

Simplified Optimal Trajectory Control for 1 MHz LLC Converter with Wide Input Voltage Range

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Abstract— 48 V bus converter is widely used in telecom and networks power architecture. This paper presents LLC converter as single stage solution for isolated and regulated bus converter, and addresses the control challenges for this converter. In this paper, Simplified Optimal Trajectory Control (SOTC) is used to control 1 MHz LLC converter with input voltage range 40 V:60 V and frequency range 0.8 MHz: 1.8 MHz. Digital implementation of 2-step SOTC is proposed for the high frequency LLC using a low-speed microcontroller. SOTC can achieve optimum transient response for an LLC operating at resonant frequency but has limited impact at wide gain range. A feedforward compensation is proposed in conjunction with SOTC to achieve optimum transient response at wide input voltage range. Moreover, soft-start-up with adaptive switching frequency is proposed to achieve start-up under limited current stress over the whole input voltage range. Experimental results are demonstrated on a 1 MHz LLC 48 V bus converter using 90MHz TMS320F28069 piccolo MCU.

Keywords— LLC resonant converter, optimal trajectory control, transient response, digital control.

I. INTRODUCTION

The LLC resonant converter has been trending as a high efficiency DC-DC converter. The LLC features soft switching for primary and secondary devices and can operate at high switching frequency with high efficiency and high power density. Many applications utilize resonant converters such as front-end converters [1], battery chargers, and bus converters. For the 48 V/12 V bus converter, the DC-DC is required to provide regulation of output voltage at 12V over a range of input voltage, typically 40 V:60 V for datacenter and 36 V:72 V for telecommunication.

The LLC has been used in the 48 V bus converter as a DC transformer (DCX) with cascaded regulation stage like buck converter [2] or buck-boost converter [3]. Nevertheless, the LLC converter can provide regulation through frequency modulation and has been proposed as a single-stage solution for 48 V bus converter [4]. However, controlling LLC with fast transient response is challenging.

LLC has inconsistent dynamic behavior at different gains or different switching frequencies, which makes it difficult to obtain fast and consistent transient response using conventional voltage mode control [5]. The output voltage has an oscillatory

response at high voltage gain, and a slow damped response at low gain. Several control schemes have been introduced to achieve fast transient response with the LLC. Average current mode control [6] is introduced to damp the oscillatory response of the LLC especially at high gain by controlling the resonant current i_{Lr} . Average current mode control clamps the resonance between the resonant tank and output capacitor to give consistent dynamic performance at different voltage gain points; however, the loop gain bandwidth is still low. Bang-Bang charge control is proposed in [7] to achieve fast transient response by controlling the input charge to the resonant tank. However, this method requires a single-ended measurement of resonant capacitor voltage (V_{Cr}), which is not easy to obtain in a high-frequency full-bridge configuration. Charge current control is also introduced by controlling the switch charge [8], but this controller requires an additional current transformer to measure the switch current which is a bulky component for an application like the high power density bus converter.

Simplified Optimal Trajectory Control (SOTC) can achieve very fast load transient response by simple measurement of output voltage (V_o) and load current (i_{Load}) signals [9], [10]. However, SOTC assumes operating at resonant frequency (f_o) where the LLC converter runs at the same switching frequency ($f_s = f_o$) at all loading conditions for all loading conditions. This paper presents a digital implementation of SOTC for a 1 MHz LLC in a frequency range of 0.8 MHz : 1.8 MHz with low-cost low speed 90 MHz MCU.

The paper is organized as follows: Section II presents the 1 MHz LLC converter as a single stage, high efficiency, high power density solution for 48 V bus converter with input voltage range 40 V : 60 V. Section III discusses the implementation of SOTC for a 1 MHz LLC. Section IV discusses control challenges for an LLC with wide input voltage range and proposes feedforward compensation for fast transient response. Section V discusses soft start-up of full-bridge LLC with wide input voltage range. Section VI presents the experimental results on 1 MHz – 1kW LLC.

II. LLC RESONANT CONVERTER FOR 48 V BUS APPLICATION

The 48 V bus converter is a fundamental block in the power architecture of many applications such as network and telecom

datacenters. In this paper, a 1 MHz, 1kW full-bridge LLC resonant converter is proposed as a high-efficiency, high power density solution for 48 V bus converter. The converter can achieve peak efficiency of 97.8% and fits in standard quarter brick size, as shown in Fig. 1, with power density 700W/in³. The LLC converter provides isolation and regulation through frequency modulation in a single stage solution. Primary and secondary devices turn on with zero voltage switching (ZVS) and secondary rectifiers (SRs) have zero current turn off. Soft switching enables for operating at high switching frequency to minimize the magnetic components size while maintaining high efficiency [1]. The converter is designed with a novel PCB winding matrix transformer; four elemental transformers are integrated with a resonant inductor using the same winding and a single core structure. This enables a very high-efficiency and power-density operation. The designed LLC converter is required to provide 12V regulation from a wide input voltage range of 40 V~60 V. The resonant tank parameters are designed to cover a gain range of 0.8 to 1.2 that corresponds to switching frequency range of 0.8 MHz : 1.8 MHz, as shown in Fig. 2. The converter is controlled with SOTC to achieve fast transient response. Further discussion on the implementation of SOTC for high-frequency LLC with wide input voltage range is presented in the next sections.

