Power Cycle Modulation Control of LLC Resonant Converters for Wide Voltage Gain Range Applications

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***Abstract*—This paper proposes Power Cycle Modulation (PCM) control method of LLC converters for wide voltage gain range applications. Instead of switching frequency modulation, the proposed PCM method operates the LLC converter according to a control period comprising an on cycle operation mode for a duration T_{on} and an off cycle operation mode for a duration T_{off}. T_{on}, T_{off} and the optimal switching frequency during T_{on} are adjusted based on the sensed input and output voltages. Optimal switching pulse pattern can be maintained under the low output voltage and high input voltage conditions, which ensures the high efficiency. A 65W prototype is built to verify the feasibility and validity of the proposed control method.**

Keywords—Power Cycle Modulation, LLC converter, wide input, wide output

I. INTRODUCTION

In recent years, the renewable energy resources are widely used to save the energy and protect the environment. The inherent nature of these resources has brought many challenges related to high efficiency, high power density, wide voltage ranges, and multiple functions. DC-DC converters are required to meet with a wide voltage range so as to provide a regulated and stable output in many applications like power supplies for data centers and servers, telecommunication, battery chargers for electrical vehicles, and USB Power Delivery (USB-PD) adapters. Hence, DC-DC power conversion of high efficiency and high power density over a wide voltage range is the key for these applications [1]-[2].

Among various DC-DC topologies, LLC resonant converter is gaining more and more attention than ever before because of features such as Zero Voltage Switching (ZVS), galvanic isolation, and high switching frequency operation which reduces the overall size of the system. However, it is challenging to optimize the design of conventional LLC converter in wide gain range applications.

Various methods have been proposed to expand the voltage gain variation of LLC converter while maintaining high efficiency. Theoretically, they can be divided into two types. The first one is through introducing extra component. However, adding new components will inevitably increase extra cost, which is not desirable. The second one is to use new control technique. Asymmetrical PWM (APWM) control can be adopted to expand the LLC voltage gain range [3]-[5], However, APWM control will cause the offset current in the transformer and increase the possibility of the transformer core saturation. Phase-Shift Modulation (PSM) has been proposed to reduce the resonant tank input RMS voltage to adjust the output voltage [6]-[9]. However, PSM control needs small magnetizing inductor value that will increase the conduction loss and can only be applied to full bridge LLC topology. Burst mode control can be used in LLC converter to improve the light load efficiency [10]-[12]. The time period of burst ON and OFF cannot be controlled under different load conditions and it will lead to larger voltage ripple and low burst efficiency under wide input and output voltage range. Besides, this method is usually used at extreme light load condition to consume less power at converter standby mode. With the existing method, a wide voltage gain variation range cannot be achieved while still maintaining high efficiency and high power density.

In this paper, PCM (Power Cycle Modulation) control is proposed. With PCM control, the LLC converter can always operate at high efficiency mode over wide input and output voltage range. ZVS can be achieved over the entire operation range. Narrow switching frequency variation range and high efficiency operation can be achieved while covering the wide voltage gain range. For the prototype used to verify the proposed PCM method, nearly 5.7:1 voltage gain variation range can be achieved with the help of PCM.

II. PROPOSED PCM CONTROL

A. PCM control principle

Fig.1 gives the half bridge LLC converter. In an LLC converter, the switching frequency F_s is used to control the output voltage. Different switching frequencies will produce different output voltages. In contrast to the conventional LLC operation, operation of LLC converters with PCM control includes the following:

1. The LLC converter operates at F_s for a pre-determined time duration, as indicated by T_{on}; this operation mode is defined as on cycle operation mode.

2. At the end of on cycle operation mode, the resonant converter stops operating (operates at off cycle operation mode) for another pre-determined time duration T_{off}.

3. At the end of off cycle operation mode, (after T_{off} time period), the resonant converter operates at on cycle operation mode again (F_s for T_{on} time period). The operation repeats itself.

