Improved Dual-Path Energy Recovery Circuit using a Current Source and a Voltage Source for High Resolution and Large-Sized Plasma Display Panel

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Abstract- **An improved dual-path energy recovery circuit (ERC) using a current source and a voltage source for plasma display panel (PDP) is proposed. The proposed ERC uses the voltage source to charge a panel and the current source to discharge the panel. Thus, the proposed circuit can make the panel charge to V_S and discharge to 0V, fully and it is possible to achieve zero voltage switching (ZVS) of all switches in H-bridge inverter and zero current switching (ZCS) of all switches in the ERC. Moreover, it has less conduction and switching loss in ERC devices by the dual energy recovery paths for charging and discharging the panel. Furthermore, it has features of canceling the gas discharge current, high performance and the low cost ERC components. The operation principle and features of the proposed ERC are presented in detail and verified with 42-inch SD PDP.**

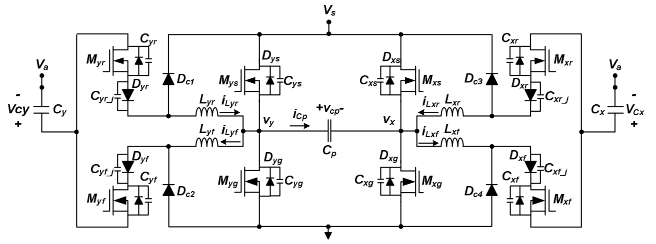
I. INTRODUCTION

Flat panel displays (FPDs) such as liquid crystal display (LCD), organic light emitting diodes (OLED) display and plasma display panel (PDP) can replace a conventional cathode ray tube (CRT) because there has been a continuous increase in the demand for a large size, high resolution and high information capacity with the digital broadcasting and the infrastructure of digital net works represented by the Internet. Among the FPDs, PDP has become a promising high-definition display technology for the digital broadcasting due to the wider view angle, larger screen, higher brightness, higher contrast and thinness. Because of the relative merits, the PDP is expected to widen its share in the digital display market. However, high cost and high power loss of the PDP has been obstacles to attract consumers. Thus, low cost and high efficiency become the main requirements in a high resolution and large-sized PDP with the limited space and weight [1]. The Y electrode and the X electrode are in the front glass plate. A dielectric layer covers these electrodes. A protective layer (MgO) is deposited on the dielectric surface to protect the dielectric from sputtering and to provide large secondary electron emission under ion impact. The address electrode, which is orthogonal to the Y and X electrodes, is in the rear glass plate. Three color phosphors of red, green, and blue are deposited above the address electrodes. The barrier ribs between the data electrodes play a role to separate each discharging cell. The space between the two opposing substrates is filled typically with a gas mixture of Ne and Xe and the pressure of the gas is approximately 400–500 torr.

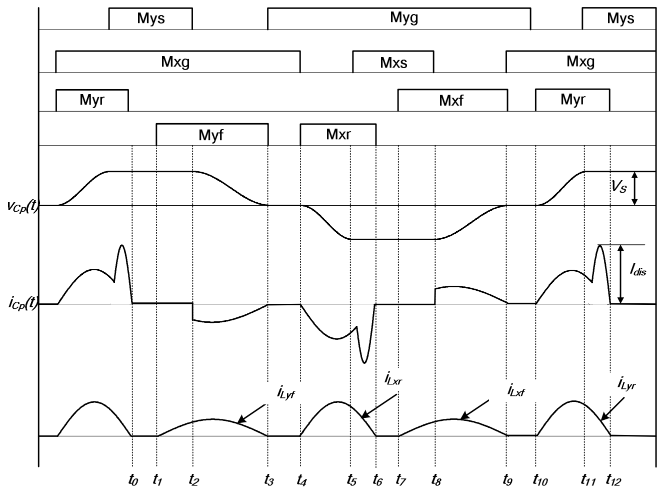
Recently, a well-known address display separation (ADS) driving method is generally adopted to display the image on the PDP by most of PDP makers. In this method, the PDP operation is composed of three intervals: reset, address, and sustain periods. During reset period, all PDP cells are initialized. Then, during address period, selective write discharges are ignited to form a required image by applying data. However, since the address discharge itself emits an insufficient visible light, ac high-voltage square-wave sustaining pulses generated by the sustain circuit are continuously applied between X and Y electrodes for the strong light emission of selective cells during sustain period [2].