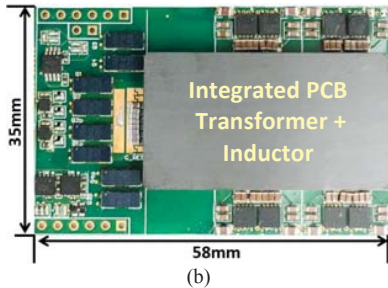
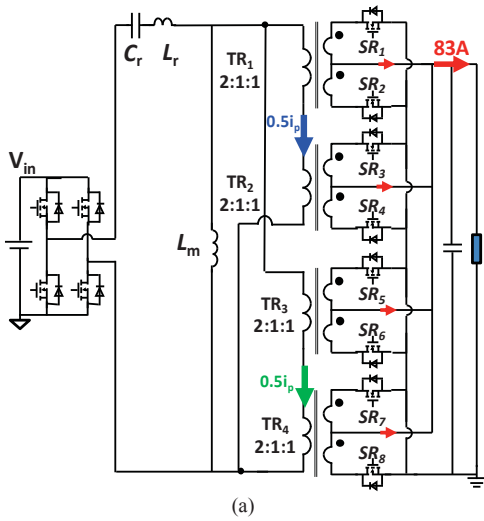


Fig.1. 1 MHz / 1kW full bridge LLC converter with matrix transformer. (a) Schematic of proposed converter. (b) Prototype in quarter brick footprint.

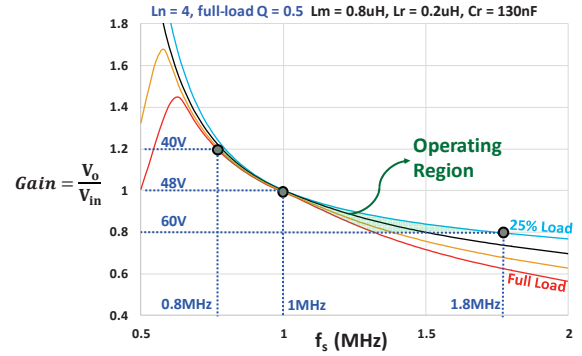


Fig.2. Designed gain characteristics (c/c) of LLC with voltage gain from 0.8 to 1.2.

III. IMPLEMENTATION OF SIMPLIFIED OPTIMAL TRAJECTORY CONTROL (SOTC) FOR FAST TRANSIENT RESPONSE

A. Steady state operation and state-plane of LLC

SOTC can achieve fast load transient response based on the understanding of large signal dynamics of the LLC resonant tank [9]. The resonant tank has three dynamic components: resonant inductor current (i_{Lr}), resonant capacitor voltage (v_{Cr}), and magnetizing inductor current (i_{Lm}), which can be visualized through 3D state-space. However, the magnetizing inductor (L_m) is clamped by the rectangular voltage excitation on the secondary winding. L_m only resonates in series with resonant inductor L_r when the secondary rectifier (SR) is not conducting at ($f_s < f_o$). In this case, the magnetizing current i_{Lm} dynamics can be described through the resonant current (i_{Lr}). Therefore, the dynamics of the resonant tank can be described through 2D state-plane of only i_{Lr} , and v_{Cr} . Fig. 3. shows the steady state trajectory of the LLC operating at three different operating modes.

1) Region I: ($f_s = f_o$)

In this region, the resonant current i_{Lr} and voltage v_{Cr} have perfect sinusoidal waveforms. The trajectory of normalized resonant inductor current i_{LrN} and normalized resonant capacitor voltage v_{CrN} appears as a perfect circle composed of two half circles representing two symmetric half cycles, where:

$$v_{CrN} = \frac{v_{Cr}}{V_{in}}, \quad i_{LrN} = \frac{i_{Lr}}{V_{in}} \times \sqrt{\frac{L_r}{C_r}} \quad (1)$$

Where V_{in} is the nominal input voltage. The area of the trajectory in Fig. 3(a) reflects the energy of the resonant tank and, hence the load.

2) Region II: ($f_s < f_o$)

Here, the trajectory has two half circles ($t_0:t_1$ and $t_2:t_3$) representing the two halves of the resonant cycle. there are two extra charging modes ($t_1:t_2$ and $t_3:t_4$) as the switching cycle is higher than the resonant cycle. In these two charging modes, the amplitude of i_{LrN} , and v_{CrN} are increasing simultaneously; indicating charging of the resonant tank energy. This can be seen from the increase in trajectory area.