Key waveforms of LLC converters with PCM control are illustrated in Fig. 2. The output current of on cycle operation mode is denoted by I_{o_on}. The output current of off cycle operation mode is denoted by I_{o_off}, which is 0. During off cycle operation mode, the resonant converter does not use any power (or any energy) from the input source. It is noted that there are two time periods in PCM operation. One is the switching period of the resonant converter during the on cycle operation mode which is $T_s = 1/F_s$. The other is the PCM period, also referred to as the control period $T_{control}$. The PCM period is defined as (1). The Power Cycle Ratio (PCR) is defined as shown in (2). The output current and voltage can be calculated as shown in (3). Theoretically, I_o can be regulated from 0 to I_{o_on} by using PCM. By changing the PCR, the output voltage can be continuously adjusted in a wide range.

$$T_{control} = T_{on} + T_{off} \tag{1}$$

$$PCR = \frac{T_{on}}{T_{control}} \tag{2}$$

$$I_o = I_{o\_on} \times PCR, \quad V_o = I_o \times R_{load} \tag{3}$$

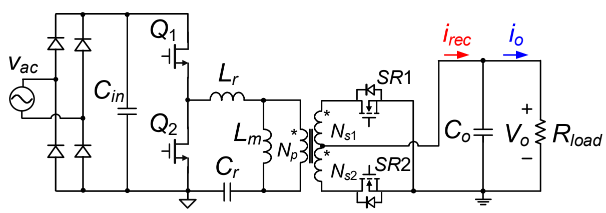


Fig. 1. Half bridge LLC converter

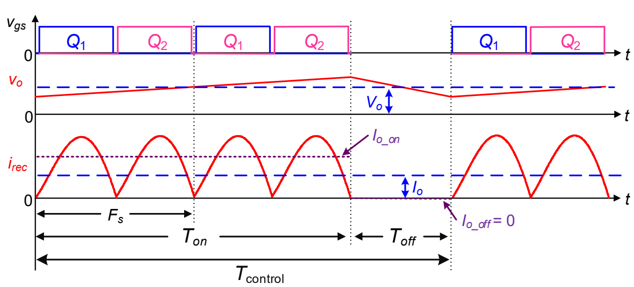


Fig. 2. Key waveforms of PCM control law

$T_{control}$ may be a constant value for easier implementation. For example, $T_{control}$ may be fixed at 50us. Then, the equivalent PCM frequency, or control frequency, $f_{control}$, is 20 kHz. $f_{control}$ can be viewed as the on-off frequency of the switching converter. The input voltage V_{in} and the output voltage V_o will be used to select F_s (the switching frequency during on cycle operation) and the off time, T_{off}. Since T_{off} can be continuously adjusted, the output voltage can also be continuously adjusted. With MCU implementation, the accuracy of the time step from the MCU can be as small as, e.g., 1 nanosecond (ns), and the output voltage can be regulated very accurately, in the range of, e.g., 0.01% of the required output voltage. This is more than enough to meet normal requirements.

B. PCM implementation with low cost MCU

In some conditions, it is more desirable to set the minimum T_{off} time to a small value, e.g., less than 25%, or less than 10%, or less than 5% of the control period, such as 2% of the control period, $T_{off\_\min}=0.02*T_{control}$. For example, when $T_{off\_\min}$ equals 2% of $T_{control}$, $T_{on\_\max}=0.98*T_{control}$. The maximum PCR, $PCR_{\_\max}=0.98*T_{control}/T_{control}=98\%$. This arrangement will bring more accurate PCR resolution when a low cost MCU is used. With a low cost MCU, the minimum time step (time resolution), T_{step}, is usually large, such as 32ns or 100ns. If it is assumed T_{step}=32ns, $PCR_{\_\max}$=98%, and $T_{control}$=50us. Then the $T_{off\_\min}$=0.02*50us=1us. If everything else is kept constant and if T_{off} is changed from 1us to 1us+32ns=1.032us, the PCR will be changed from 0.98 to (50–1.032)/50=0.97936. This represents a PCR change of (0.98–0.97936)/0.98=0.065%. This indicates that by changing one bit (32ns) of T_{off} time, the output voltage will change by 0.065%, which is acceptable.

