Pamukkale Univ Muh Bilim Derg, 24(5), 837-845, 2018

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

Application of 24V/20A LLC resonant converter for OLED TVs

OLED TV'ler için 24V/20A LLC rezonanslı dönüştürücü uygulaması

Çağatay ÖZÇELİK[1*], Atiye Hülya OBDAN[2]

[1,2]Electrical Engineering Department, Faculty of Electrical and Electronics Engineering, Yildiz Technical University, Istanbul, Turkey

cagatayozcelik55@gmail.com, obdan@yildiz.edu.tr

Received/Geliş Tarihi: 09.05.2017, Accepted/Kabul Tarihi: 20.12.2017 doi: 10.5505/pajes.2017.79653

* Corresponding author/Yazışılan Yazar

Research Article/Araştırma Makalesi

Abstract

This study aims to come out with a double transformer resonant converter design that is serially connected in the primary part and parallel connected in the secondary part while using LLC topology. With the help of serial resonance characteristics, the power MOSFETs are conducted at zero voltage switching, therefore the switching power losses on the semiconductor devices are minimized. In the recommended converter, the primary part of two transformers are connected in series in order to transmit the load currents to output in a balanced manner. In the secondary part, the transformers are parallel connected in order to provide equal distribution of load currents. This, in return, decreased the current stresses on the secondary part of the transformers and on the output rectifying diodes. This study provides the working principle of the series resonant LLC converter topologies by designing the PSIM simulation model and laboratory prototype with 24V/20A output for OLED TV power source.

Keywords: Resonant LLC converter, Zero voltage switching, Electromagnetic interference, Switching losses

Öz

Bu çalışmada, LLC topolojisi kullanılarak çift transformatör yapısı ile transformatörlerin primer tarafları seri sekonder tarafları paralel bağlı olacak şekilde rezonanslı dönüştürücü ele alınmıştır. Seri rezonans karakteristiği sayesinde güç Mosfet'leri sıfır gerilim altında iletime girmektedir, böylece yarı iletkenler üzerindeki kayıplar azalmıştır. Önerilen dönüştürücüde transformatörlerin primer sargıları birbirlerine seri bağlanmıştır, bu sayede çıkış tarafına akım dengeli bir şekilde sağlanmıştır. Sekonder tarafta transformatörlerin sargıları birbirlerine paralel bağlanmıştır böylece yük akımı eşit biçimde dağıtılmış aynı zamanda transformatörlerin sekonder sargılarının ve çıkış doğrultucu diyotlarının akım stresi azalmıştır. Bu çalışmada LLC rezonanslı dönüştürücünün çalışma prensibi ele alınmıştır ve OLED TV güç kaynakları için 24V/20A çıkışlı devrenin PSIM simülasyon modeli ve prototipi oluşturulmuştur.

Anahtar kelimeler: LLC rezonanslı dönüştürücü, Sıfır gerilimde anahtarlama, Elektromanyetik girişim, Anahtarlama kayıpları

1 Introduction

Nowadays, power supply units should have high efficiency with small size and lighter weight. In order to meet this requirements, converters should use high switching frequencies, and at the same time should have high efficiency. Two-stage structure power supplies are widely used in the medium level power implementations. Normally, power supply with power factor correction (PFC) topologies can be applied with around 92-95% power conversion efficiency. The power supply has to attain more than 90% efficiency in order to meet the requirements; thus, the power conversion efficiency must be more than 95%. In order to obtain high efficiency, soft switching methods have been discussed in [1]-[4]. The LLC resonant converter topology is a popular candidate for low output voltage, high current converters. This circuit combines some of the attractive features of basic series and parallel resonant topologies and avoids their negative effects [5],[6]. Synchronous rectification was implemented in the secondary to improve the resonant converter efficiency [7],[8]. Series resonant converter (SRC) at no load situation, the output voltage cannot be regulated completely [9]-[12]. One of the main disadvantages of parallel resonant converter(PRC) is that the circulating energy is really high and because of this situation efficiency decreases for high line and light load [13]-[15]. The half-bridge converter type is generally applied at the primary part to achieve the zero voltage switching (ZVS) for all power semiconductor devices without no more additional circuit. Besides, in order to achieve low profile power supply with higher power demand, two transformers configuration is used in most application [16].

Due to their high contrast, wide color gamut and light weight, products with OLED displays are becoming widely used. OLED technology has been primarily used in small sized displays. High levels of power consumption are observed as the screen size increases. The input power supply limit in OLED TV's has been increased up to 600 W in order to support applications that demand extra power, such as Ultra HD, sound systems and Double Tuner (LNB).

For example; in Figure 1, an OLED panel's current drawing waveform is shown. As you can from Figure 1, OLED panel requires great amount current when it comes to current demanding which is pretty different from conventional LCD backlight structure. Generally, in conventional LCD backlight in TV application, the voltage range is greater than OLED but when it comes to current rating, OLED panels require a lot more energy than conventional LCD backlight structure which means it requires more power. On the other hand, low profile TVs are today's trend so that the power supplies on this OLED TVs should also be low profile even if they require more power. For this reason, two transformers with series primary parallel secondary connection is used for this application in order to achieve low profile and high power ratings.

This study shows a series resonant LLC converter for OLED television power supply. In this converter, the transformers have series connection in the primary part in order to guarantee the balanced secondary part current. Besides, the transformers have parallel connection in the secondary part to decrease the current stress on the secondary parts of the transformers; Thus, the load current is equally shared by them. The converter switching frequency is operated above series resonant frequency. In this way, the conduction loss is less than the below resonance working condition. In the below resonance working condition, the converter can have greater efficiency for lower output voltage implementations, where SBR diodes can be currently used for the secondary-side diodes so that reverse recovery disadvantages are less important [17],[18].