To generate these alternative current (ac) high-voltage sustaining pulses in the ac PDP, a well-known simple H-bridge inverter, sustain driver, is generally adopted to convert a direct current (dc) voltage to a high-frequency ac voltage. However, as mentioned previously, the PDP is regarded as a capacitive load (C_p) due to the dielectric and the protective layers. Therefore, when applying ac high-voltage and high-frequency square-wave pulses between and electrodes, subsequent excessive surge charging and discharging currents will give rise to electromagnetic interference (EMI) noises and heating problems in all switching devices. Especially, this surge current could considerable energy loss of $2C_pV_s^2$ for each cycle in the non-ideal resistance of circuit and PDP during charging or discharging interval.

To relieve these problems, the energy recovery circuit (ERC) must be embedded in the sustain driver for PDP [3-13]. Most PDP makers have used the circuit proposed by Weber et al. due to its high efficiency and good flexibility [3]. Also, many researches have been done to get better efficiency and simpler structure than that of the prior circuit [4-13]. The circuits proposed in [4-6] feature a very simple structure. However, expensive power devices are required and the overall system efficiency and performance are degraded due to the excessive circulation current. Other circuits have been proposed to lower current or voltage stress of the power switches [7-8]. Although the lower rating devices can be used in the proposed circuits and higher efficiency and performance were obtained, the structure of the driver is complex and the cost is high because more switches are used. To get high efficiency in the energy recovery circuit, many ERCs has been studied [9-13]. They have solved the problem in the circuit by Weber et al. The Weber's circuit used the resonance between a inductor and a panel capacitor to charge and discharge the panel. However, since there are parasitic component such as an equivalent series resistor (ESR) and a diode forward voltage drop in driving circuit board, the panel voltage cannot be fully charged and discharged. Thus, the circuits have used the current source or shifting bias voltage level to solve the drawback in the prior circuit [9-13].



(a)



(b)

Fig. 1. Proposed circuit and its key waveforms (a) Circuit diagram of the proposed ERC (b) Key waveforms

In the paper, improved ERC using a current source and voltage source is proposed to get reduction of power consumption in the ERC and the H-bridge inverter. The proposed circuit uses the current source and the voltage source to discharge or charge the panel so there are zero voltage switching (ZVS) in the main H-bridge inverter switches and zero current switching (ZCS) in the ERC switches. The proposed ERC uses address voltage as a voltage source so a remained current can compensate the huge gas discharge current in H-bridge inverter after charging the panel. Also, the improved circuit has different rising and fall time of the rectangular sustaining pulse. A fast rising time related with plasma discharge and a slow falling time unrelated to plasma discharge are required to improve the image quality and energy efficiency. Furthermore, there are low power consumption and well heat dissipation in ERC switches and inductors by dividing energy recovery paths. Therefore, the proposed ERC can get higher efficiency and higher performance in high resolution and large-sized PDP.

II. PROPOSED ENERGY RECOVERY CIRCUIT

Fig. 1 shows a circuit diagram and key waveforms of the proposed ERC. Address bias voltage source is used to charge the panel. To divide the ERC paths, there are four inductors. An operational principle of the proposed circuit is explained as follows. The circuit operation has 12 modes, but since mode 0 ~ mode 5 and mode 6 ~ mode 11 are symmetric, mode 0 ~ mode 5 will be only considered. Following assumptions are made for the analysis of the operation.

- All parasitic components are neglected.
- The capacitance of C_x and C_y are much larger than the panel capacitance.
- The voltages of the C_x and C_y are over $V_S/2-V_a$.
- The switches have a output capacitor and an intrinsic body diode.