Similarly, if the minimum time step, T_{step}=100ns=0.1us, and $T_{control}$=50us and $T_{off\_\min}$=1us, the PCR change from 0.98 to (50–1–0.1)/50=0.978. Or the PCR change will be (0.98–0.978)/0.98=0.2%. This is also a very small number for the output voltage change. It should be noted that T_{step} of 100ns means the clock frequency of the MCU is only 10MHz, which may be implemented with a very low cost MCU. It is noted that a clock frequency of 32MHz (32ns time step) is also a very low cost MCU.

Therefore, by setting $T_{off\_\min}$ to a non-zero, but small value, such as 2% of $T_{control}$, a very high output voltage resolution can be achieved even when a low cost MCU is used.

C. Benefits of proposed PCM control

The inherent nature of PCM control is real-time calculated T_{off} value. Output voltage can be continuously regulated based on the PCR=($T_{control}$ - T_{off})/$T_{control}$. Benefits of proposed PCM control can be concluded as follows.

(1) For full load or close to full load operation (for example, 90% of full load operation), normal PFM is used to achieve the highest full load efficiency to meet severe thermal requirements. When the load current is lower than the full load current, PCM is introduced which can adopt full load switching frequency to optimize the switching pattern during PCM. Then the off cycle time (T_{off}) can be automatically adjusted to produce the required load current by feedback loop. This operation is desirable to maintain an almost flat efficiency curve over a wide load current range.

(2) The design of LLC converters is greatly eased since it can only focus on how to achieve the gain requirement and highest efficiency at full load PFM operation. The lower gain

requirement and corresponding optimized switching pattern can be automatically fulfilled with PCM control.

(3) With the MCU implemented PCM control, the load current level can be estimated automatically based on the T_{off} value. Larger T_{off} means lighter load (lower current) and smaller T_{off} means heavier load. This is an important information since the switching frequency during T_{on} and T_{off} time period can be continuously adjusted based on different light load conditions indicated by real-time T_{off} value.

(4) Smooth transition between PCM and PFM operation can be achieved (T_{off} equals to 0), which means no resonant inductor current oscillations.

(5) No current sampling is required and only input and output voltage information is needed, which means that PCM is simple and suitable for IC integration.

(6) PCM control frequency ($f_{control}$=1/$T_{control}$) is set at around 20 kHz to achieve higher light load efficiency. Audible noise and extra conducted electromagnetic interference (EMI) noise related to $f_{control}$ can be avoided.

(7) Different from burst mode, $T_{control}$ period (such as 50us for 20kHz PCM frequency) is controllable and the output voltage ripple can be quantitatively designed with appropriate output capacitor value based on the selected $T_{control}$ of PCM.

III. Design Considerations of Proposed Method for USB-PD Application

Recently, a USB-PD specification is proposed, which allows the load and power supply to negotiate for multiple standard power delivery levels. USB-PD is useful when providing power to multiple devices. Table I gives the specifications of the LLC converter in Fig.1. This converter is for USB-PD application and the rated power is 65W.

In order to achieve 5V to 20V output variation range, with conventional switching frequency control, the switching frequency of the LLC converter must be changed over wide range which compromises the design and sacrifices the performance (such as the efficiency, power density, etc.). With the help of PCM control, it is achievable for the LLC topology to be applied to the low power USB-PD application. A detailed design example is given in the following parts.

TABLE I. Specifications of LLC Converter for USB-PD

Input	186-264Vac, 220Vac Rated
Output	5V/3A, 9V/3A, 15V/3A, 20V/3.25A,
Power	65W Max

A. Input capacitor selection

As shown in Fig. 1, full-bridge rectifier along with an electrolytic capacitor is adopted after AC input. The capacitor value of C_{in} should be taken into consideration to obtain desirable input DC voltage variation. Smaller C_{in} can reduce the capacitor and converter size, but will aggravate the gain design. In this case, the minimum input DC voltage is selected as 260V at 220Vac input full load condition, which is believed a reasonable trade-off between the size and design. At 186Vac input, the valley voltage of the input capacitor could be as low as 210V. The DC input voltage on C_{in} could vary from 210V to 370V. The estimated voltage gain variation range can be calculated as (20/210):(5/370)=7:1.

