Development of High Voltage Module for an Electrostatic Painting Robot System

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Abstract—The electrostatic painting system is widely used in many industry applications. The electrostatic painting system projected charged paint particle toward conducting bodies. Paint particles were highly accelerated during projection process, because of electrostatic charges. Electrostatic painting process takes advantage of the principal of physics to achieve better coverage and to lessen the environmental impact by allowing smaller amounts of chemicals to be used. In this system, a high voltage module is essential component. The high voltage generates electrostatic field used to accelerate projection toward conducting bodies. The high voltage module is composed of voltage multiplier and transformer. In this paper, the development of voltage multiplier and transformer in high voltage module was described. The simulations results are described using PSIM tools. In addition to, experimental results from a laboratory prototype are presented to validate the feasibility of the proposed electrostatic painting system

Keywords—*electrostatic painting, high voltage module, voltage multiplier, high voltage transformer*

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]-[3]. 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.
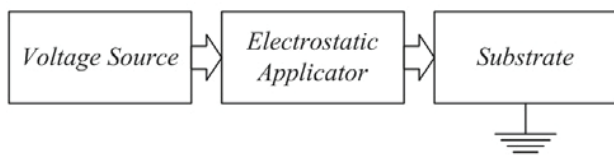

Fig. 1. Electrostatic Painting System [3]

Fig. 1 shows configuration of electrostatic painting system. As mentioned above, to operate electrostatic painting system, very high voltage is required. The voltage source shown in Fig.1 produce the high voltage adopted each painting system. The electrostatic applicator controls the deposition of powder onto the parts being sprayed. The charging system creates a force within the sprayed paint particles enabling them to attach themselves to bare, grounded, metal parts.

This paper presents the development of high voltage module 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. 2 shows the high voltage generating module of electrostatic painting system. This module generates high voltage with negative polarity. The ac voltage is used as input and rectified. The dc to dc converter controls input voltage of LLC resonant converter. Then, the LLC resonant converter controls frequency and amplitude and transfer to high voltage cascade [4]-[8]. The high voltage cascade generates high voltage by transformer and voltage multiplier.
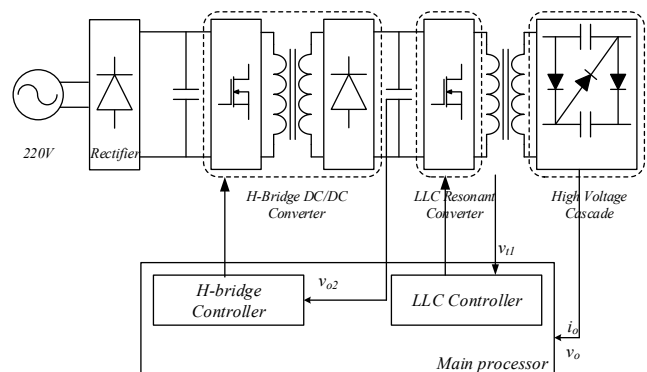

Fig. 2. System configuration for high voltage generation

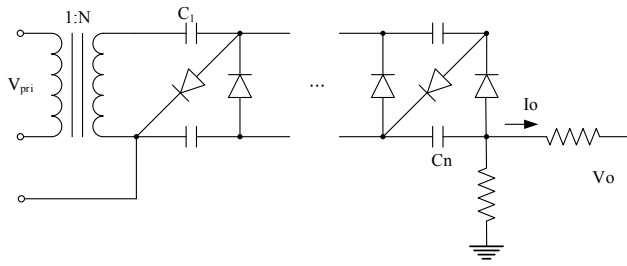## B. Design of high voltage modules

Fig. 3. High voltage cascade circuit.

Fig. 3 shows high voltage cascade topology. It is composed of a voltage multiplier, transformer and feedback resistor. The transformer is a part of LLC resonant converter. The output of LLC resonant converter is the primary voltage of transformer. The regulated voltage magnitude and frequency is transferred to voltage multiplier by transformer. The voltage multiplier is assumed that the number of stage is n. The each stage contains capacitor and diode. The feedback resistor measure output voltage of high voltage cascade.
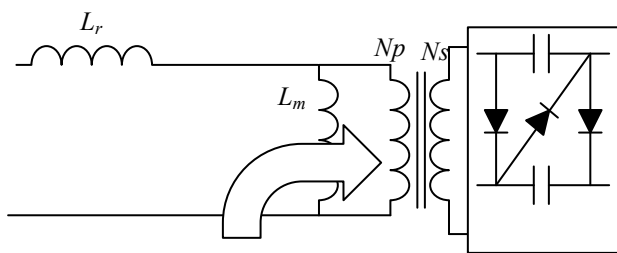