Mode 0 **(t_0~t_1)**: M_{ys} and M_{xg} have been turned on and the panel voltages, v_{Cp} , is V_S at mode 0.

Mode 1 **(t_1~t_2)**: Mode 1 begins when M_{yf} is turned on at t_1. A current of L_{yf} is built up until t_2 with slope of $(V_S-V_{cy}-V_a)/L_{yf}$. The built up current can help the panel discharge to 0V. The inductor current, i_{Lyf}, can be expressed as follows.

$$i_{Lyf}(t) = \frac{V_S - V_a - V_{Cy}}{L_{yf}}(t - t_1) \tag{5}$$

Mode 2 **(t_2~t_3)**: Mode 2 begins when M_{ys} is turned off. By a series resonance of panel capacitor C_p and inductor L_{yf} with the built up initial current $i_{Lyf}(t_2)$ current and V_a+V_c bias voltage, the panel voltage, v_{Cp}, is decreased to 0V until t_3.

$$v_{Cp}(t) = V_S + (V_S - V_a - V_{Cy})\left(1-\cos\frac{t}{\sqrt{C_pL_{yf}}}\right) - i_{Lyf}(t_2)\sqrt{\frac{L_{yf}}{C_p}}\sin\frac{t}{\sqrt{C_pL_{yf}}} \tag{6}$$

Mode 3 **(t_3~t_4)**: M_{yg} is turned on at t_3 and the panel voltage, v_{cp}, maintains zero. At this mode, the switch M_{yg} can be turned on the ZVS condition and the panel can be fully discharged *0V* because the current source, $i_{Lyf}(t_2)$, can help the panel fully reach to *0*V although there are the parasitic components and the bias voltage is larger than $V_S/2$.

Mode 4 **(t_4~t_5)**: When M_{yg} is turned off and M_{xr} is turned on, mode 4 begins. At mode 4, the panel voltage can be charged to V_S by a series resonance of panel capacitor C_p and the inductor L_{xr} with V_a+V_{cx} voltage bias. The panel voltage can be expressed as follows.

$$v_{Cp}(t) = (V_a + V_{Cx})\left(1-\cos\frac{t}{\sqrt{C_pL_{xr}}}\right) \tag{7}$$

Mode 5 **(t_5~t_6)**: After the panel voltage is charged to V_S and M_{xs} is turned on, the gas discharge will be occurred. Since the voltage source which is larger than $V_S/2$ is used, the panel voltage can be charged fully to *Vs* and M_{xs} can achieve the ZVS even if there are parasitic components. Moreover, the remained ERC inductor current, $i_{Lxr}(t_5)$, can be compensated the huge gas discharge current of main H-bridge inverter after the panel is charged to *Vs*. After the panel voltage is reached to V_S, the current is decreased as follows.

$$i_{Lxr}(t) = i_{Lxr}(t_5) - \frac{V_S - V_a - V_{Cy}}{L_{xr}}(t - t_5) \tag{8}$$

The ERC switch, M_{xr}, and diode D_{xr} can achieve the ZCS because those are turned off when the remaining inductor current, i_{Lxr}, becomes zero at t_6. Then, the mode 5 is finished.

In the circuit diagram, diodes such as D_{c1}~D_{c4} are used for clamping a drain-source voltage of ERC switches similar to the conventional driver. Generally, the prior circuit has used ERC inductors in parallel because of heat dissipation. However, the proposed circuit can improve the heat dissipation and the power loss in ERC inductors by dividing the ERC current path. Moreover, the falling time of sustaining pulse can be designed longer than a rising time because the falling time is not related to the gas discharge as shown in Fig. 1 (b). Root mean square (RMS) current value of the falling ERC inductors, L_{yf} and L_{xf}, can be small, remarkably. Thus,