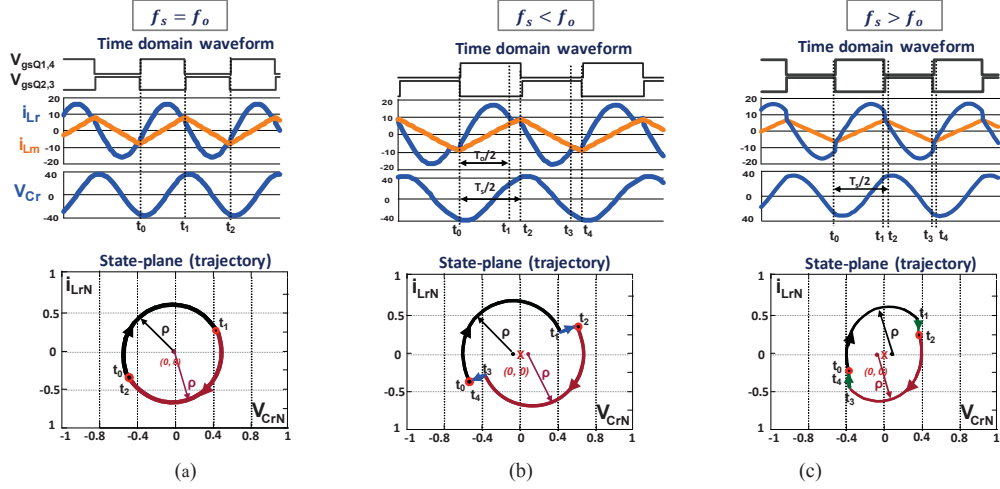


Fig.3. State-plane (trajectory) of LLC at steady-state. (a) $f_s = f_o$. (b) $f_s < f_o$. (c) $f_s > f_o$.

3) Region III: ($f_s > f_o$)

In this region, the trajectory has two incomplete half circles ($t_0:t_1$ and $t_2:t_3$) since the switching cycle is smaller than the resonant cycle. There are also two extra discharging modes ($t_1:t_2$ and $t_3:t_4$) where the amplitude of i_{LrN} drops sharply; indicating discharging of the resonant tank energy. This can be seen from the reduction in trajectory area.

It can be seen from the state-plane of the LLC in Fig.3 that the energy of the resonant tank can be charged by making the switching cycle higher than the resonant cycle. Contrarily, The tank energy is discharged by making the switching cycle less than the resonant cycle.

B. Simplified Optimal Trajectory Control (SOTC)

The concept of SOTC is to measure i_{Load} to detect the transient, as shown in Fig. 4. At load step up, the width of the primary signal is expanded by ΔT_{up} for only one cycle to charge the resonant tank to the new steady-state energy level over two steps, one step on each half cycle as shown in Fig. 5a. At load step down, the width of the primary signal is shrunk by ΔT_{down} for only one cycle to discharge the resonant tank as shown in Fig. 5b. Therefore, the tank energy is charged/discharged during load transient within only one cycle to match with the new load and achieve fast transient response. The values of ΔT_{up} and ΔT_{down} are derived in [9] and listed in (2).

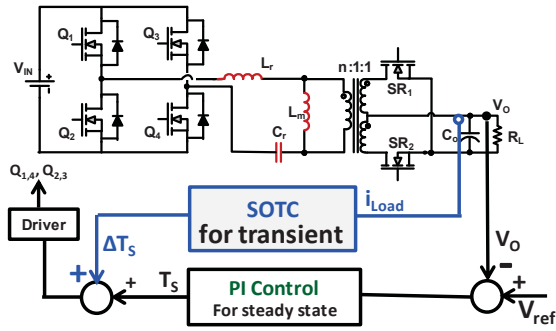


Fig.4. Block diagram Simplified Optimal Trajectory Control (SOTC)

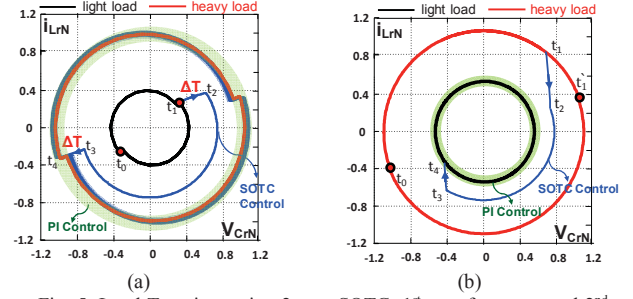


Fig. 5. Load Transient using 2-step SOTC; 1st step from $t_1:t_2$ and 2nd step from $t_3:t_4$. (a) Load step up – charging resonant tank. (b) Load step down – discharging resonant tank.

$$\Delta T_{up} = L_m \frac{I_{HL} - I_{LL}}{n V_{in}}, \quad \Delta T_{down} = \frac{1}{4f_o} \left(1 - \sqrt{\frac{I_{LL}}{I_{HL}}} \right) \quad (2)$$

Where: I_{LL} is light load current, I_{HL} is heavy load current and n is transformer turns ratio.

A low bandwidth (BW) PI controller is used along with the SOTC controller for fine regulation around the new steady-state point. Assuming operating at resonant frequency, all Loads operate at the same switching frequency as seen from the gain c/c of the LLC in Fig. 2. Thus, the effort of the PI controller is minimal during transient.

SOTC can be implemented using a digital controller [10]. The MCU samples V_o , and i_{Load} at each switching cycle and calculates the SOTC control law; including ΔT and PI calculations. In case of transient, the MCU updates the pulse width modulation (PWM) module for the next switching cycle to charge/discharge the resonant tank.