Fig. 4. Equivalent circuit of high voltage cascade impedance

Fig. 4 shows the equivalent circuit of impedance of high voltage cascade. High voltage cascade is seemed as capacitor. So, to design transformer and capacitance, the frequency analysis of high voltage cascade is useful. For this analysis, the Psim tool was used as shown in fig. 5.
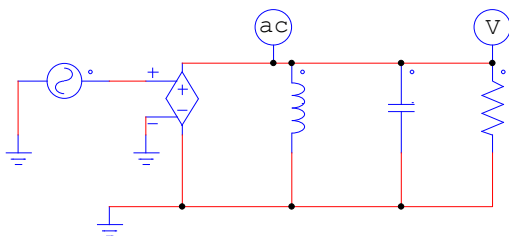

Fig. 5. Frequency analysis of high voltage cascade equivalent circuit usign PSIM

It is possible to design main component of high voltage cascade by frequency analysis.

Input impedance of the circuit, shown in fig. 5. can be given by

$$Z_{in} = \frac{L/C}{R + j\omega L + 1/j\omega C} \qquad (1)$$

The impedance characteristic is that magnitude of impedance is peak at resonant frequency. At low frequency region, the inductive characteristic is dominant, whereas the capacitive characteristic is dominant at high frequency region. And the phase extremely changed at resonant frequency.
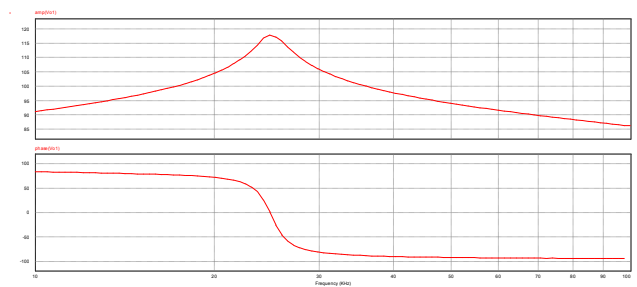

Fig. 6. Frequency analysis results

The target resonant frequency is 25 kHz. By tuning the inductance and capacitance, the desired characteristic was developed as shown in fig. 6. The magnitude has peak value at resonant frequency and phase changed from 90 degree to – 90 degree. The tuned value of inductance and capacitance is 97uH and 0.4367uF. Using this parameters, transformer was developed.

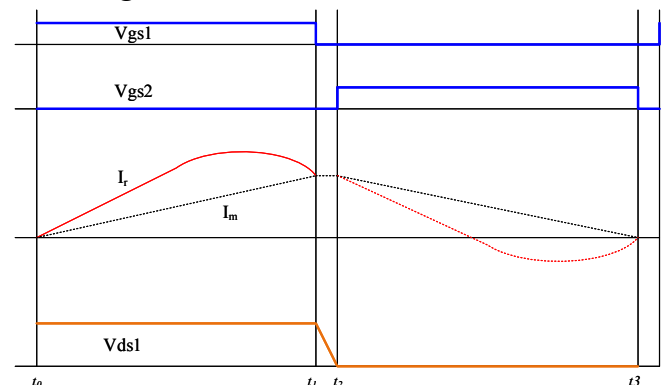## C. Operation of High Voltge Module with High Voltage Controller

Fig. 7. Typical waveform of LLC resonant converter at resonant frequency

To operate high voltage module, the high voltage controller, composed of half bridge dc to dc converter and the LLC resonant converter, is combined to this module as shown fig.1. The half bridge dc to dc converter controls magnitude of output voltage and the LLC resonant converter controls frequency as variation of load.

The typical waveform of LLC resonant converter at resonant frequency is shown in fig. 7. The voltage transferred from LLC converter is primary voltage of transformer. The secondary side voltage of transformer is input voltage of voltage multiplier.

The output voltage of high voltage multiplier and voltage drop by diode, shown in fig. 3, are given by

$$V_o = 2NV_{pri} \qquad (2)$$

$$V_{drop} = \frac{I_o}{fC}(\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{1}{6}n) \qquad (3)$$

Where N is the turn ratio of transformer, Io is the output current, f is input frequency, C is capacitance and m is the number of stage.