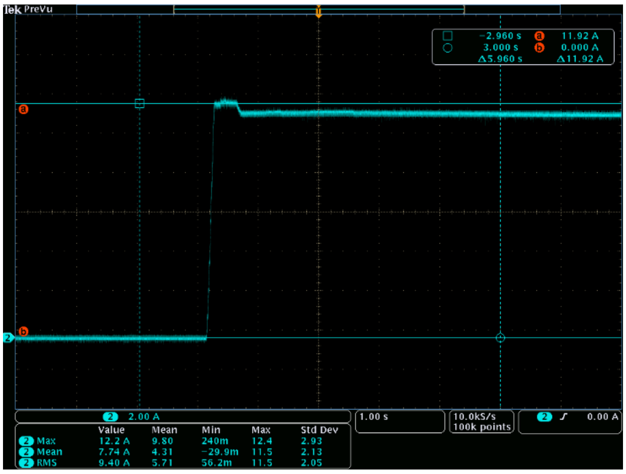

Figure 1: OLED panel current waveform.

2 LLC converter configuration

In Figure 2 the recommended LLC converter is shown. The major benefit of the converter is the ability of the Mosfets to be turned on at ZVS, which decreases the power losses and increases converter efficiency in return. The adjustment of the switching frequency allows the regulation of the output voltage (V_0) which is evident in the converter with input voltage (V_{in}) half bridge power Mosfets are Q_1 and Q_2, C_r, L_r, L_{m1} and L_{m2} are resonance tank, T_{R1} and T_{R2} are the transformers and D_1-D_2 are secondary part devices which are used for rectifying. The primary parts of the transformers are series connected in to ensure that they have equal winding currents of T_{R1} and T_{R2}. Moreover, the second parts of the two transformers are parallel connected to distribute the load current, thus decreasing stresses loaded on top of the currents at the windings that are second in line importance.

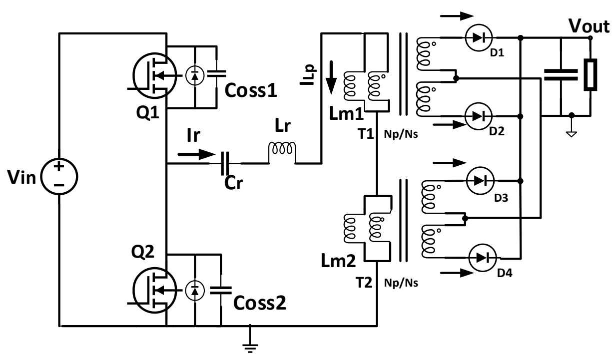

Figure 2: LLC converter topology with series-primary parallel-secondary connection configuration.

2.1 Operation principle

In this working condition, it is conceivable to seperate six modes within one switching period. The first subinterval t0 could be selected arbitrarily. t_0 is chosen as the instantaneous when, with Q_1 is in conduction state and Q_2 is not conducting the resonant network has a positively going zero crossing. Figure 3 and Figure 4 give the key waveforms and operation modes of the converter.

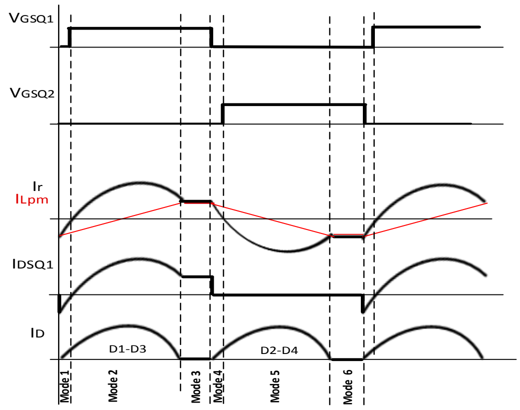

Figure 3: Theoretical key waveforms of the operation modes in the converter.

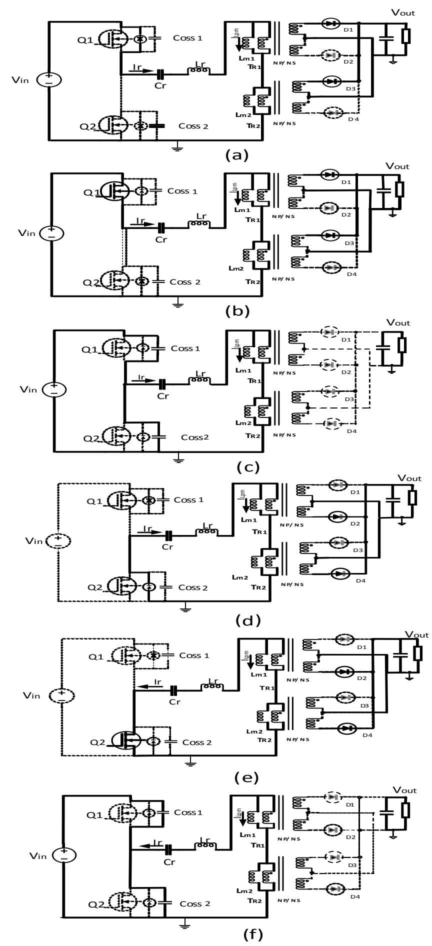

Figure 4: Operation modes of the converter. (a): Mode1, (b): Mode2, (c): Mode3, (d): Mode4, (e): Mode5, (f): Mode6.

Mode 1: When drain-source voltage of Q_1 becomes zero, body diode of Q_1 starts to conduct in order to keep resonant tank current flowing. After body diode of Q_1 conducts, Q_1 gate signal is applied so that ZVS is achieved.

Mode 2: Q_1 gate signal is active and Q_1 is on. At the beginning of this phase, drain-source capacitance of Q_1 is fully discharged and then Q_1's body diode became active. This situation allows zero voltage switching. After Q_1 signal is applied, Q_1 starts to conduct and diodes D_1 and D_3 are active.

Mode 3: At the beginning of this interval, I_{Lr} equals I_{Lm} so that there is no energy flowing through the output. Q_2 is off and drain-source capacitance of Q_2 is discharging in this phase. At the same time, drain-source capacitance of Q_1 is charging to input voltage.

Mode 4: Q_1 and Q_2 are off state which is deadtime interval. At the starting of this interval, the body diode of Q_2 starts conducting. This permits I_r to flow back to the dc supply. D_2 and D_4 start conduct so that energy is flowing through the output.