B. Transformer turns-ratio and resonant frequency

The LLC resonant converter design goal is to achieve minimum loss at normal operation condition together with the capability of achieve required maximum gain to ensure wide operation range. To meet severe thermal requirements at full load normal operation condition, the transformer turns-ratio of LLC converter should be chosen based on 220Vac input and 20V output full load operation condition. In this case, the optimal efficiency performance can be ensured. Theoretically, the transformer turn ratio can be calculated as

$$N_{tx} = \frac{V_{in}}{2V_o} \tag{4}$$

where M is the gain of the resonant tank, N_{tx} is the transformer turn ratio which is defined as N_p/N_s. Since the input DC voltage could vary from 260V to 310V, the calculated N_{tx} varies from 6.5 to 7.75. In real world, the turns-ratio is chosen as 6:1, so that the voltage gain is slightly below unity, and the converter is always operated in buck mode at 220Vac input. The benefits of the buck mode LLC converter operation is: 1) lower current stress due to removal of circulation current; 2) easier ZVS and tolerable to slow turn-off transient (dv/dt); 3) smaller transformer size due to smaller air gap and less windings.

The series resonant frequency f_r should be chosen based on the optimization of the performance at 220Vac normal operation. The consideration of f_r selection should include but not limited to the magnetic components design and fabrication, thermal design, EMI consideration, and trade-off of the driving losses, switching losses and conduction losses, and so on. In this design example, GaN (Gallium Nitride) switches with much lower $R_{ds(on)}$ and Q_g are adopted for main switches, which ensures high frequency (MHz) operation. In this design example, f_r is chosen around 600kHz.

C. Resonant tank design

The resonant tank parameters has the following relationships with λ, f_r and Q:

$$\lambda = \frac{L_m}{L_r} \tag{5}$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{6}$$

$$Q = \frac{\sqrt{L_r / C_r}}{R_{ac}} \tag{7}$$

where λ denotes the inductor ration. Q denotes the quality factor.

a) Choosing inductor ration λ

The minimum operation voltage of LLC resonant converter is determined by its peak voltage gain. Therefore, to achieve wide operation range of LLC resonant converter, it is essential to achieve enough voltage gain. Converter voltage gain when λ varies has been demonstrated in Fig. 3. It can be observed that the voltage gain amplitude of the converter decreases as the λ increases. When the input voltage is low, the voltage gain of the converter may not meet the requirements. At the same time, when the input voltage changes, the converter's switching frequency variation range will be wide.

It is observed that the gain of the converter can easily meet the design requirements when the λ value is small. However, when the value of L_r is fixed, L_m is small, which results in a large magnetizing inductor current and increases the conduction losses. Besides, when λ is small, it can be observed that a small change in the switching frequency will bring about a steep rise or a steep drop in the voltage gain, which is disadvantageous to the loop design and stability of the converter. Therefore, the value of λ should not be too small, and λ is generally selected between 2 and 6 for engineering application.

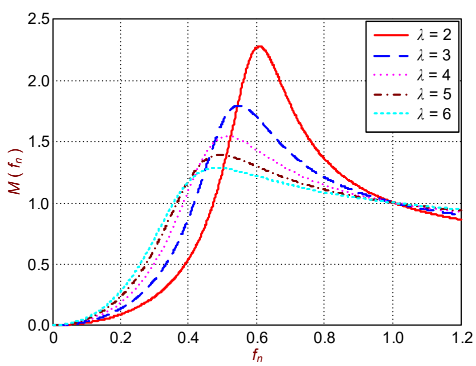


Fig. 3. LLC converter voltage gain when λ varies

b) Choosing Q

Based on first harmonic approximation method (FHA), LLC converter voltage gain M can be calculated as (8). f_n is the normalized frequency, which is equal to f_s/f_r. When the resonant tank input impedance Z_{in} is resistive, the frequency is denoted as f_{res}. When the converter operates in the frequency region of $f_{res}<f_s<f_r$, the ZVS turn-on of the main switches is guaranteed. When the imaginary part of Z_{in} is equal to zero, the corresponding quality factor Q_{res} can be calculated as shown is (9). Q_{res} denotes the maximum quality factor when converter works in the inductive region. Substitute (9) into (8), the corresponding converter voltage gain can be calculated as (10). The converter works poorly at the operating point of 186Vac input and 20V output with full load. In this case, converter is difficult to achieve the ZVS. Quality factor Q should be selected based on this operation condition. M_{max} denotes the maximum voltage gain. Substitute M_{max} into (10), the minimum normalized switching frequency can be obtained as (11). Based on (9) and (11), to ensure a certain margin, the maximum quality factor Q_{max} can be calculated as (12).

