Development of LLC Resonant Converter for an Electrostatic Painting Robot System using a High Voltage Module

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Abstract— A LLC resonant converter can achieve wide operation range with high efficiency. In the LLC converter, a wide range of output power is controlled by a narrow variation in operating frequency. For these advantages, the LLC resonant converter is used widely in industrial applications. Especially, in an electrostatic painting system, the LLC resonant converter is combined with high voltage generating module and controlled by a variable frequency to adjust wide output load. This paper presents development of the LLC resonant converter for electrostatic painting system. Experimental results from a laboratory prototype are presented to validate the feasibility of the proposed electrostatic painting system.

Keywords—electrostatic painting, llc resonant converter, resonant frequency, zero voltage switching

I. Introduction

Because of nonpolluting aspects, an electrostatic painting system in automotive industrial field has been focused. In electrostatic painting system, atomized paint particle is projected toward a conductive parts [1]. To spray paint particles, the high voltage generating module and controller are required. The high voltage module is composed of a high voltage cascade and controller. The high voltage cascade or multiplier generates the high voltages, approximately 100 kV and the high voltage controller controls output of high voltage modules. The LLC resonant converter is used in this controller to control input voltage of high voltage cascade. By controlling a narrow frequency range, the LLC resonant converter controls wide output load range [2]. The resonant converter is sorted by resonant tanks. In series resonant converter (SRC) include series connected resonant component and parallel resonant converter (PRC) include parallel connected resonant component. On the other hand, LLC resonant converter has more resonant component and has both characteristics of SRC and PRC. This paper presents the development of LLC resonant converter for electrostatic painting system. Experimental results from a laboratory prototype are presented to validate the feasibility of the proposed electrostatic painting system.

II. System Configuration and Control Design

A. System Configuration

Fig.1 shows the high voltage generating module of electrostatic painting system. This module is composed of a PFC part, a half bridge converter, LLC converter and high voltage cascade. The PFC part controls power factors by matching phase of input current and voltage. And the half bridge converter transfer power to LLC resonant converter. The LLC resonant converter uses square voltages as inputs and has resonant tanks as shown in Fig.1. The output of LLC resonant converter is used as primary voltage of transformer. So, the high voltage cascade include transformer and current sensing part. The topology of proposed LLC resonant converter is shown in Fig.2.

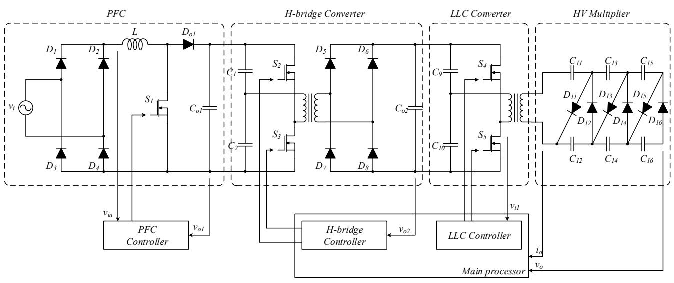


Fig. 1. System configuration and control block diagram.

B. Design of LLC Resonant Component

Fig. 2 shows LLC resonant converter topology. It seems a series resonant converter. As mentioned before, the resonant tank include a resonant inductance, a magnetization inductance and capacitors.

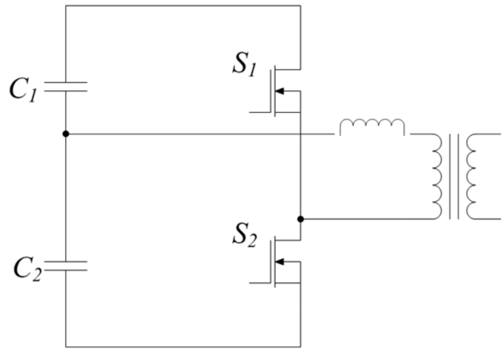


Fig. 2. LLC Resonant Converter .

To proper control LLC resonant converter, the proper design of resonant component is essential [2]-[6]. The components are resonant frequencies and quality factor determined by resonant inductance, transformer's magnetizing inductance and resonant capacitance. Fundamentally, the resonant tanks of an SRC presents a minimum impedance to the sinusoidal current at the resonant frequency, regardless of the frequency of the square-wave voltage applied at the input. As the frequency of the square-wave is varied, the resonant impedance varies to control power transferred to the load. In SRC, only one resonant frequency is existed as follows,

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \, . \tag{1}$$

However, in the LLC resonant converter, the magnetizing inductance is added and the LLC resonant converter has two resonant frequencies as follow,

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \, , \quad f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \tag{2}$$

$$Q = \frac{\sqrt{L_r C_r}}{n^2 R} \tag{3}$$

where f_{r1} and f_{r2} are two resonant frequency, L_r and C_r are resonant inductance and capacitance, Q is the quality factor, n is turn ratio, R is resistance and L_m is magnetizing inductance. At no load, the LLC resonant tank's frequency at peak resonance is same as f_{r2}. And As the output load increases, the frequency changes toward f_{r1}. In this paper, the resonant frequency, $f_{r1,}$ is 16 kHz and Q is 0.25. Fig.3 shows the DC gain characteristics.

