A Novel LLC Resonant Controller with Best-In-Class Transient Performance and Low Standby Power Consumption

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***Abstract*—This paper introduces a novel LLC resonant controller with better light load efficiency and best-in-class transient performance. A new control algorithm – hybrid hysteretic control, is proposed which combines the benefit of charge control and frequency control. It maintains the good transient performance of charge control, but avoids the related stability issues by adding slope compensation. The slope compensation also helps to sense the resonant capacitor voltage by only using lossless capacitor divider. Burst mode operation is developed to improve the light load efficiency. By turning on the power devices for only a short period during light load, it helps to reduce the equivalent switching frequency and achieve high efficiency. The effectiveness of the proposed controller has been validated in a 12 V/120 W half-bridge LLC converter, as well as a commercial power supply unit.**

Keywords—LLC, Resonant Converter, Light Load Efficiency, Transient Performance, Burst Mode

I. INTRODUCTION

Many consumer applications with mid-high power consumption, including large screen televisions, AC-DC adapters, server power supplies, and LED drivers, employ PFC + LLC power supplies because they offer improved efficiency, and small size, compared with a PFC + Flyback topology. A disadvantage of the PFC + LLC power supply system is that it naturally offers poor light load efficiency and high no load power consumption [1-2]. To meet the more stringent light load efficiency and no load power consumption requirement [3-4], it is therefore necessary to use an auxiliary flyback converter that runs continuously and allows the main PFC + LLC power system to be shut down when the system enters low power or standby mode.

In this paper, a new LLC controller is proposed to achieve excellent light load efficiency and no load power consumption, which provides the possibility to get rid of the auxiliary flyback converter. Advanced burst mode operation is developed to maintain a high efficiency at light load. In this mode the LLC converter operates at relatively high power for a short burst period and then all switching is stopped for a space period, to effectively reduce the switching frequency. The burst mode is also optimized to avoid excessive high switching frequency for reduced switching loss.

A novel control algorithm – Hybrid Hysteretic Control – is also proposed to achieve the best-in-class transient performance. It is a combination of charge control [5-6] and direct frequency control [7-8]. Comparing with traditional frequency control, the proposed hybrid hysteretic control changes the system transfer function from a 2nd order system to a 1st order system, which makes it easy to compensate. The control effort is directly related to input current, so the line and load transients are best-in-class. Comparing with charge control, the hybrid hysteretic control avoids unstable condition by adding in a frequency compensation ramp. The frequency compensation makes the system always stable, and makes the output impedance lower as well. Lower output impedance makes the transient performance better than charge control. The hybrid hysteretic control also makes the control of burst mode much easier.

The proposed controller [9] has been verified in a 12V/120W half-bridge LLC converter and a commercial power supply unit. Corresponding experimental results are presented in section V.

II. HYBRID HYSTERETIC CONTROL FOR LLC CONVERTER

Hybrid hysteretic control is a proposed method which combines traditional frequency control and charge control – It is charge control with added frequency compensation ramp. Fig. 1 shows the basic operating principle of the proposed hybrid hysteretic control in a half-bridge LLC converter. The resonant capacitor voltage is divided down and level shifted (e.g. capacitor divider) to get the voltage at point A. The frequency compensation ramp is a triangular wave with constant slope. The ramp is synchronized with the high side and low side gate drive signals HO and LO. When high side switch is on, the ramp slope is positive, when low side switch is on, the ramp slope is negative. The compensation ramp has the same common mode voltage (Vcm) as the divided and level shifted version of the resonant capacitor voltage. The two voltages are then added together to get VCR node voltage. If the frequency compensation ramp dominates, the VCR node voltage will look like a triangular waveform, and the control will be similar to direct frequency control. If the resonant capacitor voltage dominates, the shape of the VCR node voltage will look like the actual resonant capacitor voltage, and the control will be similar to charge control. This is why the

