Energy Recovery Circuit for the Plasma Display Panel Sustainer

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Abstract

In this paper, several energy recovery circuits (ERC) for the plasma display panel (PDP) are reviewed and classified in a manner of operation characteristics. A typical ERC using the Regenerative Transformer (RT) is introduced and compared with conventional ones. RT-ERC can achieve zero-voltage-switching (ZVS) for main full-bridge switches and zero-current-switching (ZCS) for the resonant switches and diodes. The charging/discharging energy of panel capacitance is efficiently recovered with the RT and without a sub-circuit. The presented circuit is verified with simulation and experimental results.

1. Introduction

The merits of large screen size, wide viewing angle, rapid response, high contrast, long life and thinness make the PDP a front runner in the large size wall-hanging TV market. The AC-PDP is widely used due to its durability and memory effect. The dielectric structure introduces intercapacitances in each electrode. The full bridge inverter is normally used to charge and discharge the PDP cell. When a waveform such as the one shown in Fig.1 is directly supplied to the PDP, power consumption equals $2C_pV_s^2 f$ for each cycle and is proportional to the switching frequency. Supplying the square type voltage to the capacitive load induces a sharp charging/discharging surge current which causes serious electromagnetic interference (EMI) problem and excessive current stresses on the switch devices.

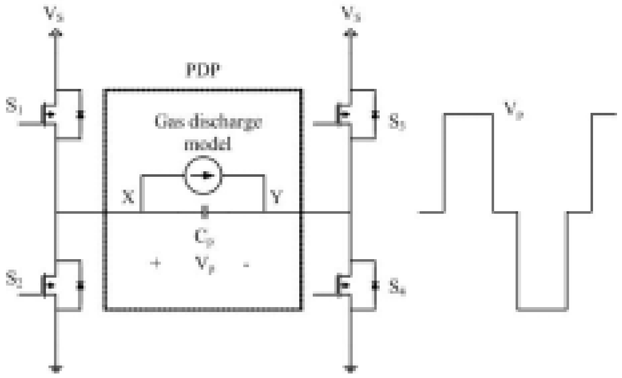


Fig. 1 Equivalent model of PDP with simple driver

To solve above mentioned problems, various energy recovery circuits (ERC) using the resonant concept have been introduced. The resonance between an external inductor and the panel capacitance not only recovers the induced energy of the panel but also provides a soft transition of the sustaining voltage to minimize the EMI noise and the current stress on the devices.

In this paper, various ERC schemes are categorized by means of the resonant type and driving method and qualitative comparisons are summarized. Also, two main topologies representing the series and parallel resonance schemes are reviewed focused on the potential problems. Recent development of ERC using a regenerative transformer to overcome the shortfall of the previous topologies is introduced.

2. Classification of ERC

The ERC can mainly be categorized by the type of the resonant scheme and the driving voltage level variation as shown in Fig. 2. The parallel resonant scheme uses a current source and the series resonant scheme uses a voltage source for the resonant energy source.

2.1 Current source parallel resonant scheme

The main characteristics of the current source ERC are as follows; the maximum number of auxiliary switch is one or zero, the charging/discharging of both inductor and load capacitor is operated by the main switches, the main switches achieve ZVS condition, the amount of current source determine the charging/discharging time, the circulating current makes conduction loss, the turn-off loss and EMI noise problem is happened by the non ZCS-off of the main switches, and DC voltage blocking capacitor preventing the saturation of the inductor is required.

2.1.1 2-level scheme current source ERC

Fig. 3(a) shows the 2-level type current source ERC. The charging/discharging voltage of the inductor is the same as the voltage of load voltage and determines the value of the current source. This circuit is the simplest configuration, requiring the DC voltage blocking capacitor. It operates forced commutation of the inductor current.