Mode 5: Q_2 is on and Q_1 is off which is off-state. At the beginning of this phase, I_r the body diode D_{Q2} stops conducting and the R_{dsonQ2}, which is internal resistance of Mosfet Q_2, becomes significant position. Therefore no considerable energy is lost. This interval finishes when I_r becomes zero.

Mode 6: Q_1 is off and drain-source capacitance of Q_1 is discharging in this phase. At the same time, drain-source capacitance of Q_2 is charging to input voltage. During this interval, no energy is flowing through the output. In the ending of this subinterval, gate signal of Q_1 is applied.

2.2 Selection of the optimum design parameters

In order to validate the converter, the converter was designed as 24V/20A output, 400 V input, 480 W. Design criteria was considered as only one transformer using for the converter. Once the design parameters was calculated, these parameters share with the two transformers equally.

The design equations for the resonant frequency, transformer turns ratio, resonant inductor and resonant capacitor are shown as below [19]-[22]:

$$n = \frac{N_p}{N_s} = \frac{V_{in}^{max}}{2(V_0 + V_F)} M_{min} \tag{1}$$

Where V_F is the secondary-side rectifier diode voltage drop.

The equivalent load resistance (R_{ac}) is:

$$R_{ac} = \frac{8n^2}{\pi^2}\frac{V_0}{P_0} \tag{2}$$

The resonant tank parameters equations are below:

$$C_r = \frac{1}{2\pi Q.f_0.R_{ac}} \tag{3}$$

$$L_r = \frac{1}{(2\pi f_0)^2 C_r} \tag{4}$$

$$L_p = m.L_r \tag{5}$$

Where Q is the quality factor chosen by 0.4, f_0 is the series resonant frequency calculated by L_r and C_r, m is the ratio between leakage and magnetizing inductance chosen by 5. f_0 is selected as 100kHz.

3 Simulation results of the LLC converter

The operation of the series resonant LLC converter is performed in PSIM simulation tool to be used in OLED TV power supply. The simulated circuit schematic is shown in Figure 5. In the simulation, the resonant converter's behaviour modeled for different load and line variations. Leakage and parasitic components are also included in this simulation in order to achieve better results. The parameters of the resonant converter is summarized in Table 1.

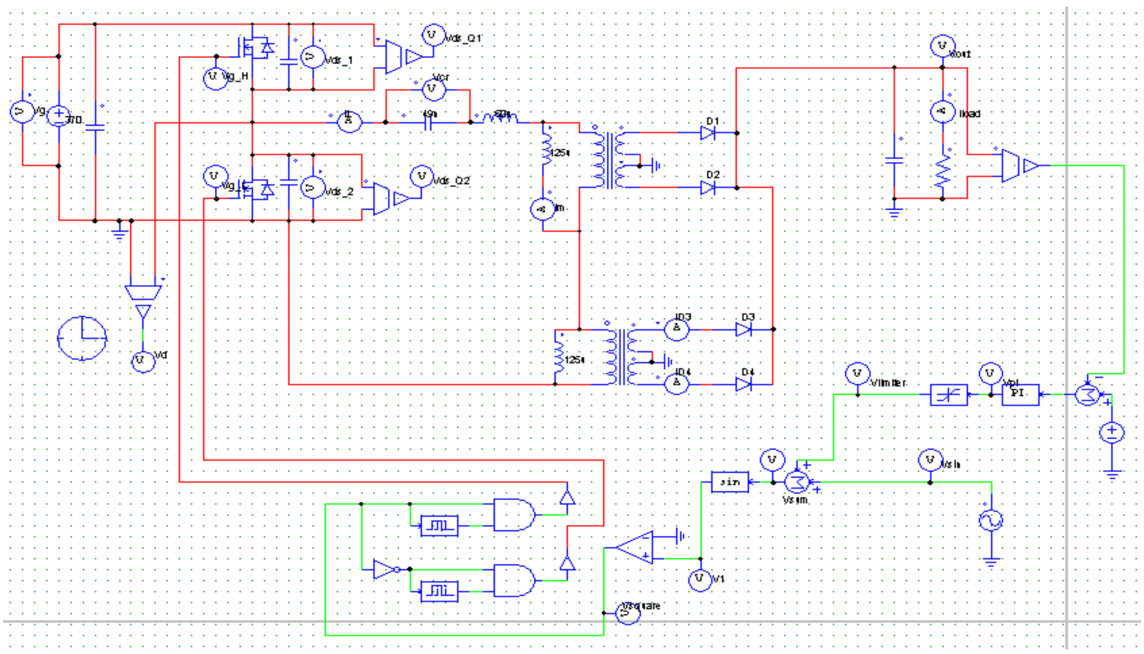

Figure 5: The simulated circuit sheme of LLC resonant converter.

In the resonant circuit, 190N65FL Mosfet and SBR30100CT Schottky Diodes are used. The center tapped configuration is shown in Figure 2, L_{m1} and L_{m2} are the magnetizing inductances of the converter. L_r is the leakage inductance of the converter which is also called as series resonance inductance. C_{Oss1} and C_{Oss2} are the output capacitance measured with the gate tied to source. V_{in} is the input voltage and generally the output of PFC circuits.

Table 1: The used simulation and experimental parameters of the converter.

Parameters	Values
Input side voltage	400 V
Output side voltage	24 V
Output load power	480 W
Switching frequency range	80-150 kHz
Resonant frequency	100 kHz
Series resonant capacitance	49 nF
Total series inductance	50 µH
Total magnetizing inductance	250 µH
One transformer turn ratio	4.5

Series resonant LLC converter could work at frequency beneath and above the oscillation frequency. Figure 6 shows the above resonance operation of the converter for 24V/20A. Over resonance operation has lower conduction power loss in comparison to the under resonance working mode. This means that in this operating mode, the converter can have better efficiency for low output voltage implementations. For example, portable PC adaptor where Schottky diodes could be used for the secondary part rectifiers and reverse recovery impacts are important. On the other hand, above resonance working condition could cause the operating frequency to increase so much at situations with light load. Additionally, the need to skip frequency arises in over frequency working condition in order to avoid great increases in switching frequency.