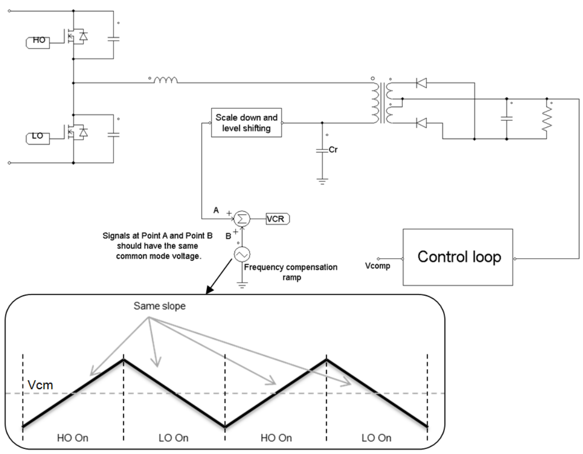

Fig. 1: Hybrid hysteretic control operating principle

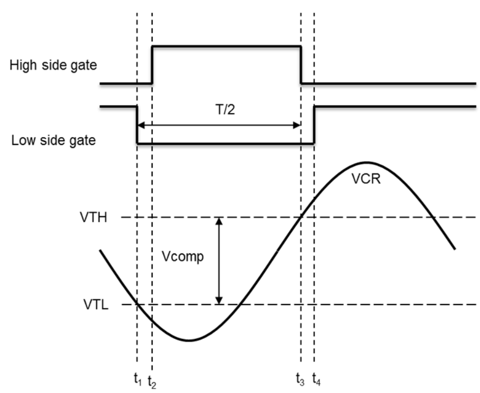

Fig. 2: Gate on/off control

control method is called "hybrid" and the compensation ramp is called frequency compensation.

There are two input signals needed for the hybrid hysteretic control – VCR and Vcomp. VCR is the sum of the scaled down version of the resonant capacitor voltage and the frequency compensation ramp. Vcomp is the voltage loop compensator output. Fig. 2 explains how the high side and low side switches are controlled based on VCR and Vcomp. The common mode voltage of VCR is VCM, and two thresholds are generated based on the following equations:

$$VTH = VCM + Vcomp/2 \quad (1)$$

$$VTL = VCM - Vcomp/2 \quad (2)$$

The VCR voltage is compared with the two thresholds. When VCR > VTH, turn off high side switch; when VCR < VTL, turn off low side switch. HO and LO turn on edges are controlled by the dead time generation circuit.

The proposed hybrid hysteretic control combines the benefit of charge control and direct frequency control. Similar to charge control, the small-signal model is a 1^{st} order system which makes the compensator easier to design. Also the control effort is directly related to input current, so the line and load transients are best-in-class. Because of slope compensation, the hybrid hysteretic control also avoids the unstable issue associated with the charge control.

III. Slope Compensation Implementation and Benefits

Capacitor divider can be used to scale down the resonant capacitor voltage. To implement the slope compensation, two well matched, controlled current sources (+2mA, –2mA) are connected to the middle point of the two capacitors as shown in Fig. 3. The on/off control signals in the two current sources come from the gate driver signals. The on/off sequence is shown in Fig. 4, considering the dead time between high side and low side gate driver signals. The ramp current is on all the time. It changes direction at the falling edge of gate driver signals.

A key thing for the slope compensation is to make the two current sources match very well. Since VCR signal is directly used for gate signal generation, a slightly mismatch between the two current sources could cause the imbalance on the circuit. If the ramp current sources are matched very well, the proposed slope compensation implementation will have an inherent negative feedback to keep the high side and low side gate signal ON time balanced, and also keep the common mode voltage at VCR node at VCM. For example, if a disturbance causes VCR common mode voltage to drop, it'll take longer for the VCR voltage to hit the higher threshold VTH. So the upper current source will be on longer, and the VCR node is charged to a higher voltage. The condition is similar for VCR common mode voltage rise.

Therefore, the proposed method will help to get rid of the need to have an extra resistor divider to ensure the dc bias on the VCR node. So the standby power consumption can be reduced.