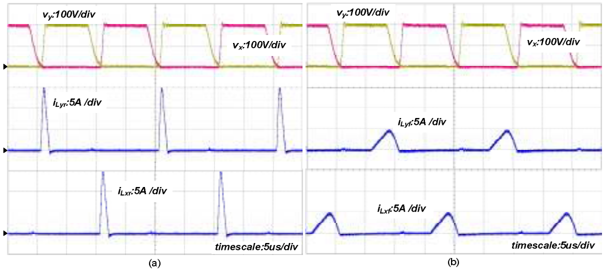


Fig. 2. Experimental waveforms (a) The panel voltage and the inductor currents during charging the panel (b) The panel voltage and the inductor currents during discharging the panel

the power consumption in D_{yf}, D_{xf}, M_{yf} and M_{xf} will be reduced. As mentioned above, the voltage source is used to charge the panel and the current source is done to discharge it. As results, the energy of the panel can be fully recovered and fed and all power switches in the H-bridge inverter can achieve the ZVS and the switching devices in the ERC are able to do the ZCS by the proposed ERC. Moreover, the large gas discharge current can be compensated by the remained inductor current after the panel voltage is charged, so the power consumption in the H-bridge switches can be reduced.

III. Experimental results

An experiment of the proposed circuit for verifying operation is performed with a 42-inch SD PDP which has about 80nF of a panel capacitance, C_p, in 200V sustaining voltage and 65V addressing voltage at 50 kHz. Components are in this circuit as follow: the H-bridge switches M_{ys}, M_{yg}, M_{xs} and M_{xg}: IXYS63N25, the M_{yr}, M_{yf} , M_{xs} and M_{xf}: IXYS63N25, diodes: 30CPF06, the inductor L_{yr}=L_{xr} for T_r=$1\mu s$:$7\mu H$, the inductor L_{yf}=L_{xf} for T_r=$2\mu s$:$40\mu H$. Fig. 2 and Fig. 3 show experimental results. As can be seen in Fig. 2, the v_{cp1} is charged and discharged without hard switching. In addition, it shows that peak values of i_{Lyf} and i_{Lxf} for a falling slope is smaller than those of i_{Lyr} and i_{Lxr} for a rising slope due to L_{yf}=L_{xf}≤L_{yr}=L_{xr}. Also, the inductor currents are almost zero after finishing the energy recovery operation. It means those have the small free wheeling currents, which are the needless power consumption. Fig. 3 shows waveforms of soft switching in the H-bridge inverter switches and the ERC switches. As you can see in Fig. 3 (a), the switches in H-bridge inverter achieve the ZVS and those in the ERC also do the ZCS as shown in Fig. 3 (b). It shows the experimental waveforms are coincided with the theoretical key waveforms.

IV. Conclusion

An improved dual-path energy recovery circuit (ERC) using a current source and a voltage source for plasma display panel (PDP) has been proposed in this paper. The proposed ERC has used two sources like as the voltage source and the current source to perform energy recovery. So, different from prior circuit, the panel voltage can be fully charged to Vs and discharged to 0V though the resolution and size of PDP is larger. The switches of H-bridge inverter can achieve the ZVS even if there are parasitic components. Even though the current source is used for discharging the panel, the ERC devices can be turned off on the ZCS condition. Moreover, it has features of canceling the gas discharge current, high performance and low power consumption by the different transition time and dual energy recovery path. Therefore, the proposed circuit can be expected to be suitable as an ERC for the high resolution PDP TVs.

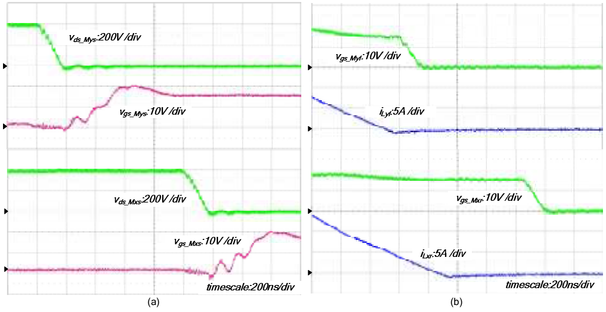


Fig. 3. Experimental waveforms (a) The ZVS in the H-bridge switches (b) The ZCS in the ERC switches

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