Figure 7 gives the output rectifier diodes current waveforms of the above resonance operation of the converter. As shown in this figure, before the diodes currents go zero, they cut off so they cannot operate under zero current switching. In this situation, reverse recovery problem occurs because of hard switching in terms of diodes. However, with using Schottky diodes in the secondary side, this problem can be eliminated.

The converter is working at 110 kHz which is greater than series resonance frequency. In order to achieve below resonance operation, primary side turn number of the transformers are increased. When the number of the primary side turn numbers increase, the operation frequency should be decreased in order to ensure regulating the output voltage.

Figure 8 shows the below resonance operation of the LLC converter. Below the oscillation frequency working condition permits the zero current soft commutation of the secondary part diodes while circulating current is larger. It moves further upward as the operation frequency moves downward from the resonant frequency. For high output voltage applications, below resonance operation is chosen since the reverse recovery loss in the secondary side diodes is an important loss parameter. Besides, below resonance working conditions have lower frequency ranges while changing the load situation because the operation frequency is determined short of the oscillation frequency also for condition with no load.

Figure 9 shows the output rectifier diodes current waveforms of the below resonance operation of the converter. As shown in the figure, the rectifier diodes achieve soft switching with ZCS(zero current switching) which is a better option for high output application.

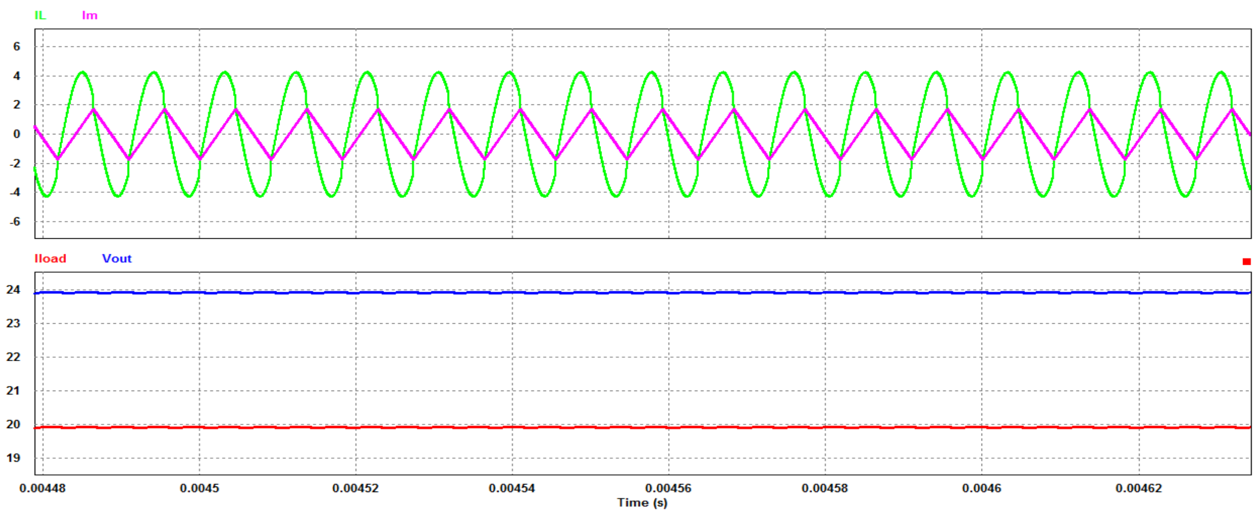

Figure 6: Above resonance operation of the converter. Resonance tank current (I_L), Magnetizing current (I_m), Output voltage (V_{out}) and Load current (I_{load}).

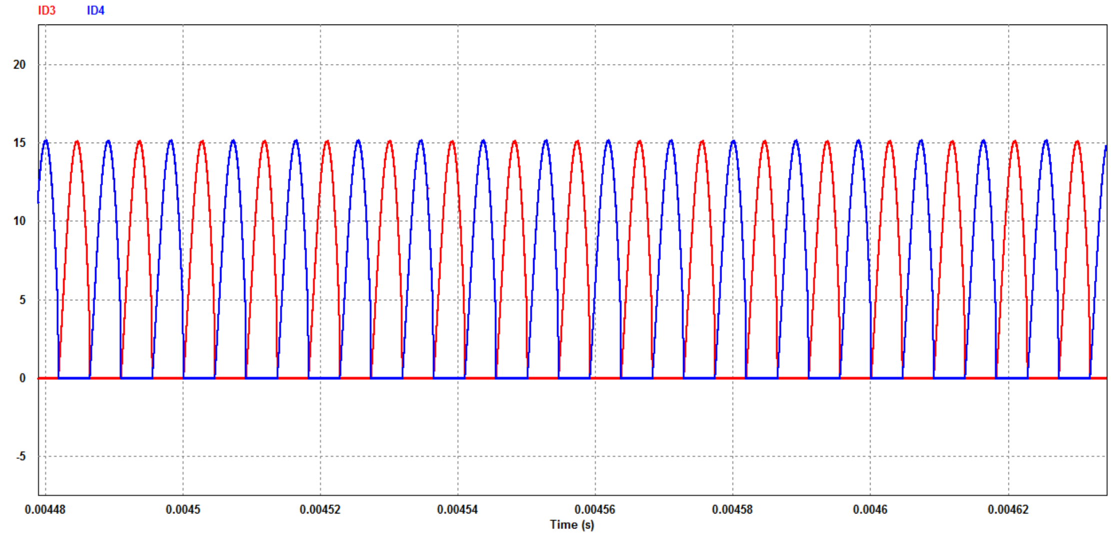

Figure 7: The rectifier diodes (I_{D3}) and (I_{D4}) current waveform of above resonance operation.