The digital controller clock speed has to be higher than the number of processing clock cycles (number of clock cycle to process control calculations) multiplied by the maximum switching frequency of the converter (f_{sMAX}). For instance, in order to implement SOTC on 1 MHz LLC with $f_{sMAX}=1.8\text{MHz}$, the digital controller clock must be higher than 400MHz, which is not feasible the bus converter application.

C. Multi-step SOTC

Multi-step SOTC has been proposed in [10] using low-speed MCUs. In this method, V_o and i_{Load} signals are sampled each m switching cycles using an interrupt pre-scaler in the MCU. The interrupt prescaler (m) is selected based on the f_{sMAX} value, MCU clock speed, and number of processing clock cycles. The interrupt prescaler (m) can be calculated as follows:

$$m > \frac{\text{number of Processing clock cycles} \times f_{sMAX}}{\text{MCU clock speed}} \quad (3)$$

Therefore, the calculation of SOTC and PI control is stretched over several m cycles and the clock speed of the MCU can be reduced. Afterwards, the control signal (PWM channel) is updated for the next m cycles to charge the resonant tank; performing $2m$ -step SOTC. The value of ΔT for multi-step SOTC is derived in [10] and listed below:

$$\Delta T_{up} = \frac{L_m I_{HL} - I_{LL}}{m \frac{n V_{in}}{n}}, \quad \Delta T_{down} = \frac{1}{4f_o} \left(1 - \sqrt{\frac{m}{2} \frac{I_{LL}}{I_{HL}}} \right) \quad (4)$$

In case of an LLC with maximum switching frequency of 1.8 MHz and 90 MHz MCU, the sampling will be every six cycles and 12-step SOTC is used, as shown in Fig. 6. In 12-step SOTC, the delay time from transient instant to the end of resonant tank charging is more than 12 switching cycles. This increases the settling time and slows down the transient response compared to the original 2-step SOTC section III-B.

D. Proposed Implementation of 2-step SOTC for 1 MHz LLC with Low-speed MCU

Faster transient response can be achieved with SOTC by either reducing the calculation time of the control law or reducing the charging time of the resonant tank. Following, both issues are discussed to reduce the settling time of the LLC during load transient.

The concept of SOTC is to use nonlinear optimal trajectory control to handle large signal transient, and use a low BW PI controller to handle steady-state regulation only. Since the PI has low BW, the variation in PI control output will be very small during transient. Hence, the PI control law can be disregarded at the transient instant since it has very small impact on transient response. Therefore, when load transient is detected, only SOTC control law is processed, and the PI control output is temporarily fixed during the SOTC operation. Moreover, when there is no large load transient detected (small signal load variation), the SOTC control law can also be disregarded as the PI controller can adequately handle small signal regulation. By calculating SOTC only at transient and PI only at steady-state, the calculation time can be reduced to less than five switching cycles instead of six switching cycle in previous implementation

The charging time of the resonant tank can be reduced by using fewer steps for SOTC. For example, 2-step SOTC charges the resonant tank within one switching cycle; however, 12-step SOTC charges the resonant tank within six switching cycles. Nevertheless, 2-step SOTC can be used for high frequency LLC with a low-speed MCU. A switching cycle counter is used to realize the switching cycle number within the 6-cycle sampling period. After the SOTC calculation is done, the controller waits for the end of the 5th cycle and updates the PWM channel to add ΔT to the 6th cycle to perform 2-step SOTC. With 2-step SOTC, the resonant tank is charged within one cycle which is six times faster than the 12-step SOTC. Afterwards, the PWM channel is updated again at the end of the 6th switching cycle to operate again at PI frequency. Using this approach, the PWM channel is updated twice in the interrupt cycle during transient to implement 2-step SOTC with faster charging time. Fig. 7 shows a typical implementation of 2-step SOTC on 1 MHz LLC with 90 MHz MCU. In the proposed implementation, the delay from transient instant to settling point is reduced to only six cycles and faster transient response can be achieved.

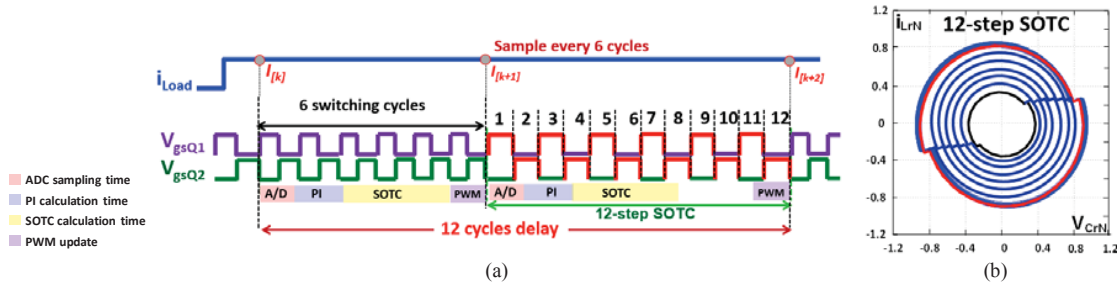


Fig. 6. 12-step SOTC at Load step-up. (a) Digital Implementation. (b) Trajectory of 12-step SOTC.