$$M(f_n)=\frac{1}{\sqrt{\left[1+\frac{1}{\lambda}\left(1-\frac{1}{f_n^2}\right)\right]^2+\left[Q\left(f_n-\frac{1}{f_n}\right)\right]^2}} \tag{8}$$

$$Q_{res}=\sqrt{\frac{(\lambda+1)f_n^2-1}{\lambda^2 f_n^2\left(1-f_n^2\right)}} \tag{9}$$

$$M_{res}(f_n)=\frac{1}{\sqrt{\frac{1}{\lambda}\left(1-\frac{1}{f_n^2}\right)+1}} \tag{10}$$

$$f_{n(\min)}=\frac{1}{\sqrt{1+\lambda\left(1-\frac{1}{M_{\max}^2}\right)}} \tag{11}$$

$$Q_{\max}=90\%\left(\frac{1}{\lambda M_{\max}}\sqrt{\frac{M_{\max}^2}{M_{\max}^2-1}+\lambda}\right) \tag{12}$$

D. Output capacitor consideration

Since power delivered to output capacitor is discontinues under PCM control, there is output voltage related to PCM control frequency $f_{control}$ ($1/T_{control}$). To satisfy ripple requirement, the needed output capacitance is shown in (13). After $f_{control}$ is fixed, the output capacitance can be determined based on different ripple requirements.

$$C_o=\frac{I_o}{\Delta V_{pk-pk}\cdot f_{control}} \tag{13}$$

E. Implementation of the f_{s_PCM}

The steady state f_{s_PCM} (on cycle period switching frequency) value should be extracted as a function of the operating input voltage and output voltage. Input AC voltage can be sensed directly by primary MCU ADC (Analog Digital Converter). Output voltage information can be supplied by secondary USB Type-C PD controller chip or sensed by transformer auxiliary winding.

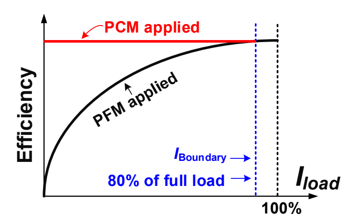


Fig. 4. Expected efficiency curve versus load current with PCM control

f_{s_PCM} denotes boundary frequency between PCM and PFM operation. In general, for LLC converter loss breakdown, there are dominated losses like the driving losses, switching losses and conduction losses. If the output power increases, the proportion of conduction losses over the delivered power becomes large. If the output power decreases, the proportion of driving losses and switching losses over the delivered power becomes large as well. The expected efficiency curve versus load current with PCM control is shown in Fig. 4. Below full load condition, switching frequency increases to accommodate the voltage gain requirement. ZVS achievement will need more deadtime and switching losses will increase. Below certain load current, the switching loss and driving loss will dominate the efficiency. In this case, PCM should be employed to decrease the driving and switching losses when the output current decreases continuously. $I_{boundary}$ denotes the load current boundary between PCM and PFM, which is regulated by changing f_{s_PCM}. f_{s_PCM} can be determined by loss breakdown analysis, PSIM simulation analysis or experimental tests, based on different input and output conditions.

IV. Experimental Verification and Discussion

After fine tune of the parameters with PSIM simulation, the design results of LLC converter are listed in Table II. Fig. 5 gives the 3D plot of the voltage gain curve of the proposed LLC converter design. It is observed that if the converter operates at PFM only mode, the switching frequency will be changed from 0.82f_n (527kHz, point A, 186Vac, 20V full load) to 5f_n (3.2MHz, point B, 264Vac, 5V half load). With the help of PCM, 1.95f_n (1.25MHz) maximum switching frequency can be achieved for 5V output, which means 59% reduction of the switching frequency variation range.