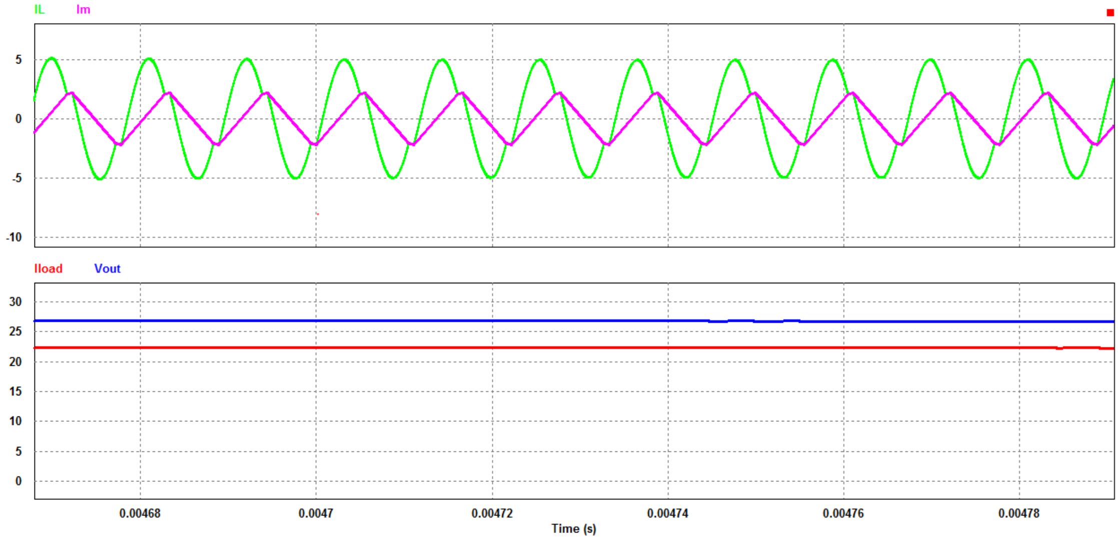

Figure 8: Below resonance operation of the proposed converter. Resonance tank current (I_L), Magnetizing current (I_m), Output voltage (V_{out}) and Load current (I_{load}).

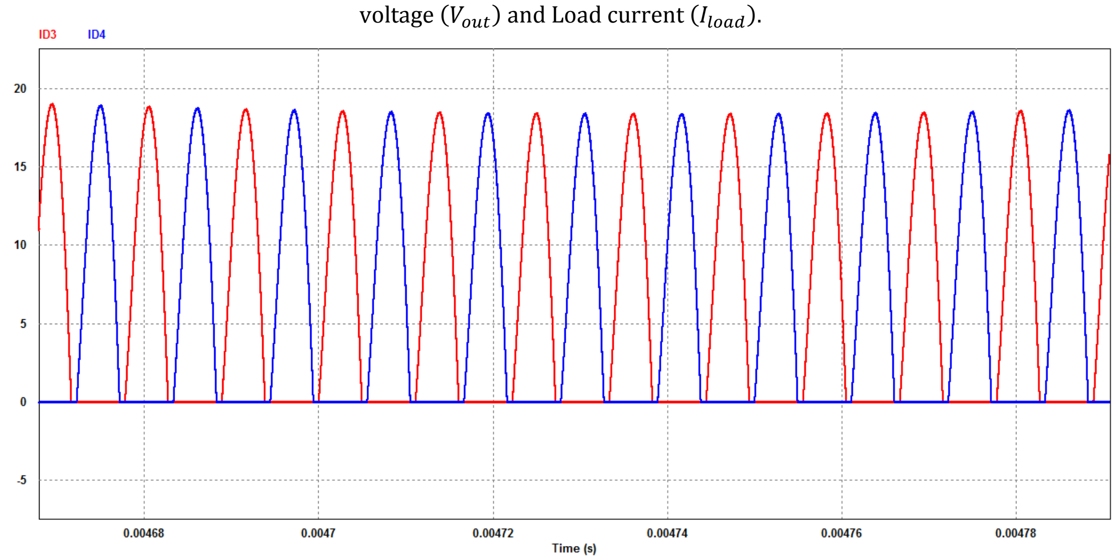

Figure 9: The rectifier diodes (I_{D3}) and (I_{D4}) current waveform of below resonance operation.

The resonant LLC converter is working at 90 kHz which is lower than the series resonance frequency with increasing primary side turn numbers increased.

When the load decreases, the output impedance gets higher value so in order to regulate the output voltage, the voltage gain of the converter should be decreased which is possible to increase switching frequency. Figure 10 shows the converter's switching frequency when the load is decreased.

Normally, when the resonant LLC converter was working at 90 kHz with full load condition, when the load decreased, the converters started to operate at 107 kHz in order to decrease voltage gain so that it can regulate the output voltage.

When the line voltage is decreased, the output can be kept regulated with decrease of the operating frequency because the voltage gain should be increased. Figure 11 shows the switching frequency of the converter when the line voltage is decreased.

Normally, the resonant LLC converter was working at 90 kHz but when the line voltage is decreased, the converter started to operate at 83 kHz in order to keep the output voltage regulated.

Upon the maximum gain frequency, the resonance tank's input impedance is inductive while the input current in the resonance tank lags the voltage implemented to the resonance tank. This allows the MOSFETs to be turned on with ZVS. Meanwhile, the impedance of input in the resonant tank tend to be capacitive and Ip leads the applied voltage of the resonant tank below the peak gain frequency. In the capacitive mode condition, the MOSFET inherent diode is in reverse recovery situation while transitioning between the switchings, which causes problems in terms of severe noise. Some other problem of entering into the capacitive mode operation is that the output voltage regulation is lost because of the reversal in the gain's slope. The lowest frequency of switching must exceed the maximum gain frequency.

Figure 12 shows the ZVS condition of the converter. ZVS is one of the main leverages to use the LLC resonant converter because it allows to operate high input voltage applications. Besides, with ZVS, the electromagnetic interference (EMI) problems could be reduced which is great for the converter's effectiveness.