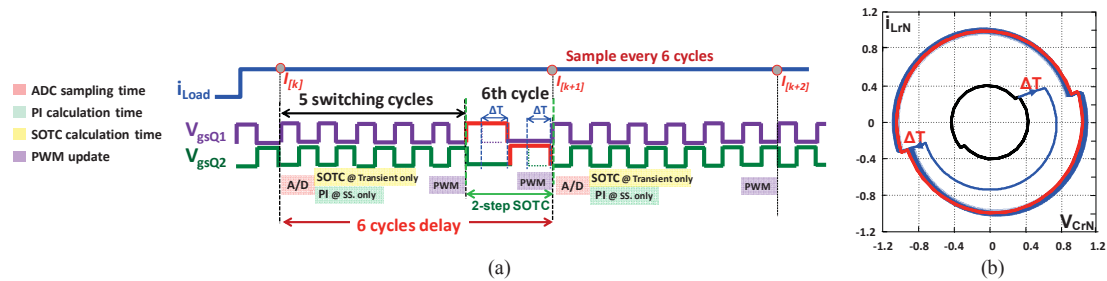


Fig. 7. Proposed implementation of 2-step SOTC for high frequency LLC. (a) Digital Implementation. (b) Trajectory of 2-step SOTC.

IV. PROPOSED SOTC WITH FEEDFORWARD COMPENSATION FOR WIDE INPUT VOLTAGE RANGE

The concept of SOTC is built on the assumption of operating at ($f_s = f_o$), where all loads operate at the same switching frequency. The SOTC charges/discharges the resonant tank at load step-up/step-down respectively. Thus, PI effort is reduced just for regulation around the new steady-state point, with a small change in switching frequency. However, when the LLC operates far from resonant frequency (gain $\neq 1$), SOTC alone cannot achieve fast transient response as shown in Fig. 8.

As seen from the gain c/c in Fig. 9, each load point operates at a different steady-state switching frequency when gain $\neq 1$. For instance, in case of load step up, SOTC charges the resonant tank from $t_1:t_2$ as shown in Fig. 10(a). Afterwards, the PI controller starts the operation to regulate around the new steady-state point, however, the new heavy load requires the switching frequency

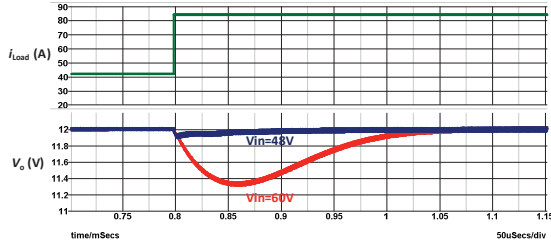


Fig.8. Load transient using SOTC at input voltage 48 V ($f_s = f_o$) and 60 V ($f_s > f_o$).

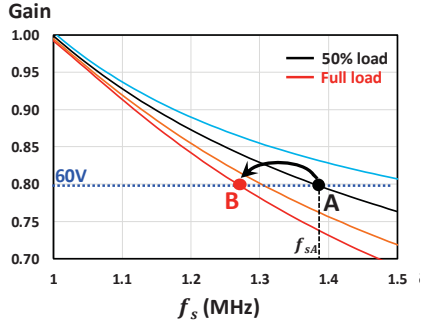


Fig.9. LLC gain c/c at gain < 1 ($f_s > f_o$).

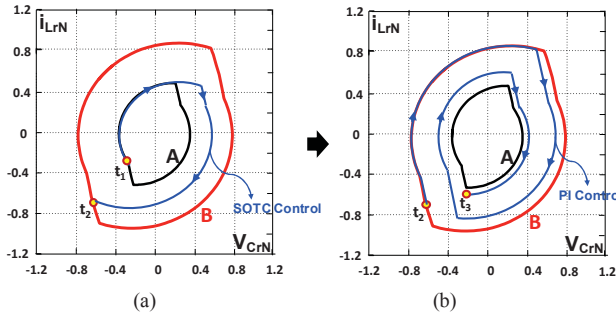


Fig.10. Trajectory of Load transient (load step up) at $f_s > f_o$: (a) 2-step SOTC to charge resonant tank from t_1 to t_2 , (b) PI operation at switching frequency of Load (A) causing discharge of resonant tank again.

to be significantly lower than the light load frequency. The PI is designed with low BW, and the output of the PI will slowly decrease from the steady-state switching frequency of light load to the switching frequency of the heavy load. Therefore, at the instant after transient detection and SOTC operation, the PI frequency will still be at f_{sA} which is higher than the required frequency for the new load point. By operating at high frequency, the PI discharges the resonant tank again within couple of switching cycles; diminishing the benefit of SOTC as shown in Fig. 10(b). Then, the PI starts to slowly change the switching frequency to regulate the output voltage. Therefore, the transient response is dictated by the BW of the PI (at gain $\neq 1$) and the load transient response is much slower than the case at resonant frequency.

