D3$ and $D8$, as indicated in Fig. 8(c). The energy stored in L_2 is recovered back to the dc bus. Then, $D3$ and $D8$ are turned off naturally without the problem of reverse recovery when I_{L2} becomes zero.

E. Stage 4 (t_3 – t_4)

After I_{L2} decreases to zero, $M3$ is turned on with ZVT at t_3 and L_2 starts to resonate with C_p , as depicted in Fig. 9(a).

Because the energy for charging the PDP is equal to that of discharging the PDP, I_{L2} will not become larger than I_{L1} if L_2 is not smaller than L_1 . Therefore, $D6$ keeps conductive and V_X remains zero. The equivalent resonant circuit is shown in Fig. 9(b). With initial conditions $V_{XY}(t_3) = 0$ and $I_{L2}(t_3) = 0$, we can derive following equations:

$$V_{XY}(t) = -V_{dc} + V_{dc} \cos[w'(t - t_3)] \quad (5-a)$$

$$I_{L2}(t) = -\frac{V_{dc} \sqrt{C_p}}{\sqrt{L_2}} \sin[w'(t - t_3)] \quad (5-b)$$

where $w' = (1/\sqrt{C_p L_2})$.

When V_{XY} decreases to $-V_{dc}$, $D7$ becomes conductive and V_Y is clamped at V_{dc} , as indicated in Fig. 9(c). Now, the voltage across L_2 is zero and the inductor current of L_2 will keep constant.

Circuit operations of t_4 – t_7 are analogous with that of t_0 – t_4 .

V. DESIGN CONSIDERATION

In practical implementation, the values of L_1 and L_2 are equal. Therefore, (3-b) and (5-b) can be rewritten as

$$I_{L1}(t) = -\frac{V_{dc} \sqrt{C_p}}{\sqrt{L_1}} \sin[w(t - t_1)] = -I_0 \sin[w_0(t - t_1)] \quad (6-a)$$

$$I_{L2}(t) = -\frac{V_{dc} \sqrt{C_p}}{\sqrt{L_2}} \sin[w'(t - t_3)] = -I_0 \sin[w_0(t - t_3)] \quad (6-b)$$

Fig. 8. Circuit operation at t_2 – t_3 . (a) Before V_B becomes V_{dc} . (b) Equivalent resonant circuit of (a). (c) After V_B becomes V_{dc} .

Fig. 9. Circuit operation at t_3 – t_4 . (a) Before V_{XY} becomes $-V_{dc}$. (b) Equivalent resonant circuit of (a). (c) After V_{XY} becomes $-V_{dc}$.

Fig. 10. Experimental circuit and associated parameters.

where

$$I_0 = \frac{V_{dc}\sqrt{C_p}}{\sqrt{L_1}} = \frac{V_{dc}\sqrt{C_p}}{\sqrt{L_2}}$$

and

$$w_0 = \frac{1}{\sqrt{C_p L_1}} = \frac{1}{\sqrt{C_p L_2}}.$$

From these equations, we know that the initial conditions of I_{L1} at stage 1 and I_{L2} at stage 2 are equal to I_0 . Comparing with (2-b) and (4-b), we get

$$A_1 = \frac{V_{dc}\sqrt{C_p}}{\sqrt{2C_1}} = \frac{V_{dc}\sqrt{C_p}}{\sqrt{2C_3}} = A_2. \quad (7)$$

Because C_p is typically much larger than MOSFET parasitic capacitance, C_1 – C_4 , A_1 and A_2 are much larger than V_{dc} . To achieve ZVT in this driving circuit, each switch must be turned on after its parasitic capacitor has been fully discharged. Therefore, from (2-b) and (3-b), we can get

$$\text{dead time} > \pi \sqrt{\frac{L_1 C_1}{2}}.$$

There is no rigorous way to determine the value of the inductors, however, make sure that it is large enough to avoid abrupt charging/discharging current but will not reduce the response rate.

The switching frequency is determined by the PDP. The luminance of the PDP increases with the frequency. In practical application, the PDP usually works from 80 to 150 kHz.

VI. EXPERIMENTAL RESULTS

Fig. 10 shows the power stage of the experimental circuit with its associated parameters. The plasma display panel under test is 8 in diagonally. Sustain electrodes (X) and (Y) are connected to X-side and Y-side drivers, respectively. Address electrodes are shorted together and connected to ground reference.

The control signals of $M1$ – $M4$ are obtained by using a full-bridge phase-shift pulsewidth modulation (PWM) control IC,

Fig. 11. Experimental waveforms of the proposed circuit. (a) Voltage across PDP and current of PDP (no light emitted). (b) Voltage across PDP and inductor current of L_1 (no light emitted). (c) Voltage across PDP and current of PDP (light emitted). (d) Voltage across PDP and inductor current of L_1 (light emitted).

UC3875. The switching frequency is 90 kHz, which satisfies the practical application of the PDP. The phase shift angle is about 150° to make sure that the gas discharge of the PDP has finished.

Fig. 11 shows the experimental waveforms of the proposed circuit. In Fig. 11(a), we can find that soft current transient is derived by using the proposed circuit. A quite ideal waveform of inductor current I_{L1} is also shown in Fig. 11(b). For the case shown in Fig. 11(c) and (d), there is light emitted and apparent discharging current appears in Fig. 11(c). The waveforms of V_{XY} and I_{L1} are slightly affected by the gas discharge current.

Fig. 12. Soft transition of MOSFETs and diodes. (a) Turn-on transient of $M2$. (b) Turn-off transient of $D5$.

The waveforms of Fig. 12 show that soft transition of the switches and the diodes is achieved in the proposed circuit. In Fig. 12(a), we could find that the inductor current starts to flow through $M2$ to discharge $C2$ at t_0 so that the V_{ds} of $M2$ decreases. After the V_{ds} becomes 0 V, $M2$ is turned on at t_1 with ZVT. The turn-off transient of $D5$ is shown in Fig. 12(b). The reverse recovery current of $D5$ is quite small we could know that $D5$ is turned off naturally. Because the X -side and Y -side drivers are symmetric, we conclude that all the switches are operated with ZVT and all diodes are turned off naturally.

Comparing the power consumption of the proposed driving circuits with that of the simplest driver shown in Fig. 2, we can find the effect of the energy recovery. Supplying the same dc-bus voltage, 200 V, the average input current of the proposed circuit is 0.10 A and that of the simplest driver is 0.14 A. Therefore, about 30% energy is recovered by the proposed circuit.

VII. CONCLUSION

A regenerative driver for the PDP has been proposed in this paper. It utilizes inductors to resonate with the equivalent intrinsic capacitance of the PDP to avoid the abrupt charging/discharging operation. It not only achieves the energy recovery

function, but also performs the soft-switching operation. All active switches are operated with zero-voltage switching and all diodes are turned off naturally without the problem of reverse recovery. Compared with prior approaches, the proposed sustain driving circuit is quite simple. The left-side and right-side circuits can be operated independently so it is not restricted to symmetrical operation and is suitable for practical applications. The presented circuit has been experimentally verified to be applicable on an 8-in PDP.

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