While the resonance current and the magnetizing current becomes equal, the MOSFET(Q_1) gate signal is cut and drain-source voltage of the low side MOSFET becomes zero. After that the MOSFET(Q_2) gate signal is applied which allows the ZVS of the MOSFETs. The same condition is available for the high side MOSFET.

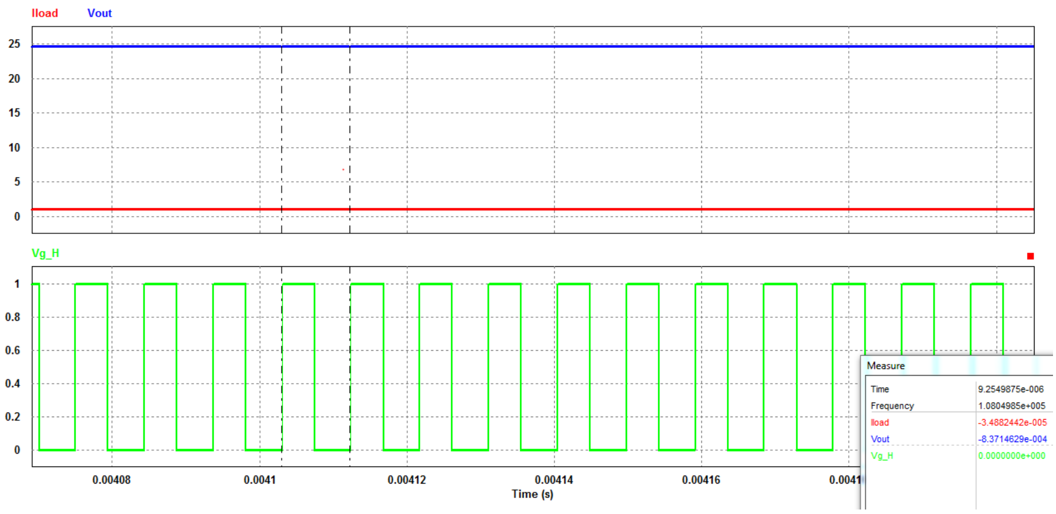

Figure 10: High side mosfet gate signal(V_{gH}) at 1A load condition.

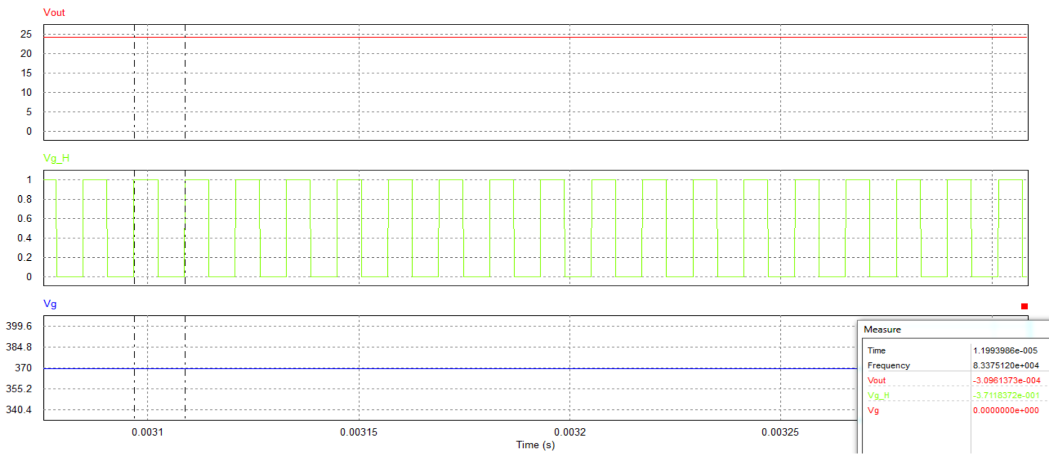

Figure 11: Output voltage (V_{out}) and high side mosfet gate signal (V_{gH}) at 370 V input voltage (V_g).

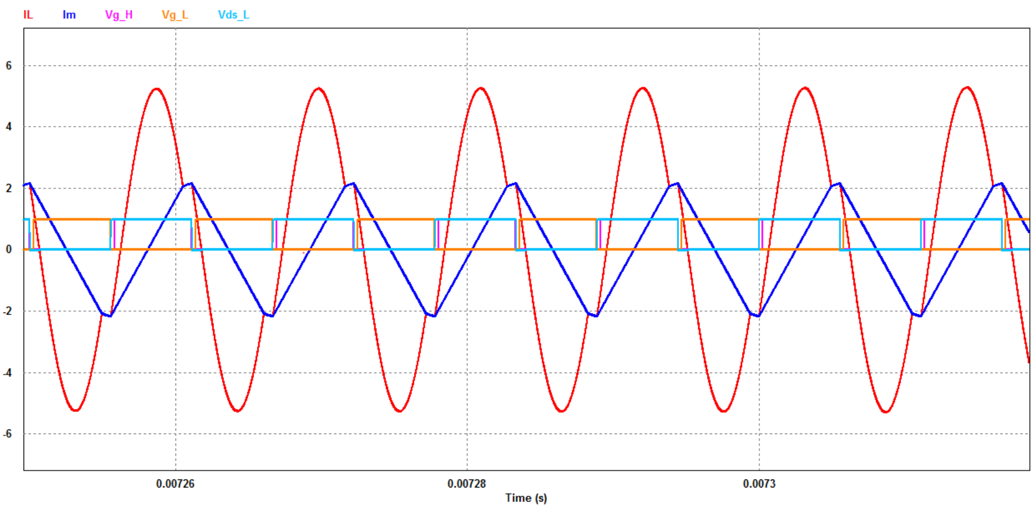

Figure 12: ZVS condition of the proposed converter. High side mosfet gate signal (V_{gH}), low side mosfet gate signal (V_{gL}), resonance tank current (I_L), magnetizing current (I_m), low side Q_2 mosfet's drain-source voltage (V_{DSL}).

4 Experimental results

In order to prove the effectiveness of the converter that the paper suggests, the experiment is conducted on a 480 W rated laboratory prototype circuit. The prototype's specs and values of the circuit are shown in Table 1. For maintaining the stability of the 400 V input range, the front stage of the converter's input terminal is selected as a boost converter PFC. The key waveforms are shown below.