A feedforward compensator is proposed, as shown in Fig. 11, to improve transient response over wide voltage gain range and wide switching frequency range. At load transient, SOTC charges the resonant tank, from $t_1:t_2$. Afterwards, feedforward sets the PI to the new steady-state frequency, so the PI starts to operate at the frequency of the new load point without discharging the resonant tank.

The feedforward compensator can be realized from the DC gain c/c of the LLC converter. The DC gain c/c relates the voltage gain of the resonant converter, to the quality factor of the converter and switching frequency. This relation can be reformulated to realize the steady-state switching frequency as a function in load current and input voltage, as shown in Fig. 12. SIMPLIS simulation tool is used to realize the DC gain c/c and implement the feedforward compensation. The simulation

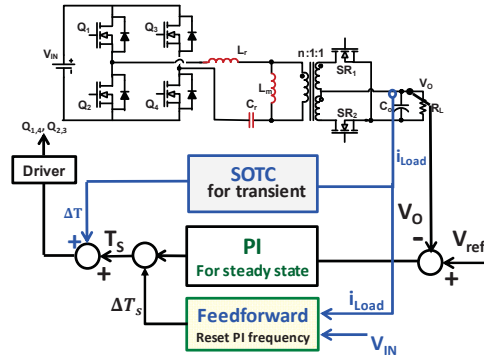


Fig.11 Block diagram of SOTC with Feedforward compensator for LLC operating at wide switching frequency range.

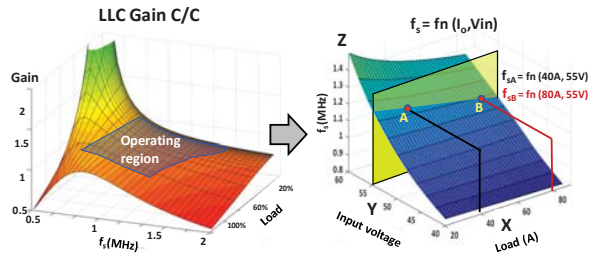


Fig.12. Realization of Feedforward compensator from LLC gain c/c .

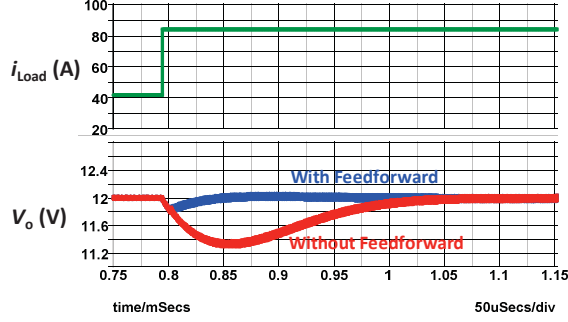


Fig. 13. SIMPLIS simulation of load transient response using SOTC + feedforward compensation at $V_{in}= 60$ V

method is preferred for accuracy and to account for the impact of the converter parasitics on the gain c/c (such as: winding resistance, line resistance, and devices output capacitances). Fig. 13 shows SIMPLIS simulation of load transient with and without feedforward compensation. The proposed feedforward with SOTC can achieve fast transient at wide switching frequency and gain ranges.

V. SOFT START-UP FOR FULL-BRIDGE LLC WITH WIDE INPUT VOLTAGE RANGE

The LLC converter needs to start-up at high switching frequency to limit the resonant current while the output voltage is building up. Soft start-up with limited current stress has been proposed in [11], [12]. The switching frequency is calculated using the trajectory of the LLC during start-up, to keep the resonant current between current band limits ($\pm I_{maxN}$). The calculated switching frequency is a function in V_o and is stored as a look-up table in the MCU. However, starting a full-bridge LLC with 50% duty ratio causes high oscillations in the resonant current during the start-up. One cycle settling method is used to settle the resonant tank to the start-up trajectory by using customized duty ratio for the first cycle. Fig. 14 shows the trajectory during the first cycle. First, positive voltage is applied for time T_1 to move from $(0,0)$ to $(\Delta V_N, \Delta I_N)$. Then, negative voltage is applied for time T_2 to move the trajectory from $(\Delta V_N, \Delta I_N)$ to the current limit $(-I_{maxN})$. $T_1 + T_2$ represent the first cycle time to settle the tank and are calculated as follows:

$$T_1 = \frac{\alpha}{\omega_o}, \text{ where } \alpha = \sin^{-1} \frac{\Delta I_N}{\rho_1} \quad (5)$$

$$T_2 = \frac{\beta_1 + \beta_2}{\omega_o}, \text{ where } \beta_1 = \sin^{-1} \frac{\Delta I_N}{\rho_2}, \beta_2 = \sin^{-1} \frac{I_{maxN}}{\rho_2} \quad (6)$$

Fig. 15 shows the simulation results with and without the one cycle settling method. The resonant current can settle very quickly by using customized duty ratio on the first pulse.