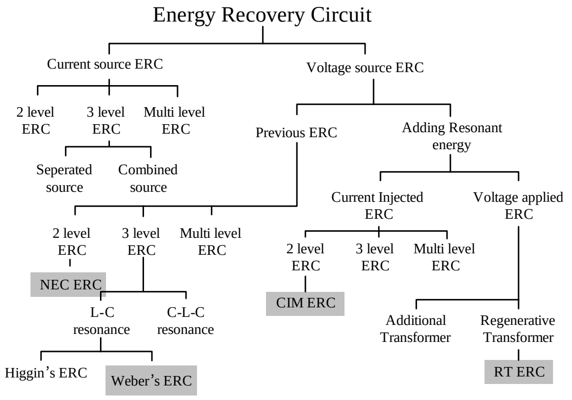


Fig. 2 Classification of energy recovery circuit

2.1.2 3-level scheme current source ERC

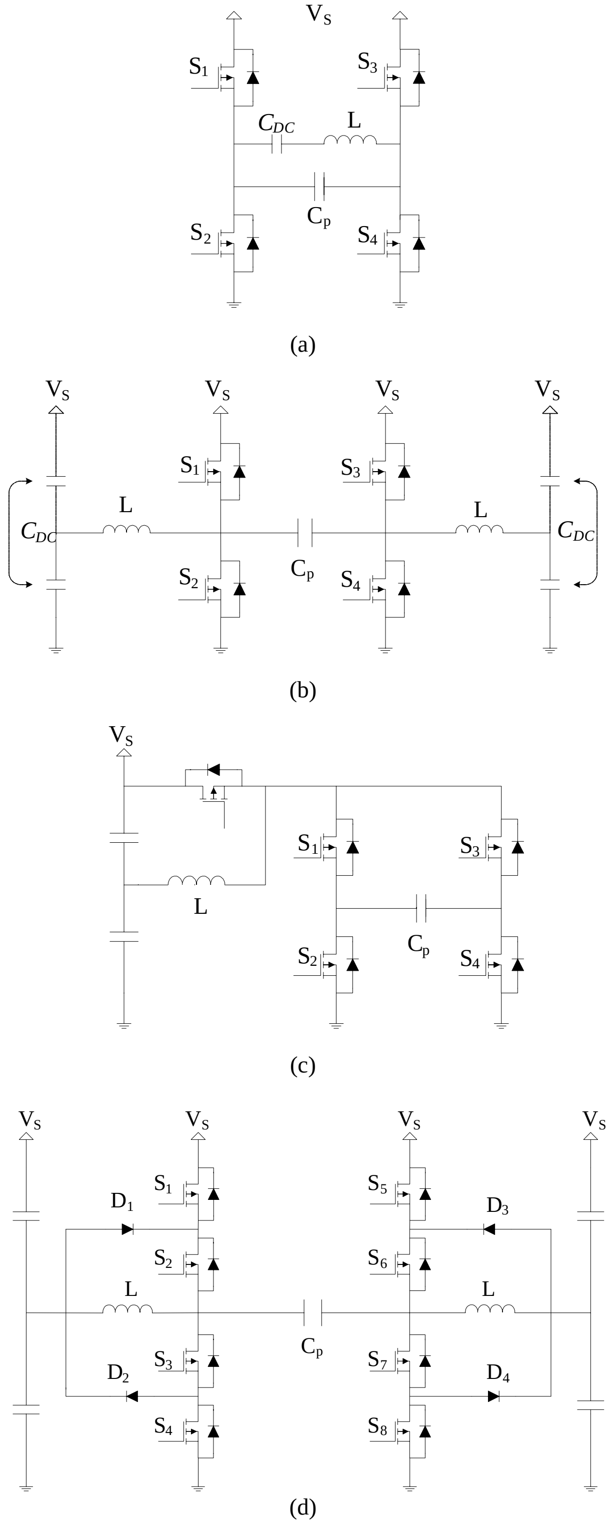
The 3-level type current source ERC is shown in Fig. 3(b). The voltage difference between the source and capacitor determines the inductor charging/ discharging voltage. The maximum of 4 capacitors operate as the voltage source as well as the DC voltage blocking devices. The other configuration of current source is shown in Fig. 3(c). Two inductor of the 3-level type ERC is combined to one an auxiliary switch. In this topology, the frequency is increased two times, the number of DC voltage blocking capacitor is reduced to two, the forced commutation of inductor current is required, and the auxiliary switch on the main power pass increases the conduction loss and current stress. Therefore, this circuit is not suitable for the large size PDP.