Clearly, before turning off the switch, the voltage of the drain-source is reduced to zero and a negative current is present on the switch. Thus, ZVS turn-on is achieved for both switches Q_1 and Q_2. Figure 13 reflects the primary side currents of the transformers with light load. Figure 15 shows the primary side currents with full load. As figure 15 shows, transformers have same primary currents so that balanced load current is provided. Figure 16 shows that secondary side currents of rectifier diodes. As figure 16 shows, secondary load current is shared with the diodes so that secondary rectifier diodes current stresses are decreased. Figure 14 shows the power switch gate voltage and drain-source voltage in light load condition. Figure 17 shows the power switch gate voltage and drain-source voltage in full load condition. As Figure 14 and Figure 17 show, ZVS is achieved for this converter in both load conditions. The efficiency of the converter is shown in Figure 18. As the load is increased, efficiency becomes better.

5 Conclusions

This work gives a resonant LLC converter with series-connected in primary part and parallel-connected in secondary part in order to realize the balanced secondary winding currents. On the other hand, working at above resonance frequency enables the circulating current to be minimized so that conduction loss is less than the below resonance operation. When working above the resonance frequency, the reverse recovery problems of the secondary side diodes should be taken into account. However, with using Schottky diodes, this drawback could be minimized. Working below resonance allows the ZVS for the secondary part rectifier diodes which completely eliminates the reverse recovery problems of these diodes. On the other hand, circulating current is high which should also be taken into account. Also, one of the most important components of the LLC resonant converter is ZVS in reduction of switching losses and EMI problems. The resonant LLC converter's simulation and experimental circuit are shown and the effectiveness of the converter is discussed. Moreover, 480 W laboratory prototype with two transformers configuration is presented in this study with key waveforms. The study concludes that OLED Tvs require high power density while maintaining effectiveness as shown in the simulations and experiments.

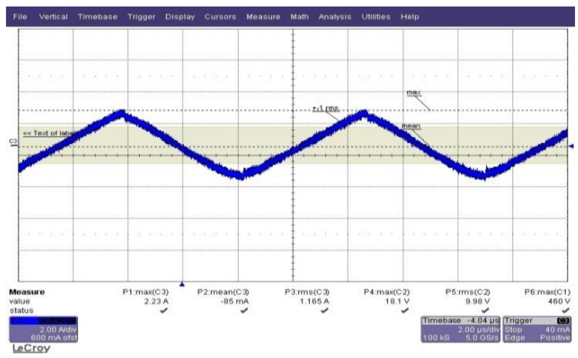

Figure 13: Primary side current of the converter in light load condition.

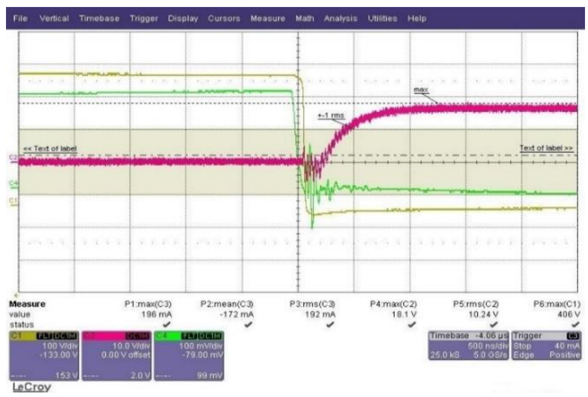

Figure 14: Experimental waveforms in light load condition. Drain-source voltage of Q_1 (Yellow), Q_1 gate signal (Red) and Q_2 gate signal (Green).

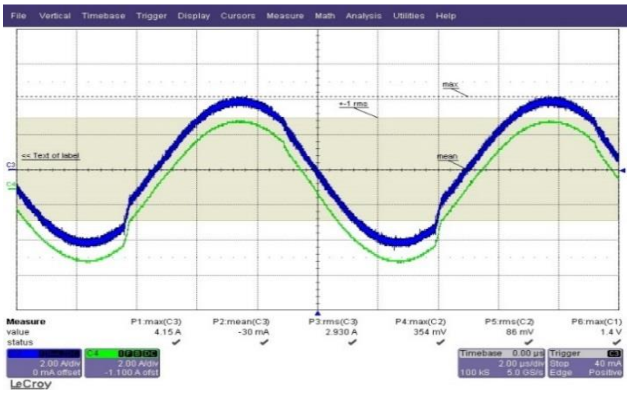

Figure 15: Primary side currents of transformers T_{R1} and T_{R2} in full load condition.

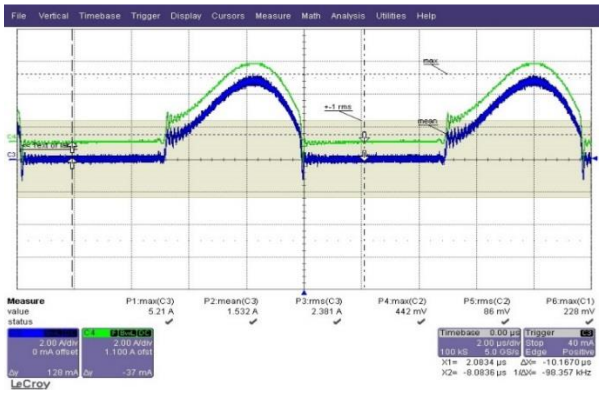

Figure 16: Secondary side currents of rectifier diodes D_3 and D_4 in full load condition.