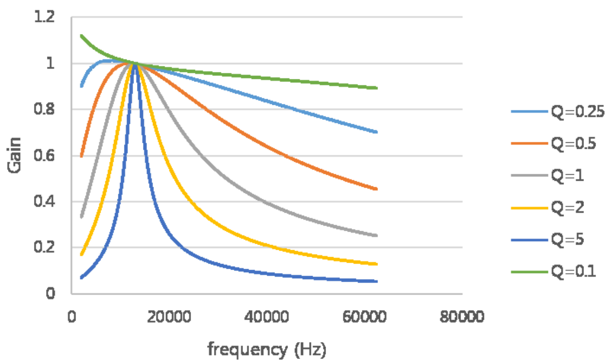


Fig. 3. DC characteristics of the proposed LLC resonant converter

The LLC resonant converter operated around upper resonant frequency will cover all load Q values and work efficiently for wide load range. The dc gain characteristics are divided into two region ZCS and ZVS region. Operating converter at above resonant frequency, f_{r1}, it is possible to operate ZVS.

C. Operation of LLC Resonant Converter

Fig.4. shows typical waveforms of LLC resonant converter with the switching frequency at resonant frequency, f_{r1}. From the top, a gate signal of MOSFET 1, MOSFET2, the resonant inductance current I_r, the magnetizing current I_m and the drain-source voltage of MOSFET are shown in Fig.3. The switching frequency in Fig.4 is same as fr1. Fig.4 shows operation mode of LLC resonant converter.

Mode 1 [t_0~t_1]: When switch S1 turn on at t_0, Mode 1 begins. In this region resonant current, I_r, increases. At t_1, the resonant current, I_r, becomes equal to the magnetizing current, I_m. Then Mode 1 ends.

Mode 2[t_1~t_2]: When switch S1 turns off, the resonant current falls to the value of magnetizing current. Therefore, there is no transferred power to the secondary side. During this period, the resonant current is diverted from S1 to S2. The drain-source capacitance, Cds, of S2 discharges, which makes its voltage zero. And then, the body diode of S2 begins to conduct. At end of mode2, t_2, the source voltage, V_{ds1}, drops to zero and then, the switch S2 turns on. This is zero voltage switching (ZVS) turn on.

Other modes are repeated above procedures.

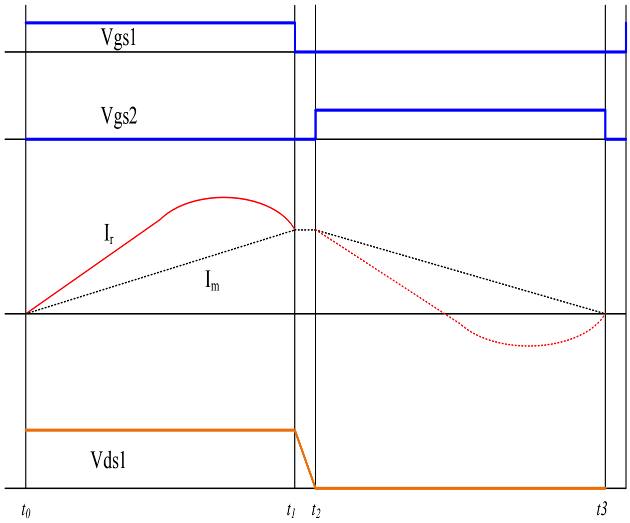


Fig. 4. Typical waveform of LLC resonant converter at resonant frequency .