TABLE II. Design Results of LLC Converter

Parameter	Symbol	Value
Input capacitors	C_{in}	60 uF
Output capacitors	C_o	420 uF
Resonant inductor	L_r	34 uH
Magnetizing inductor	L_m	90 uH
Resonant capacitor	C_r	1.8 nF
Transformer turns ratio	$N_P : N_{S1} : N_{S2}$	18:3:3
Resonant frequency	f_r	643 kHz

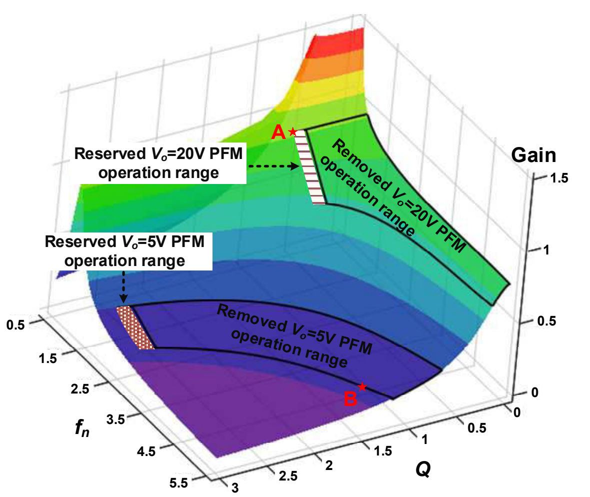


Fig. 5. Switching frequency variation range reduction with PCM

It is worth noting that, with PFM, the switching frequency will be pushed to very high range for 5V output light load condition. The switching losses and magnetic losses will be unendurable. PCM control method makes it possible for LLC topology to be applied to single stage low power USB-PD application.

A 65W prototype is built to demonstrate the proposed control method, which is shown in Fig. 6. This prototype achieves breakthrough power density of 24.5 W/in^3 uncased. Two RM6 cores with PC200 material from TDK company are used for transformer and resonant inductor implementation. Half bridge driver SI8273 from Silicon labs is used for GaN switches' driving. NCP4305 from Onsemi is used for secondary SR driving scheme.

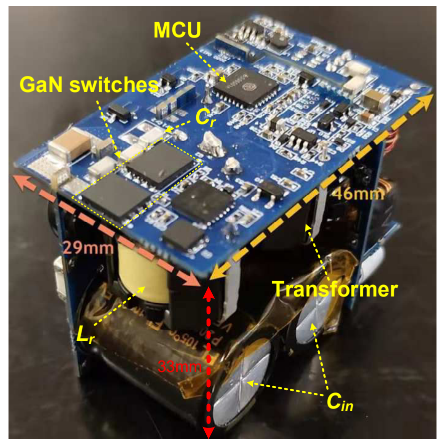


Fig. 6. Prototype photo

Fig. 7 give the steady state waveforms at 220Vac input, 20V/2A output condition. The $T_{control}$ of PCM is around 43 us, which means 23 kHz PCM frequency. f_{s_PCM} is selected as 870kHz. It is noted that the input DC voltage could vary from 260 to 310V at 220Vac input. In this case, the T_{off} will vary accordingly based on the calculation results of the PID controller. The output voltage can be well regulated at 20V with 112mV peak-to-peak ripple voltage.

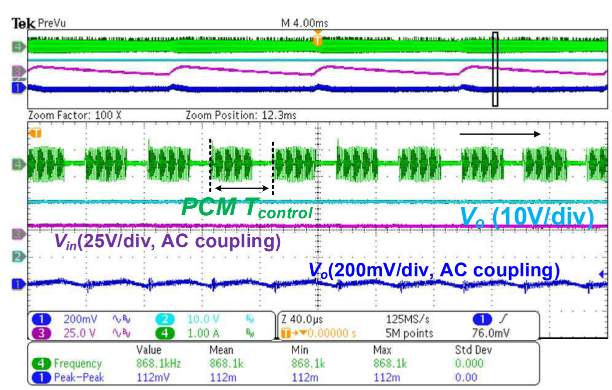
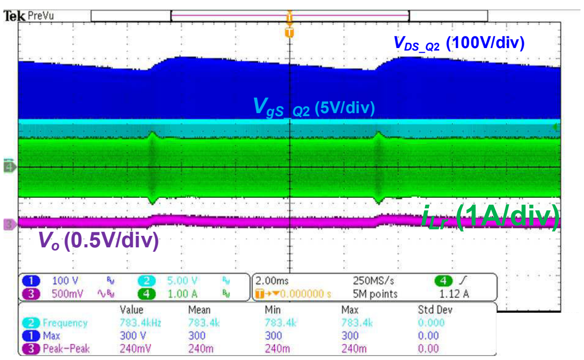