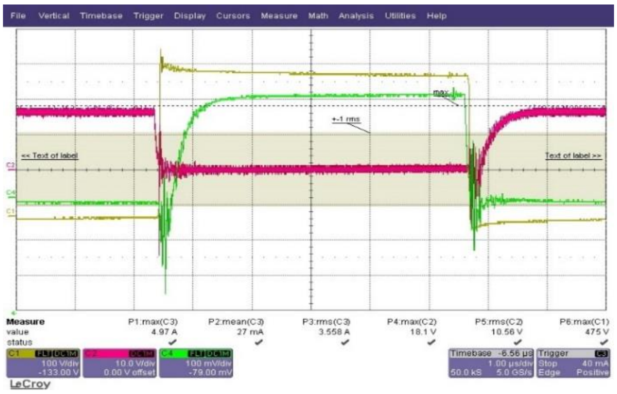

Figure 17: Experimental waveforms in full load condition. Drain-source voltage of Q_1 (Yellow), Q_1 gate signal (Red) and Q_2 gate signal (Green).

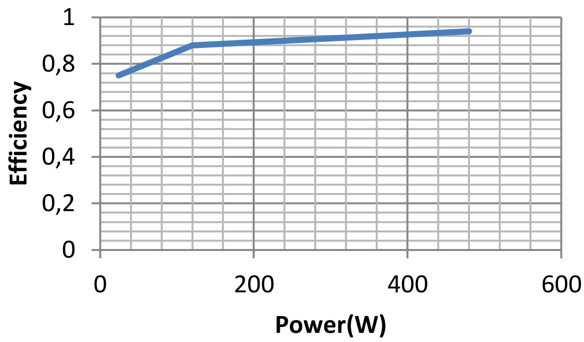

Figure 18: Power-Efficiency curve of the prototype converter circuit.

6 References

[1] Rosetto L. "A simple control technique for series resonant converters". *IEEE Transactions on Power Electronics*, 11(5), 554-560, 1996.

[2] Johnson S, Erickson R. "Steady-state analysis and design of the parallel resonant converter". *IEEE Transactions on Power Electronics*, 3(2), 93-104, 1988.

[3] Steigerwald R. "A comparison of half bridge resonant converter topologies". *IEEE Transactions on Power Electronics*, 3(2), 174-182, 1988.

[4] Lin B R, Chen JJ, Yang CL. "Analysis and implementation of dual-output LLC resonant converter". *IEEE International Conference Industrial Technology*, Chengdu, China, 21-24 April 2008.

[5] Fang X, Hu H, Chen F, Somani U, Auadisian E, Shen J, Batarseh J. "Efficiency-oriented optimal design of the LLC resonant converter based on peak gain placement". *IEEE Transactions on Power Electronics*, 28(5), 2285-2296, 2013.

[6] Kim JW, Moon GW. "A New LLC Series Resonant Converter with a Narrow Switching Frequency Variation and Reduced Conduction Losses". *IEEE Transactions on Power Electronics*, 29(8), 4278-4287, 2014.

[7] Wu X, Hua G, Zhang J, Qian Z. "A new current driven synchronous rectifier for series-parallel resonant (LLC) DC-DC Converter". *IEEE Transactions on Industrial Electronics*, 58(1), 289-297, 2011.

[8] Fu D, Liu Y, Lee FC, Xu M. "A novel driving scheme for synchronous rectifiers in LLC resonant converters". *IEEE Transactions on Power Electronics*, 24(5), 1321-1329, 2009.

[9] Cobos JA, Garcia O, Uceda J, Hoz A. "Self Driven Synchronous Rectification in Resonant topologies: Forward ZVS-MRC, Forward ZCS-QRC and LCC-PRC". *International Conference on Industrial Electronics, Control, Instrumentation and Automation*, San Diego, USA, 13 November 1992.

[10] Fu D, Liu Y, Lee FC, Xu M. "A Novel Driving Scheme for synchronous rectifiers in LLC resonant converters". *IEEE Transactions on Power Electronics*, 24(5), 1321-1329, 2009.

[11] Oruganti R, Yang J, Lee FC. "Implementation of optimal trajectory control of series resonant converters". *IEEE Power Electronics Specialists Conference,* Blacksbourg, USA, 21-26 June 1987.

[12] Bhat AKS. "Analysis and Design of a Modified Series Resonant Converter". *IEEE Transactions on Power Electronics*. 8(4), 423-430, 1993

[13] Vorperian V, Cuk S. “A Complete DC Analysis of the Series Resonant Converter. *IEEE Power Electronics Specialists Conference,* Cambridge, USA, 14-17 June 1982.

[14] Oruganti R, Yang J, Lee FC. “State plane analysis of parallel resonant converters”. *IEEE Power Electronics Specialists Conference*, Toulouse, France, 24-28 June 1985.

[15] Liu R, Batarseh I, Lee CQ. “Comparison of capacitively and ınductively coupled parallel resonant converters”. *IEEE Transactions on Power Electronics*, 8(4), 445-454, 1993.

[16] Erkmen B, Demirel İ. “A very low-profile dual output LLC resonant converter for LCD/LED TV applications”. *IEEE Trans. Power Electronics*, 29(7), 3514-3524, 2014.

[17] Emsermann M. “An approximate steady state and small signal analysis of the parallel resonant converter running above resonance”. Fourth International Conference on Power Electronics and Variable Speed Drives, London, UK, 17-19 July 1990.

[18] Kim ES, Kim JH, Kang SI, Park JH, Lee JS, Huh DY, Jung YC. “Low profile LLC series resonant converter with two transformers”. *Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 1885-1889, Palm Springs, USA, 21-25 February 2010.

[19] Choi H. “AN-4151 half-bridge LLC resonant converter design using FSFR-Series fairchild power switch (FPS™)". https://www.fairchildsemi.com/application-notes/AN/AN-4151.pdf (10.12.2016).

[20] Park KB, Lee BH, Moon CW, Youn MJ. “Analysis on center-tap rectifier voltage oscillation of llc resonant converter”. *IEEE Transactions on Power Electronics*, 27(6), 2684-2689, 2012.

[21] Chang, CH, Cheng CA, Cheng HL. “Modeling and design of the LLC resonant converter used as a solar-array simulator”. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2(4), 833-841, 2014

[22] Chen Y, Liu YF. “Latest advances of LLC converters in high current, fast dynamic responce, and wide voltage range applications”. *CPSS Transactions on Power Electronics and Applications*, 2(1), 59-67, 2017.