The LLC starts with a fixed switching frequency profile where the switching frequency is calculated as a function in the output voltage for soft start-up under a predetermined current band limit ($\pm I_{maxN}$). However, with a fixed switching frequency profile, higher input voltage than nominal causes extra current stress that could damage the converter. Lower input voltage leads to insufficient energy transfer to the output capacitor for start-up. For an LLC operating at wide input

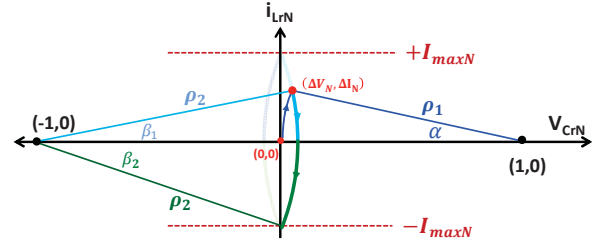


Fig. 14. Trajectory of LLC during the first cycle with customized duty ratio to settle the resonant tank.

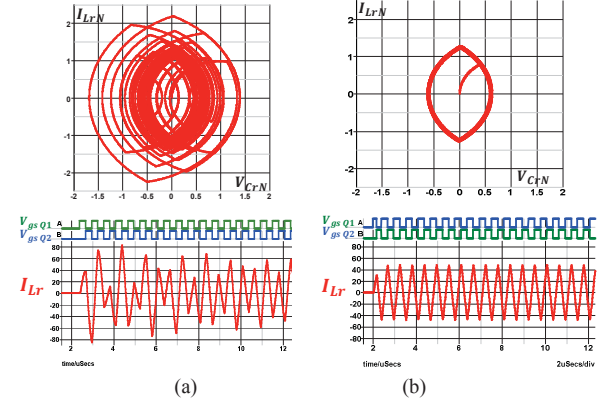


Fig. 15. SIMPLIS simulation of start-up. Top is the trajectory, and bottom is time domain waveforms of resonant current and control signals. (a) With 50% duty ratio on first cycle. (b) With customized duty ratio on first cycle (one cycle settling).

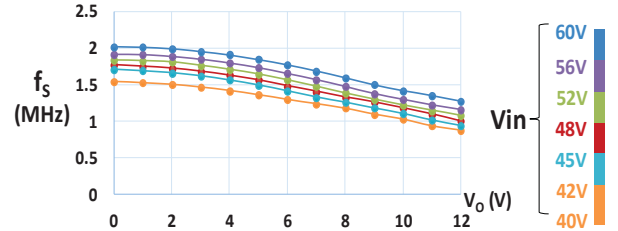


Fig. 16. Switching frequency profile for the start-up.

voltage range, the switching frequency is adapted with V_{in} to ensure the same current stress is applied, and to guarantee successful start-up at the whole input voltage range. Fig. 16 presents a set of switching frequency profiles for start-up at different input voltages. At higher input voltage, higher switching frequency is used to keep the current stress the same at all input voltage range.

VI. EXPERIMENTAL RESULTS

The experiment is carried out on a 1 MHz LLC with $L_m = 800$ nH, $L_r = 200$ nH, and $C_r = 130$ nF. The prototype can deliver up to 1 kW in quarter brick size with power density of 700 W/in³. The tested efficiency shows peak efficiency of

98.8% and full-load efficiency of 98.7% as shown in Fig. 17 The simplified trajectory control for load transient is implemented using a 90 MHz MCU (Piccolo F28069). Fig. 18 shows load transient at 48 V at 4 A/us slew rate. Faster settling time can be achieved with the proposed implementation of 2-step SOTC compared to 12-SOTC. Fig. 19 shows a comparison between the transient response of the proposed 1 MHz resonant LLC solution and the state-of-art solution for a bus converter based on 130KHz - 800W full-bridge phase-shift topology. The two converters are tested from 50 % to 100 % load at the same external capacitor value of 2.2 mF. The results conclude that the high frequency LLC resonant converter with SOTC control can achieve superior transient response to low frequency PWM solutions. Fast response at different gain points is achieved by integrating the feedforward compensator with SOTC control. The transient response is verified at 40 V and 60 V as shown in

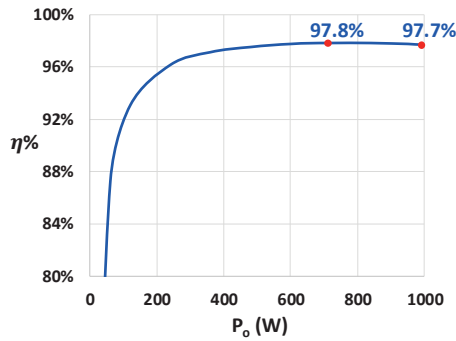


Fig.17. Tested efficiency of 1 MHz – 1kW LLC 48 V bus converter

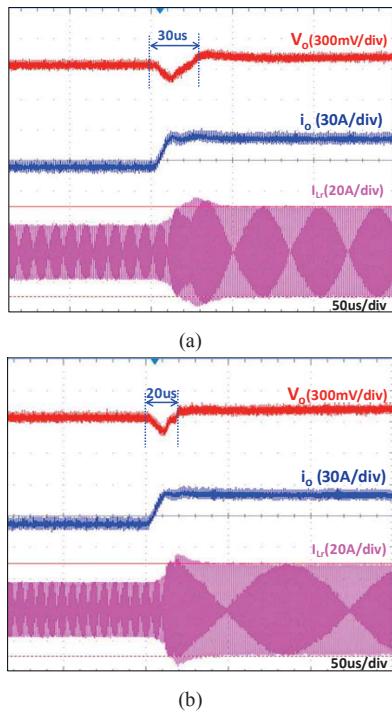


Fig.18. 30A to 60A Load transient response at 48 V with SOTC. (a) 12-step SOTC. (b) Proposed implementation of 2-step SOTC .