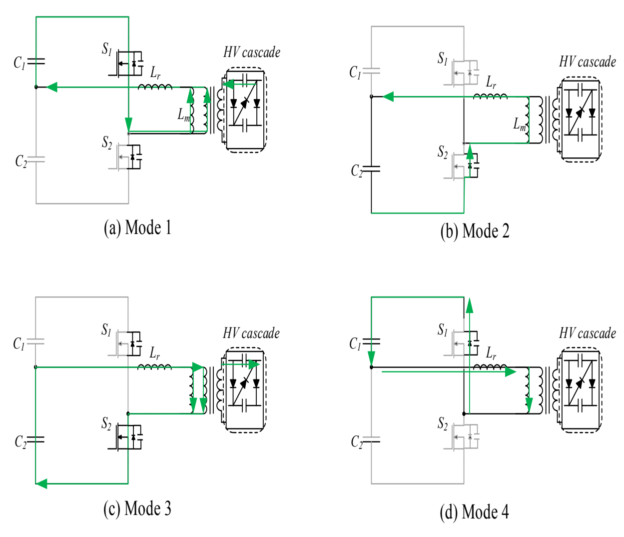


Fig. 5. Operation Mode of the LLC resonant converter .

The ZVS operation is only achieved in inductive region. This region include switching frequency at resonant frequency, f_{r1}, and above f_{r1}. The one of the reasons of using LLC resonant converter is ZVS operation. The LLC resonant converter is achieved ZVS by switching at and above resonant frequency, f_{r1}. So, to keep the current of circuit lags behind its applied voltage is the way to achieve ZVS.

III. Simulation and Experimental Results

Fig.6 shows the simulation model of the LLC resonant converter. The specification of the proposed LLC resonant converter prototype is shown in Table 1.

TABLE I. SPECIFICATIONS OF THE PROTOTYPE

Resonant frequency fr1	kHz	16
Resonant capacitor Cr	uF	2.11
Transformer Turn ratio (Np:Ns)	-	0.003805:1
Leakage inductor	uH	46.7
Magnetizing inductor	uH	611
Input voltage of LLC Converter	V	36 ~ 44
Output Voltage	V	5000
Output Power	W	10

The output of the LLC resonant converter is the high voltage cascade, which is high voltage generating module of electrostatic painting system. The high voltage cascade has 20 stages, which generates 100 kV multiplied by 20 of input of transformer.

The simulation results at full load is shown in Fig. 7. The output voltage of the electrostatic painting system is showed in top plot. The primary current is the third plot and this current is approximately sinusoidal. The 5th top plot is output current of electrostatic painting system and 100 μA at full load. The 6th top plot is the drain-source current of switch S1. The negative spark shows the recovery current. And the bottom plot is the drain-source voltage of the switch S1. At Vds1 drops zero, ZVS operation is achieved as mentioned section Ⅱ.

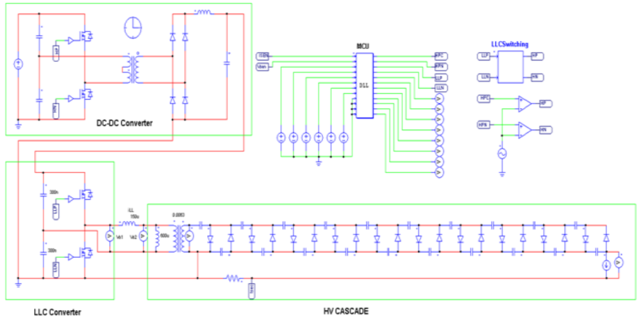


Fig. 6. The block for simulation of the LLC resonant converter

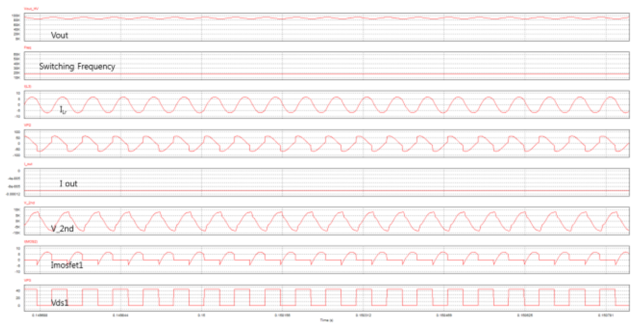


Fig. 7. LLC resonant converter operation at full load condition .

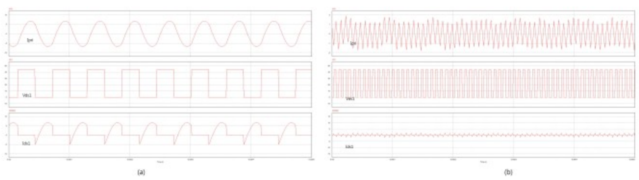


Fig. 8. Simulation results at (a) full load (b) light load (10%) condition

Fig.8 shows the simulation results at varied load condition. The primary current, the drain-source voltage and drain-source current of switch S1 are represented in Fig. 8. The first plot is achieved at full load condition and the latter is at 10% load condition. The operation frequency is 16 kHz at full load condition and 50 kHz. The operation frequency increase as load condition decreases.