III. SIMULATION AND EXPERIMENTAL RESULTS

Fig.8 shows the simulation model of the high voltage cascade equivalent circuit. The simulation model is composed of the LLC resonant converter, high voltage cascade equivalent circuit. The LLC resonant converter controls switching frequency and magnitude. Then the output voltage and current characteristics are measured.
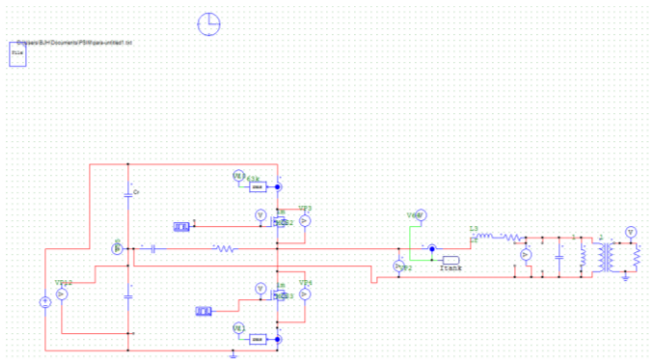

Fig. 8. The block for simulation of the high voltage cascade equivalent circuit

From the frequency analysis the high voltage cascade was designed and simulated as shown in fig. 8. Fig. 9 shows the simulation results at condition that switching frequency is same as resonant frequency.
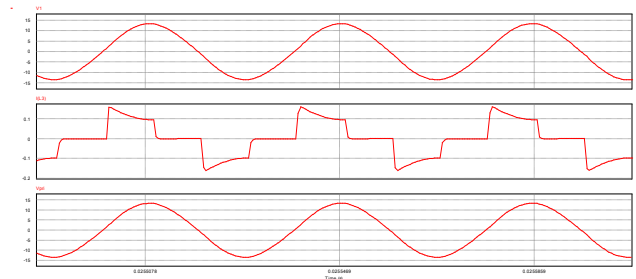

Fig. 9. Simulation results at resonant frequency .

The specification of the high voltage module proto type, simulated as shown in fig. 10, is shown in Table 1.

TABLE I.   SPECIFICATIONS OF THE PROTOTYPE

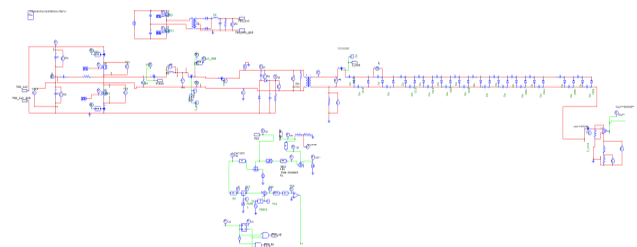| Parameter	Unit	Value
Resonant frequency fr1	kHz	25
Resonant capacitor Cr	uF	1
Transformer Turn ratio (Np:Ns)	-	0.004264:1
Leakage inductor	uH	7.7
Magnetizing inductor	uH	97
Output voltage of high voltage module	V	-100,000
Output current of high voltage module	uA	200
Output Power	W	20

Fig. 10. The total block for simulation of high voltage module

The total simulation model was developed as shown in fig. 10. It is composed of 220V ac source, the half bridge dc to dc converter, the LLC resonant converter, and high voltage cascade. The high voltage cascade was designed as shown table

1. The number of stage of high voltage multiplier is set to 12 stage. To generate -100 [kV], the secondary voltage of transformer is approximately more than 8000 [V]. The voltage drop by diodes is approximately 30 [V]. The simulation switching frequency is set to resonant frequency and the load condition is full load.

Fig. 11 shows the simulation results at frequency resonant. The first plot is the output voltage of high voltage module. It is approximately -100 [kV]. The second plot is the primary voltage and the next plot is the secondary side voltage of transformer. The lowest plot is the output current of high voltage module.
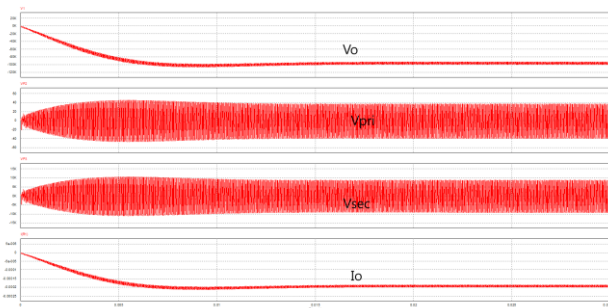