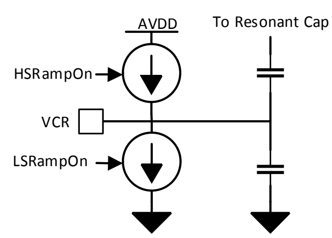

Fig. 3: Slope compensation implementation

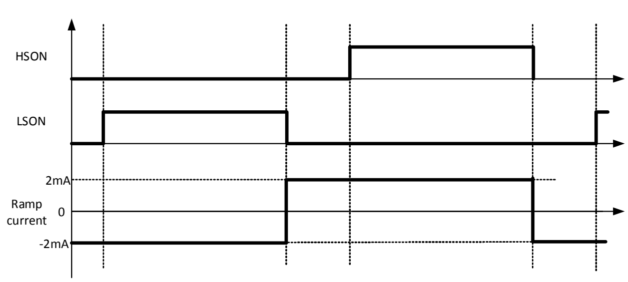

Fig. 4: Ramp current on/off sequence

IV. BURST MODE CONTROL

The efficiency of an LLC converter drops rapidly with falling output power. To maintain reasonable light load efficiency it is necessary to operate the LLC converter in burst mode. In this mode the LLC converter operates at relatively high power for a short burst period and then all switching is stopped for a space period. During the burst period excess charge is transferred to and stored in the output capacitor. During the Space period this stored charge is used to supply the load current. Providing an effective light-load scheme is a particular problem for an LLC controller that is located on the primary side of the isolation barrier.

The hybrid hysteretic control makes the control of burst mode very straight forward. As shown in Fig. 5, system switches when the voltage loop compensator (Vcomp) is higher than the burst mode threshold level (BMT). When Vcomp is lower than BMT, system will continue to switch to ensure a minimal 15 pulses on time before shut down. the control effort is selected between the higher of Vcomp and BMT, as shown in Fig. 6. Burst mode should not apply during startup. So if soft start isn't done yet, send the Vcomp (controlled by soft start ramp). In order to avoid the excessive resonance after burst on period, the last pulse of each burst on period is turned off when the resonant capacitor voltage equals Vin/2. In hybrid hysteretic control, this means that VCR node voltage equals the common mode voltage VCM. This operation keeps the resonant capacitor voltage to about Vin/2 for each burst off period, thus enabling the burst pattern to settle as soon as possible during burst on period, and improve the burst mode efficiency.

The burst mode operation is also optimized for fast transient performance. For load transient from light load to heavy load, especially from no load to full load, the LLC converter needs to fast exit from burst mode. At burst mode, Vcomp is smaller than BMT; when there is a load transient, Vcomp increases quickly and becomes larger than BMT. The control effort will be switched to Vcomp even it is still during burst off period, which provides a fast exit from burst mode operation.

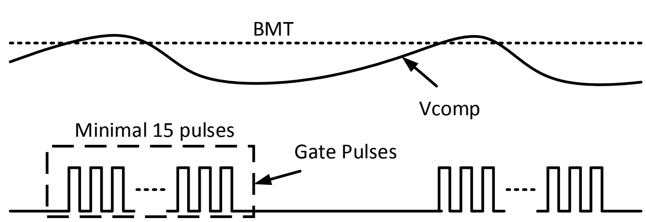

Fig. 5: Burst mode operation principle

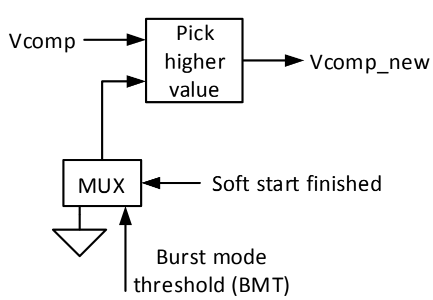

Fig. 6: Burst mode control block diagram

V. EXPERIMENTAL VERIFICATION

A 12V/120W half-bridge LLC converter is developed using the proposed controller as shown in Fig. 7. The DC input voltage ranges from 340 V to 410V. Fig. 8 shows the burst mode waveform at 390 V dc input voltage and 0.1A load. The low side gate signal LO shows that the converter is only turned on for a short period, which causes large output voltage ripple. But the effective switching frequency is much reduced and the converter efficiency is improved. Table 1 lists the power consumption at certain light load conditions. The no load power consumption is less than 40 mW.