2.1.3 Multi-level scheme current source ERC

Fig. 3(d) shows the multi-level type current source ERC. The voltage stress is reduced to the half of the three level's. The multi-level capacitors can also be used for the DC-blocking capacitor. The number of switches is twice as many as the 3-level ERC and clamping diodes are required. The forced commutation of the inductor current is also happened.

2.2 Voltage source series resonant scheme

The voltage source ERC consists of the voltage source, panel capacitance and series inductor network. The charging/discharging time is determined by the half of the resonant period, which is controlled by the auxiliary switches. Due to the auxiliary circuit, it has complicated structure and driving method. However, the resonant current flow only during charging/ discharging period, it is suitable for the high driving voltage and large size PDP. The soft switching of auxiliary switch helps to minimize the conduction loss and EMI problems.



(a)

(b)

(c)

(d)

Fig. 3 Current source Energy Recover Circuit; (a) 2-level type, (b) 3- level type using two inductor, (c) 3-level type using one inductor and an auxiliary switch

2.2.1 2-level scheme voltage source ERC

Fig. 4(a) shows the 2-level type voltage source ERC [1]. It has simple configuration and requires one resonant inductor. The auxiliary switch is turned off with ZCS.

2.2.2 3-level scheme voltage source ERC

The 3-level type voltage source ERC is shown in Fig. 4(b). The series resonance is occurred by the input voltage. During the charging/discharging period, the auxiliary switches are turned off at 1/2Vs, which cause the high surge current due to the capacitive energy. The other type ERC using auxiliary voltage source is shown in Fig. 4(c) [2]. The auxiliary capacitor is charged to $1/2V_S$ and used for the resonant voltage source. During the charging/ discharging period, the panel capacitor configures the series resonant network with resonant inductor. The auxiliary switches are turned off with ZCS condition.

2.2.3 Multi-level scheme voltage source ERC

Fig. 4(d) shows the multi-level type voltage source ERC. The voltage stress of the main switches is reduced to half of the 3-level type. 4 groups of the auxiliary resonant circuit are required. The numbers of switches are doubled. The ZCS-off condition of the auxiliary switches are achieved

The current source ERC has simple structure and easy driving scheme. Due to the conduction loss and device stress, it is suitable for the low cost circuit which is capable to drive low capacitive energy. The voltage source ERC is complicated for its structure and driving mechanism. However, separations of the transient time from main switch operation makes it available driver for the high capacitive energy recovery application. Conduction loss and current stress are also minimized.

3. ERC with Regenerative Transformer

The conventional circuits have simple LC resonant method and involve the imperfection of ZVS switching due to the parasitic resistance including on-resistances of switches and the diode on drop. Increase of the parasitic resistance results in the recovery efficiency to be degraded. The high surge current causes EMI and switching stress. Reduction of the inductor produces similar result and not desirable in the aspects of driving loss and EMI [5].