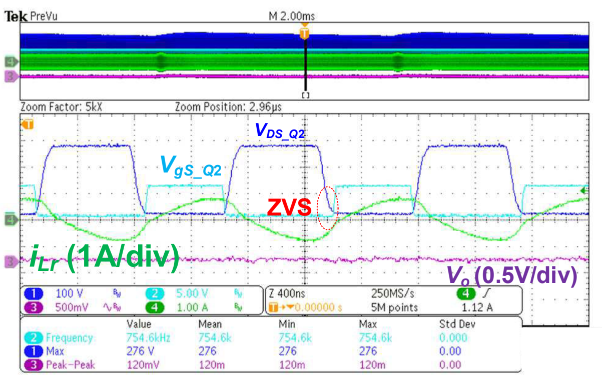
Fig. 7. 220Vac, 20V/2A, steady state

Fig. 8 give the steady state waveforms at 220Vac input full load condition. The LLC converter is controlled by PFM only. The zoom-in waveforms shows that ZVS operation of the primary switches is well maintained.

Fig. 9 give the steady state waveforms at corner cases. In In Fig. 9 (a), for 186Vac input full load output condition, the LLC converter is controlled by PFM only and operates at boost mode. ZVS can be achieved. For 264Vac input, 5V no load output condition, f_{s_PCM} is selected as 2MHz for this special case, to accommodate the gain requirement, as shown in Fig. 9 (b).

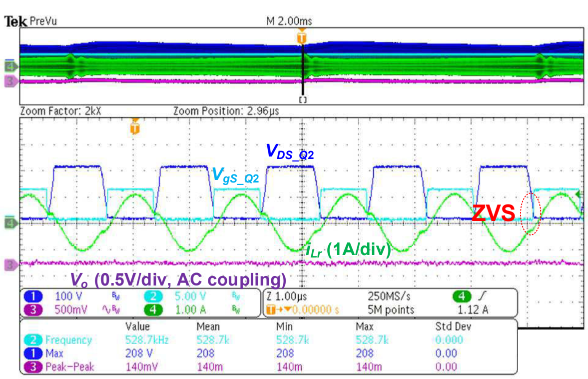


(a) Line cycle waveforms

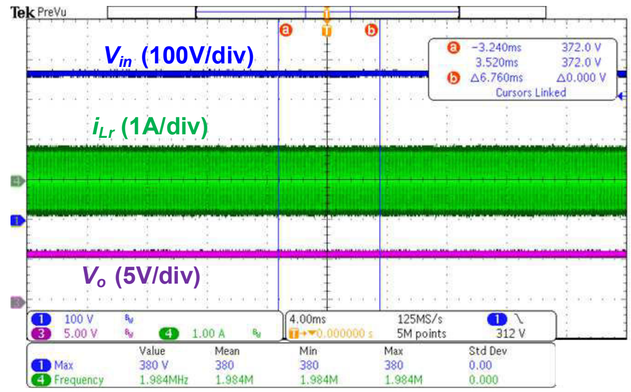


(b) Zoom-in waveforms

Fig. 8. 220Vac, 20V/3.25A, PFM only, steady state



(a) 186Vac, 20V/3.25A, PFM only, steady state



(b) 264Vac, 5V/0A, PCM only, steady state

Fig. 9. Corner case waveforms

Fig. 10 gives the waveforms of the load step change from 0.4A to 2.6A (220Vac input, 20V output). It can be observed that smooth transition between PCM and PFM operation is ahcieved and there is no resonant inductor current oscillations. Settling time is 2.2ms, with around 600mV voltage drop. Fig. 11 gives the steady state waveforms of 220Vac input, 2.6A output condition. It can be observed that PCM and PFM are both used to regulate the output voltage. Smooth transition between PCM and PFM operation can also be ahcieved without resonant inductor current oscillations.