Fig. 9 and Fig. 10 show the test results for load transient from no load to full load and full load to no load, respectively. As shown in the waveforms, the maximum voltage dip is only around 300 mV, while many commercial LLC controllers have around 1 V voltage dip during the no load to full load transient.

The proposed method is also verified in a commercial power supply unit (12V/13A output). Fig. 11 shows the transient performance from no load to 10A load for the original board. The output deviation is around 1V. Fig. 12 shows the transient performance at the same condition for the proposed method. The output voltage deviation is only about 0.1V, which is much better than the original method. Fig. 13 shows the light load efficiency plot (including the front-end PFC stage) at low line and high line, respectively. It shows clearly that the proposed method has better light load efficiency, especially at the very light load condition.

Table 1. Light load power consumption

Vin (V)	Pin (mW)	Pout (mW)	Ploss (mW)
390.2	38.2	0	38.2
390.2	165.1	99.8	65.3
390.2	293.4	199.7	93.7
390.2	421.4	298.8	122.6
390.2	547.5	398.0	149.5
390.2	674.3	496.1	178.2

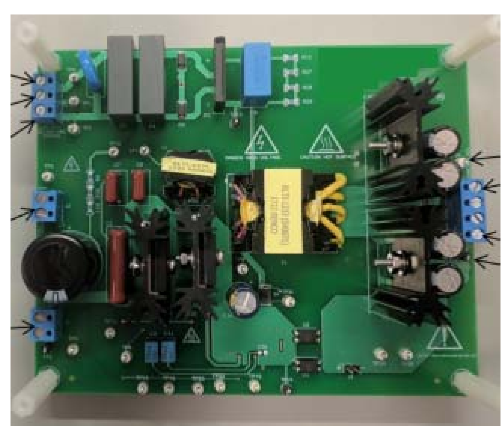

Fig. 7: 12V/120W half-bridge LLC converter prototype

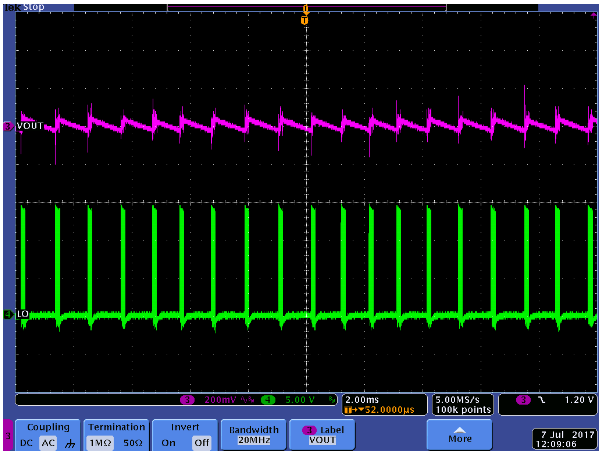

Fig. 8: Burst mode at 390 Vin and 0.1A load (Ch3 – Lo, Ch4 – Vout, AC couple)

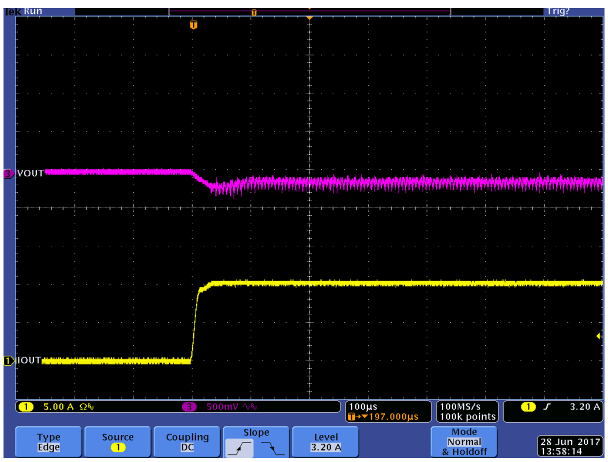

Fig. 9: No load to full load transient (Ch1 – Iout, Ch3 – Vout AC couple)