Fig. 20. Soft start is also implemented on the same MCU. Different switching frequency profiles are used for different input voltages and stored as lookup table in the MCU. Fig. 21 shows the start-up at input voltage 40 V, 48 V and 60 V at 20 A Load current. The current stress is the same at all input voltages.

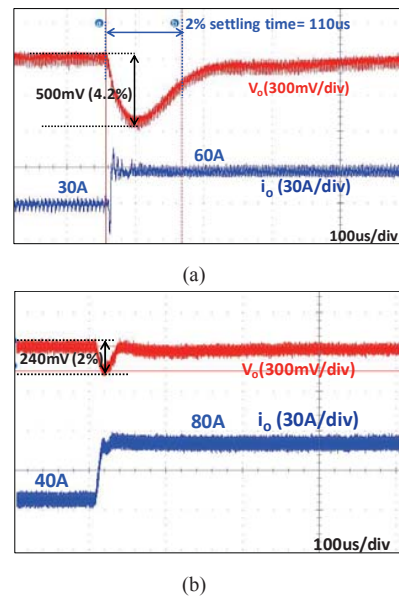


Fig.19. 50% to 100% Load transient response at 48 V (a) 130KHz commercial 800W full-bridge phase-shift converter. (b) Proposed 1 MHz -1kW LLC resonant converter using SOTC control

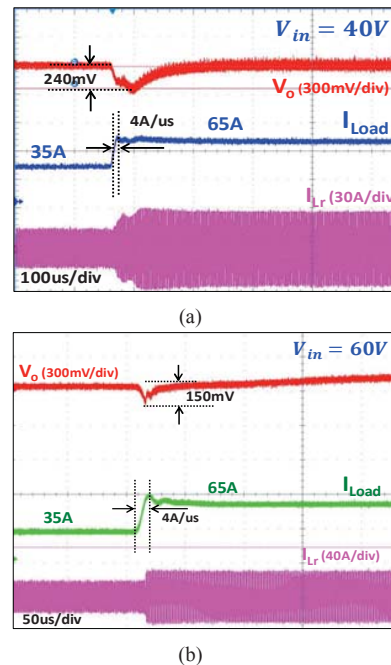


Fig.20. 35A to 65A Load transient response using SOTC with feedforward compensator. (a) $V_{in}=40V$ (b) $V_{in}=60V$.

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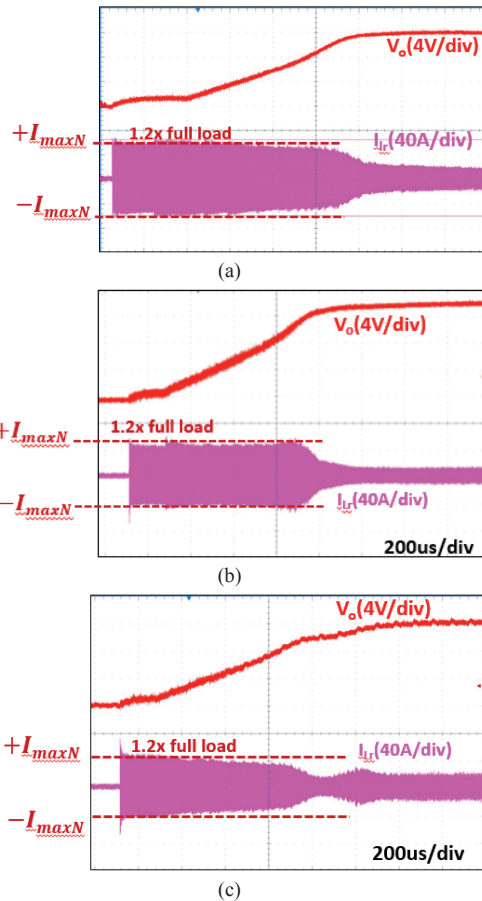


Fig.21. Soft start-up at current stress of 1.2 times the full load current at 20A Load: (a) $V_{in}=48$ V (b) $V_{in}=60$ V, (c) $V_{in}=40$ V.

VII. CONCLUSIONS

In this paper, Digital implementation of SOTC for 1 MHz LLC with wide input voltage range is presented. Digital implementation of 2-step SOTC for high frequency LLC is proposed. The 2-step SOTC can achieve very fast transient response while using low-cost low-speed controller. Furthermore, the challenges of SOTC at wide switching frequency range are addressed. A feedforward compensator is proposed in conjunction with SOTC to obtain optimum transient response at wide input voltage range and wide switching frequency range. Experimental results are demonstrated on 1 MHz – 1kW LLC with input voltage range 40 V~60 V and switching frequency range 0.8 MHz~1.8 MHz using 90MHz MCU. Fast load transient is achieved by using 2-step SOTC and feedforward compensator.

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