In order to compensate the shortage of resonant energy, the current injection mode (CIM) ERC has

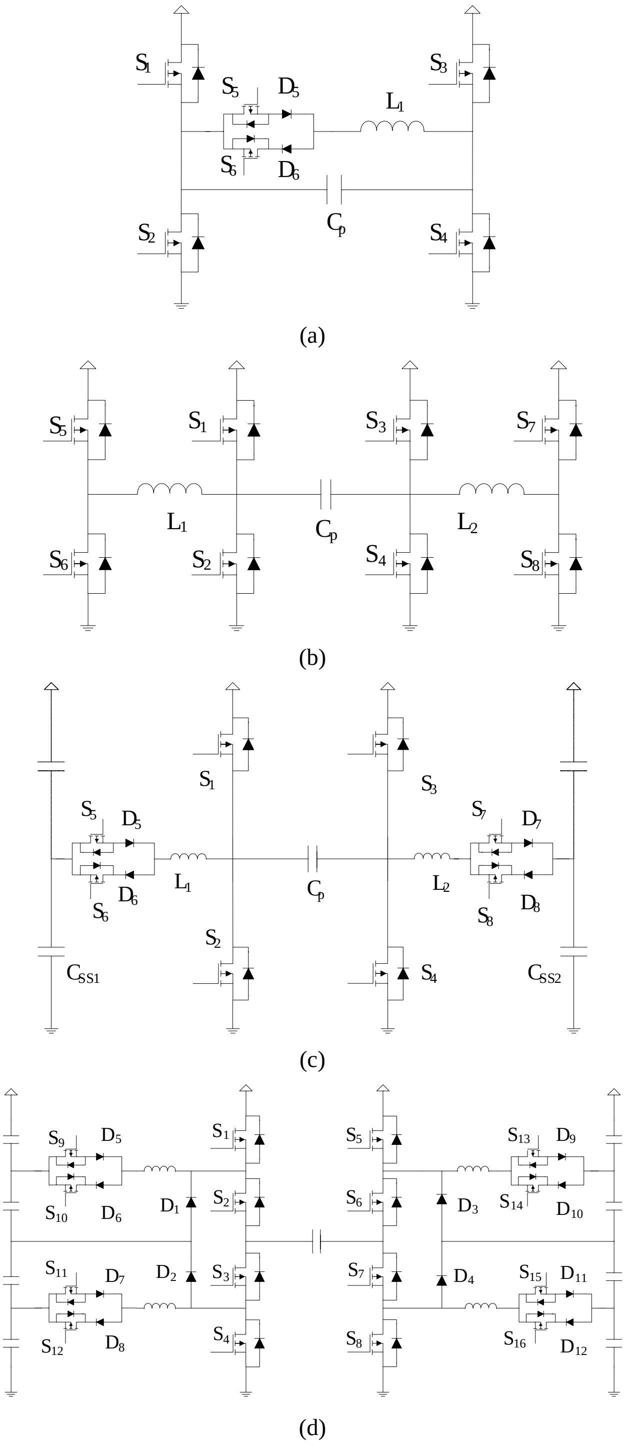


Fig. 4 Voltage source Energy Recover Circuit; (a) 2-level type, (b) 3- level type using two inductor, (c) 3-level type using two inductor and two capacitors, (d) multi-level type ERC

been introduced (Fig. 5) [5]. Before inverting the polarity of the panel electrodes, the inductor current is built up (called “build-up current”) and it is used to invert the panel polarity together with the energy previously charged in the panel capacitance. However, during the build-up time, it has the circulating current loss and the build-up current increases the peak and rms value of the inductor current. It thus causes more conduction loss, higher peak current stress and complicated design considerations.

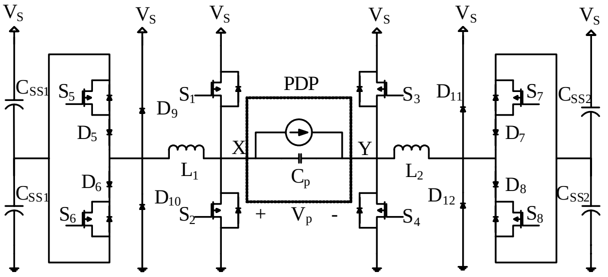


Fig. 5 Current Injection Mode ERC

3.1 Parallel Resonance type ERC

Another approach to achieve ZVS operation is the introduction of a transformer using ZVS switching that can be easily obtained by adjusting the turns ratio(α).