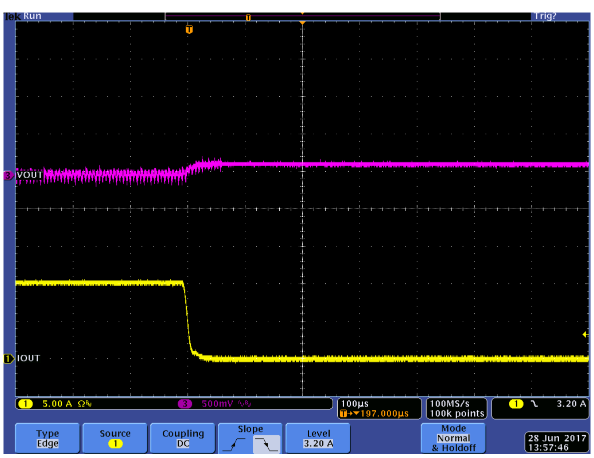

Fig. 10: Full load to no load transient (Ch1 – Iout, Ch3 – Vout AC couple)

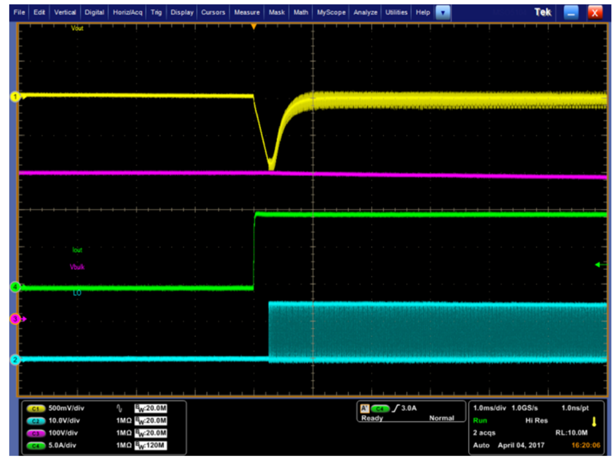

Fig. 11: No load to 10A load transient in original board (Ch1 – Vout AC couple, Ch2 – LO, Ch3 – Vin, Ch4 – Iout)

Fig. 12: No load to 10A load transient with the proposed method (Ch1 – Vout AC couple, Ch2 – LO, Ch3 – Vin, Ch4 – Iout)

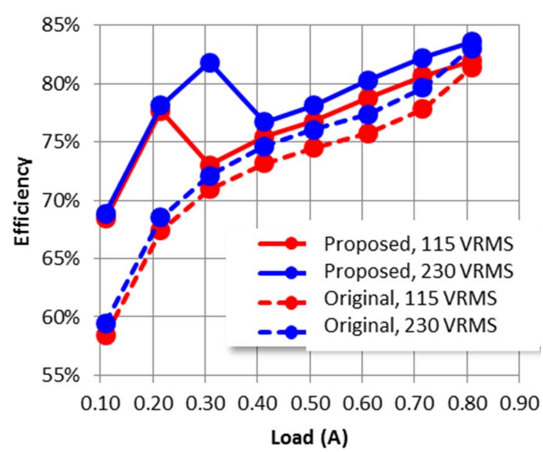

Fig. 13: Light load efficiency Comparison

VI. CONCLUSION

This paper proposes a novel LLC resonant control with a new control algorithm – hybrid hysteretic control, and an advanced burst mode operation. The hybrid hysteretic control is a combination of charge control and direct frequency control. It helps to achieve the best-in-class transient performance, and also avoid the stability issues. The burst mode operation can reduce the equivalent switching frequency at light load, to achieve very low standby power consumption. The proposed controller achieves around 300 mV voltage dip from no load to full load transient, and less than 40 mW no load power consumption, for a 12 V/120 W half-bridge LLC converter. The proposed method is also demonstrated in a commercial power supply unit, which achieves better transient performance and light load efficiency.

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