Fig.9 shows the ZVS operation. Fig.9 (a) shows the gate signal of the switch S1 and drain-source voltage. Fig.9 (b) shows enlarged plot of sector A of (a). The switch S1 turns on after Vds1 drops to zero. So, ZVS operation is achieved.

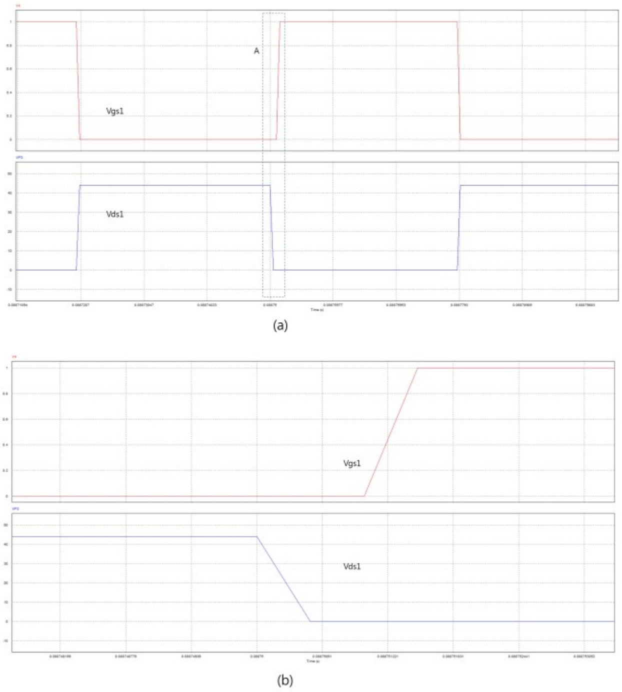
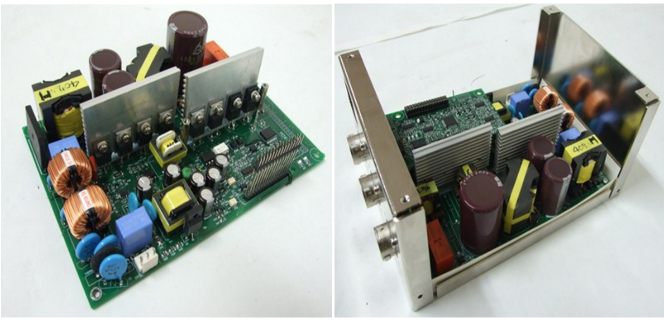


Fig. 9. ZVS operation of the LLC resonant converter

Fig. 10 shows the prototype of the LLC resonant converter for electrostatic painting system. The prototype is composed of the control part and power part. The control part include microprocessor, LCD controller and AD/DA module and the power part include smps part, sensing circuit, and gate driver of MOSFET. The MC56F8037 microprocessor is used to control prototype in real time. The input source voltage is AC 220V and output of the high voltage cascade is 100 kV. The max output power is 10W and output current is 100 μA. The front panel of controller has LCD panel to set parameter and display controller's status.



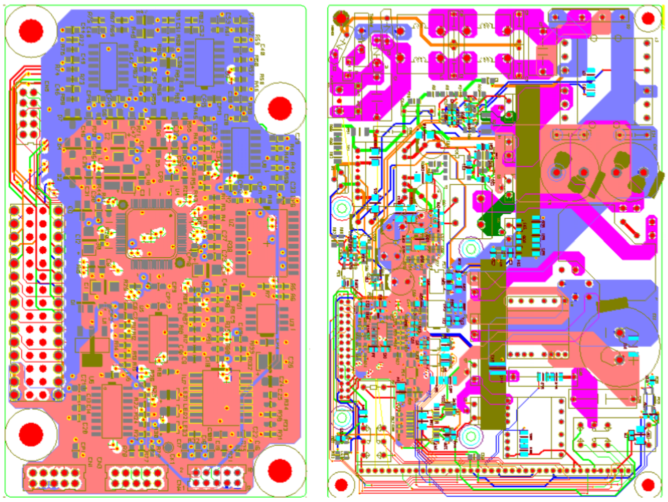


Fig. 10. The prototype of LLC resonant converter

The experimental setup is shown in Fig. 11. This set include divided high voltage resistors to measure output voltage of high voltage cascade module.