Fig.5 (a) shows the parallel resonance type ERC. The proposed circuit consists of clamping switches (S_1 ~ S_4), auxiliary switches (S_5 ~ S_8), diodes (D_5 ~ D_6), resonant inductors (L_{1k}), and the three tapped transformer(T_x). The T_x configures the parallel resonance network with the previous ERC and supplies the auxiliary voltage for the full ZVS of main switches. The leakage inductance of the transformer can be used as resonant inductors. The modes of operation are as follows.

Mode 1[t_0 ~ t_1]: Before t_0, S_1 and S_4 are on and the voltage of panel capacitance (V_P) is V_s. At t_0, both switches go to the off state, and turn S_6 and S_8 on. L_{lk} – V_{tx1} – D_6 – S_6 – C_p composes the resonant circuit. V_{cp} goes to $-V_s$ with resonance manner.

Mode 2 [t_1 ~ t_2]: At t_1, V_{cp} clamps to –Vs due to the auxiliary voltage source (V_{tx1}). Now the current starts to flow through the body diodes of S_2 (D_2) and S_3 (D_3). At this time, the ZVS condition of S_2 and S_3 is achieved.

Mode 3 [t_2 ~ t_3]: When D_2 and D_3 conducts, S_6 and S_8 is turned off and S_2 and S_3 on. The main switch can be turned on with ZVS.

The opposite side circuit operates with the same modes as above.

At the charging/discharging period, resonant current flows through the primary side of the transformer(T_{x1}) and the secondary side sustain voltage is applied to T_{x1} with respect to the turns ratio. No matter what the parasitic effect and the voltage drop induce, the panel voltage can clamp to the sustain voltage in equation (4). In this case, α should be defined as its minimum value to minimize the conduction loss of the secondary side of the transformer.

Additional transformer type ERC

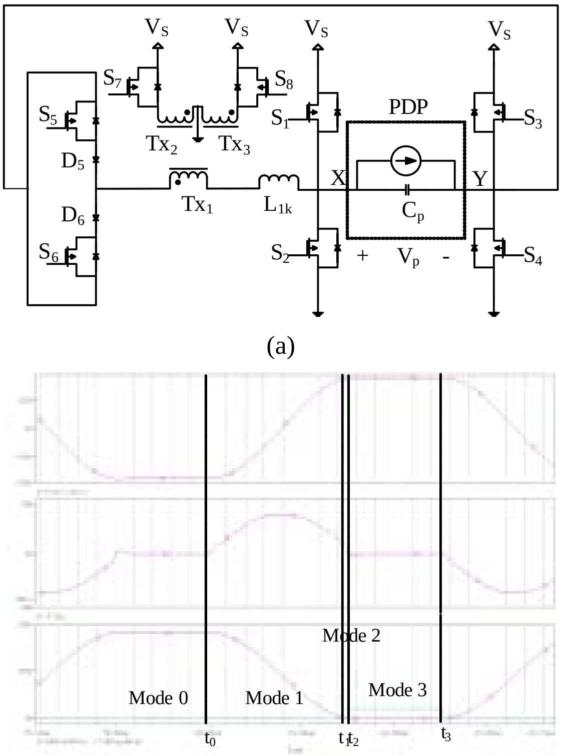
$$V_{cp}(t) = \left((1+\alpha)V_s - V_{on}\right)\left[1 - e^{-\frac{t}{\tau}}(\cos wt + \frac{R}{2\omega L}\sin \omega t)\right] + V_{on}$$

$$V_{cp,\max} = \left((1+\alpha)V_s - V_{on}\right)\left[1 + e^{-\frac{\pi R}{2}\sqrt{\frac{Cp}{L}}}\right] + V_{on} \qquad (1)$$

Where α = turns ratio of AT,

$\tau = (2L/R)$ and

$\omega = \sqrt{(1/LC_p) - (R/2L)^2}$



(a)

(b)