Fig. 11. Simulation results of operation with LLC resonant converter

Fig.12 shows the proto type of high voltage cascade. It contains transformer, voltage multiplier and feedback resistor. The specification of high voltage cascade is based on the frequency analysis above mentioned.
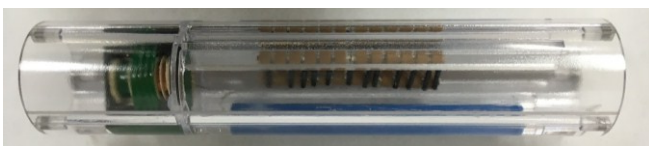

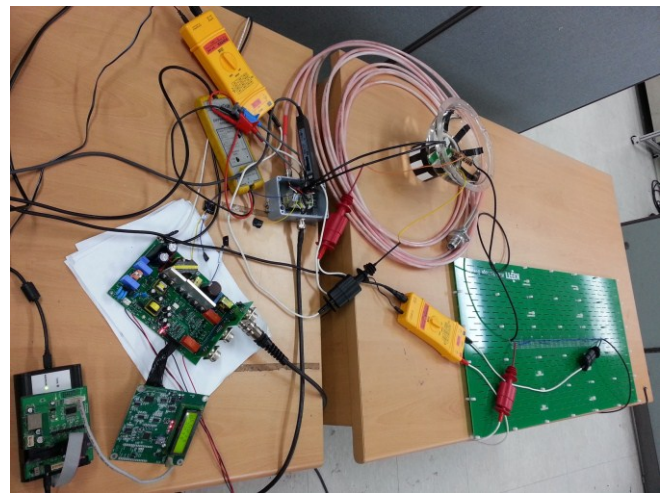Fig. 12. The prototype of the high voltage cascade

Fig. 13. Experimental Setup

The experimental setup is shown in Fig. 13. This set include divided high voltage resistors to measure output voltage of high voltage cascade module. To keep electric insulation of high voltage cascade, the insulation oil is used in experiments as shown in fig. 13. The high voltage controller, developed as mentioned in Table 1, was used to control input voltage of transformer and operation frequency. To prove transformer, transformer and output resistor is connected to high voltage controller, which contains the half bridge dc to dc converter and the LLC resonant converter.

Fig. 14 shows the experimental results of transformer test. The blue plot is the primary voltage of transformer and the green plot is the secondary voltage of the transformer. As shown in fig. 14, the secondary side voltage of transformer is multiplied by 230 times of the primary voltage of transformer.
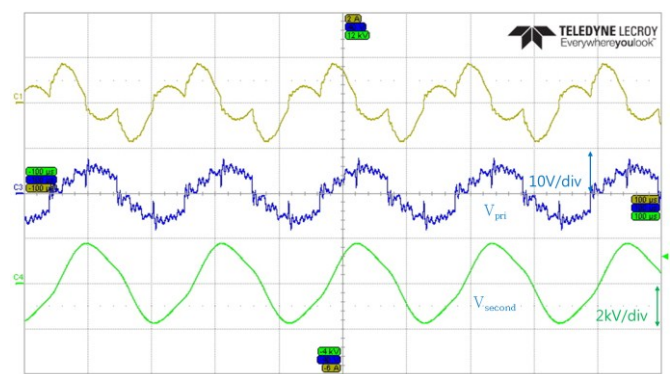

Fig. 14. Experimental Results of proto type transformer operation.

Fig. 15 shows the output voltage of proto type high voltage module. The output voltage is measured by resistor divider. So, the measured

voltage, 10 [kV], is treated as 100 [kV]. The left plot is the transient operation of output voltage. And the right plot is steady state plot.
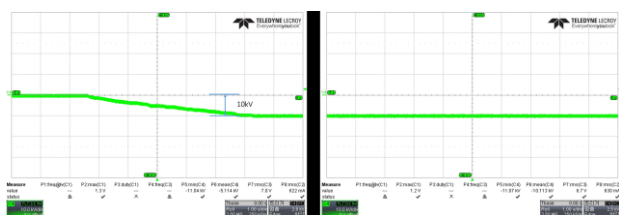

Fig. 15.   Output voltage of proto type high voltage module

IV. Conclusion

This paper presents development of the high voltage module for electrostatic painting system.. 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 and the high voltage controller controls output of high voltage modules. The high voltage cascade is composed of transformer and voltage multipliers. To design proper transformer and voltage multiplier, the frequency analysis is used. By considering input impedance of high voltage cascade, the parameter was selected to fit the target resonant frequency. This process is achieved by PSIM tools. Using selected parameter, the transformer and voltage cascade was designed and simulated. Also, Experimental results from a laboratory prototype are presented to validate the feasibility of the proposed electrostatic painting system.

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