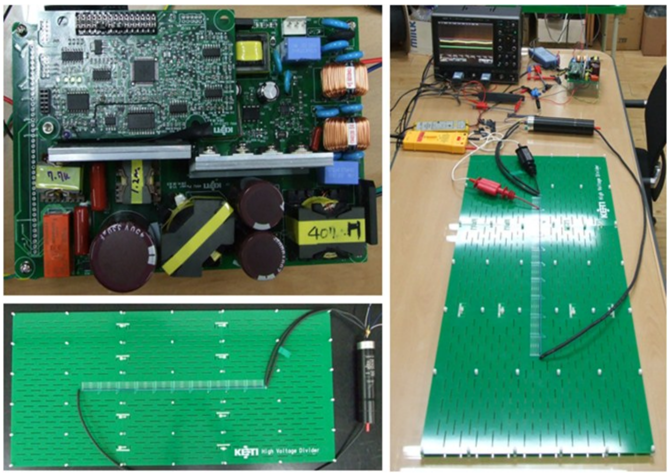


Fig. 11. Experimental Setup

The operation of LLC resonant converter is shown in Fig 12 and Fig. 13. The switching characteristic of the LLC resonant converter is shown in Fig. 12. Fig.12 (a) ~ (f) presents gating signals of switch S1 and S2 with switching frequency 16kHz, 20kHz, 30kHz, 40kHz, 50kHz and 60kHz. The prototype varies operation frequency as load condition changes. These presents the operation capability of various switching frequency. The operation frequency at full load is closed to resonant frequency, fr1, and increases as load condition decreases.

Fig. 13 shows experimental results of full load condition with resonant frequency. The resonant frequency is 16 kHz and output load is 10W, which is a high voltage cascade output full load. The switching frequency is closed to resonant frequency. So, the primary current is sinusoidal as shown in simulation results, Fig. 8 and the resonant tank capacitor voltage is also sinusoidal.

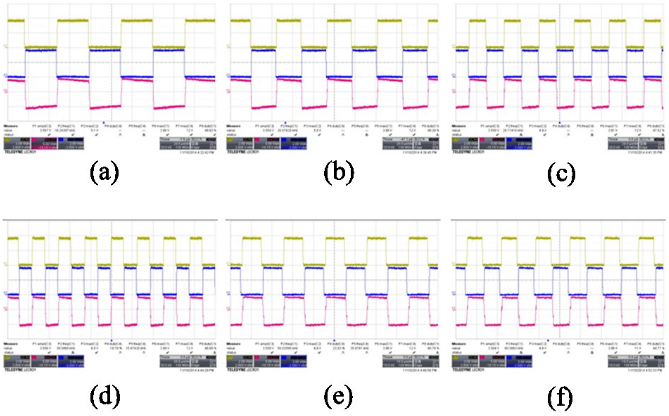


Fig. 12. Experimental results of varying switching frequency.

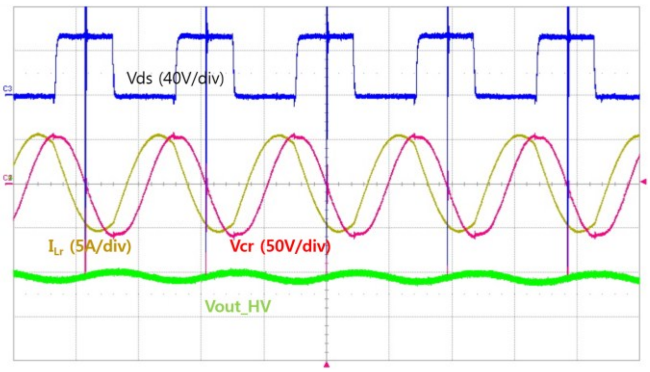


Fig. 13. Experimental results at full load with resonant frequency

IV. Conclusion

This paper presents development of LLC resonant converter for electrostatic painting system. To operate electrostatic painting gun, the high voltage generating module is required. The high voltage generating module uses output voltages of LLC resonant converter as input voltages. The advantage of using LLC resonant converter is ZVS operation and controllability for wide output load range by controlling narrow switching frequency. To ZVS operation, the switching frequency is chosen by the resonant frequency fr1 and fr2. At and above the resonant frequency fr1, inductive region, the ZVS operation is able to achieve. To achieve LLC resonant converter operation, the prototype of converter is developed. This prototype of the LLC resonant converter operates in inductive region, above 16 kHz. This is necessary condition for ZVS operation. The experiment is achieved in operation frequency 16 kHz and load condition is varied from light load to full load. To generate high power output, the operation frequency is closed to the resonant frequency. Through the experimental results, validity and quality of the reported designs are verified. The development LLC resonant converter has been applied in spray gun of electrostatic painting system.

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