Fig. 5 Additional transformer type ERC (SNU_1) and key waveforms: (a) circuit configuration, (b) key waveforms: V_{cp}, I_{cp}, V_{ds1}, V_{g1} (from top to bottom)

3.2 Series Resonance type ERC

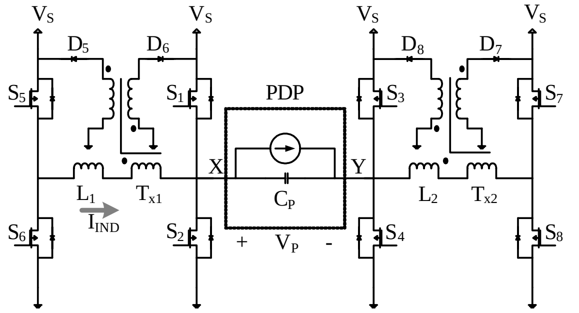
Fig. (6) shows the ERC using RT. This circuit consists of clamping switches ($S_1 \sim S_4$), resonant switches ($S_5 \sim S_8$), diodes ($D_5 \sim D_8$), resonant inductors (L_1, L_2) and regenerative transformers (T_{X1}, T_{X2}). The leakage inductance of the transformer can be used as resonant inductors. The regenerative transformer is very small because it operates at high frequency only during charging/discharging transients. The transformer recovers the capacitive energy to the input voltage source during charging/ discharging resonance. Furthermore, the primary side voltage with respect to the turns ratio determines the resonant condition. The modes of operations are as follows.

Regenerative transformer type ERC

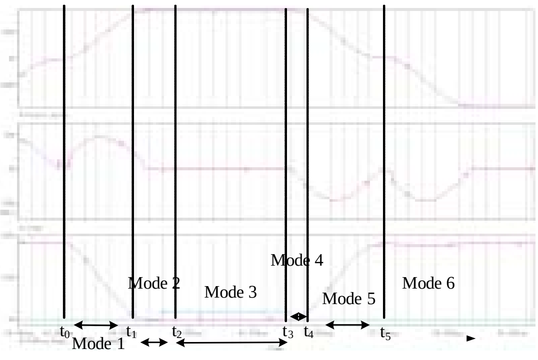
$$V_{cp}(t) = \left((1-\alpha)V_s - V_{on}\right)\left[1 - e^{-\frac{t}{\tau}}(\cos wt + \frac{R}{2\omega L}\sin \omega t)\right]$$

$$V_{cp,\max} = \left((1-\alpha)V_s - V_{on}\right)\left[1 + e^{-\frac{\pi R}{2}\sqrt{\frac{Cp}{L}}}\right] \qquad (2)$$

Where α = turns ratio of RT



(a)



(b)

Fig. 6 Regenerative transformer type ERC (SNU_2) and key waveforms: (a) circuit configuration, (b) key waveforms: V_{cp}, I_{cp}, V_{ds1}, V_{g1} (from top to bottom)

Mode 1[$t_0 \sim t_1$]: Before t_0, S_4 is on and the voltage of the panel capacitance (V_P) is zero. At t_0, S_5 is turned on. The resonant inductor (L_1) - panel capacitor (C_p) pass through S_5 and S_4, and forms a series resonant circuit. The transformer voltage (V_{tx1}) can be thought as a voltage source. If V_{tx1} is lower than half of V_S, V_P becomes V_S before the inductor current (I_{L1}) reaches zero. The transformer's current is recovered through D_5.

Mode 2 [$t_1 \sim t_2$]: At t_1, the body diode of S_1 is turned on. V_P is clamped at V_S. At this time, S_1 is turned on with 100% ZVS condition and the S_5-L_1-V_{tx1}-S_1 pass forms a closed circuit. I_{L1} linearly decreases. The transformer's current is also recovered through D_5.

Mode 3 [$t_2 \sim t_3$]: When I_{L1} becomes zero, D_5 is naturally turned off. At this time, S_5 is turned off under the ZCS condition. S_1 clamps at V_P as V_S for the proper PDP gas discharge.