The efficiency curve (220Vac input, 20V output) of the prototype with this PCM control strategy is presented in Fig. 12. It can be observed that the 94.9% peak efficiency of 20V output is obtained. Four-point average efficiency (100%, 75%, 50%, and 20% load) of 5V outpt is calculated as 82%, which is fully compliant with European CoC Tier 2 and US DoE Level VI efficiency standards. Compared with state-of-art consumer products, around 2% efficiency improvement can be achieved for 20V output condition.

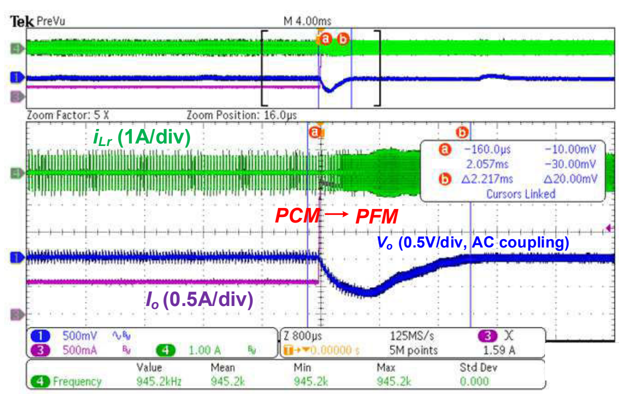


Fig. 10. 220Vac, 20V, load step from 0.6A to 2.4A

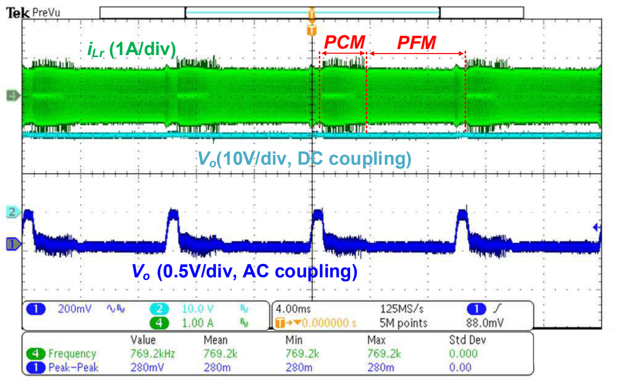


Fig. 11. 220Vac, 20V, steady state, 2.6A load

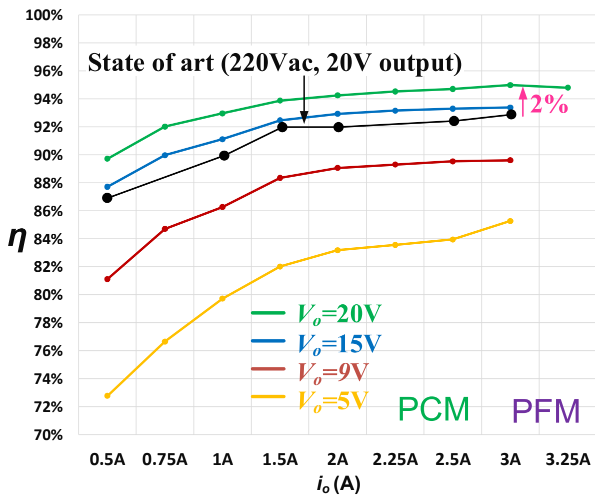


Fig. 12. 220Vac Efficiency curves

V. Conclusion

In this paper, for LLC resonant converters, PCM control is proposed to regulate the output voltage based on the PCR value. Wide output voltage variation range for LLC converter can be achieved. Proposed PCM method can be implemented by low cost MCU. Proposed 65W prototype design can cover the whole operation range of USB-PD while maintaining high efficiency, since LLC can always switch at selected optimal switching frequency point. PCM control method is suitable for high frequency operation and can be extended to other resonant topologies.

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