Mode 4 [$t_3 \sim t_4$]: At t_3, S_6 is turned on and S_6-L_1-V_{tx1}-C_P form a series resonant circuit. If V_{tx1} is lower than half of V_S, V_P becomes zero before I_{L1} reaches zero. The transformer's current is recovered through D_6.

Mode 5 [$t_4 \sim t_5$]: At t_4, the body diode of S_2 is turned on. V_P is clamped as zero. At this time, S_2 is turned on under ZVS condition and S_6-L_1-V_{tx1}-S_2 form a closed circuit. I_{L1} linearly increase. The transformer's current is also recovered through D_6.

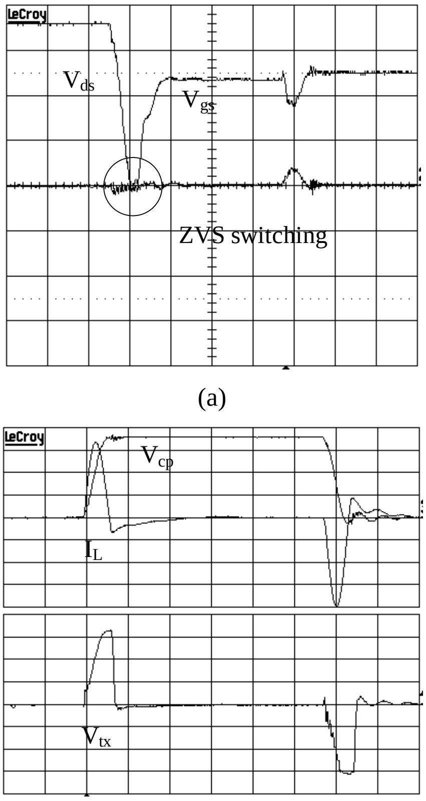
Mode 6 [$t_5 \sim t_6$]: I_{L1} becomes zero. D_6 is naturally turned off. At this time, S_6 is turned off under ZCS condition. S_2 clamps V_P as zero.

The opposite side circuit has the same operating modes as above.

The proper design can achieve 100% ZVS for clamping switches regardless of the circuit's conduction loss. Therefore the gating sequence of the clamping switches is easily implemented by sensing the drain-source voltage of the switches. In a charging/discharging mode (mode 1-2, mode 4-5) the resonant current flows through the secondary side of the Transformer and recovers to the source.

3.3 Experimental Result

Fig. 7 shows the panel voltage (V_{cp}) and the inductor current (I_L). The panel capacitance is 110 nF. The resonant inductance is 300 nH which is the leakage inductance of the transformer. The switching frequency is 200 kHz. The input voltage is 180 V. As shown in Fig. 7 (b), V_P is clamped at V_S and zero before I_{L1} reaches zero and then, I_{L1} becomes zero. Therefore, ZVS of S_1, S_2 and ZCS of S_5, S_6, D_5, D_6 are achieved. The negative current is caused by the reverse-recovery of D_5, D_6. It can be improved by using fast recovery diodes. ZVS switching is easily obtained by adjusting the turns ratio, but decreasing the turns ratio increase the conduction loss and the current stress. α can be determined to be the highest ratio close to $V_s/2$.



(a)

(b)

Fig. 7 Experimental waveform of RT type ERC (SNU_2): (a) V_{ds1} with V_{g1}, (b) V_{cp}, I_L and V_{tx} (from top to bottom)

4. Conclusion

The ERC topologies are categorized by the type of the resonant scheme and the voltage driving method. Pros and cons of each topology is discussed. ERCs employing a regenerative transformer for an auxiliary resonant energy source are introduced. This additional voltage source provides full ZVS condition and higher energy recovery capability are verified with simulation and experimental results. The proposed ERC scheme appears to be highly promising as a PDP sustainer with stable discharge characteristics.

5. References

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