http://dx.doi.org/10.11142/jicems.2013.2.3.321
321 Journal of International Conference on Electrical Machines and Systems Vol. 2, No. 3, pp. 321~329, 2013

Cascaded H-bridge Multilevel Inverter for High Precision and Linear Control of the Rate of Ozone Yielding

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Abstract – A multilevel inverter employing a cascade transformer is proposed for a silent-discharge-tube ozone generating system. The proposed inverter consists of four full-bridge inverters and fourteen transformers which have a series-connected secondary. It can accurately control the amplitude of the output voltage; hereby, it improves a linear characteristic of the rate of ozone yielding. The power regulation characteristics and operational principle of the proposed system are explained from a practical point of view. High precision ozone generating performance of the proposed multilevel inverter is verified by computer-aided simulations and experiment results.

Keywords: Multilevel inverters, Pulse width modulation (PWM), Silent discharge (SD) type ozone generating tube

1. Introduction

Of late years, ozone is widely used in home appliances and manufacturing industry because it has many valuable characteristics to the global environment. Ozone is one of the strongest oxidizing and bleaching agents, which remain no dangerous chemical residua. Generally, it is applied to treat potable water and industrial wastes. Sometimes it is used to sterilize food and to remove NO_x/SO_x, etc [1]-[5].

In commercial ozone generation systems, commonly used type of electrical discharge is the silent discharge which has a tube structure. It has a lot of promising merits such as good efficiency, high stability, easiness of control, and other useful advantages. In the silent discharge method, dielectric materials like a glass or a ceramic are inserted between electrodes. The discharge space is filled with air or oxygen. When high voltage (3kV-20kV) is applied to the electrodes, ozone is generated in the discharge space [3]-[7].

For a stable ozone generation, we need to control the amplitude and frequency of the output voltage. According to the operating frequency ranges, the power supply is divided into low-frequency and high-frequency types. The low frequency type usually employs high-turns-ratio transformers [5]. It is easy to manufacture, but its overall system size becomes larger, and it has low efficiency; moreover, the density of the generated ozone is weak at a medium voltage level. So it needs a very high voltage output to reach the required discharge power density. The higher the frequency makes the higher the power density and the lower the applied voltage [8]. In this viewpoint, the high frequency type power supply is more attractive for an ozonizer. From the recent researches [8]-[18], we can know that it usually employs a resonant circuit. This is a useful approach because it can improve the system efficiency by soft switching. Most of all, the resonant converter can easily accommodate the parasitic components of the high-voltage transformers [8]-[10], [22]. A voltage-fed resonant inverter was presented in [11]. It needs a series inductance to stabilize the discharge. Because the series inductor is located on the high-voltage side of transformer, the converter becomes complicated and costly. A current-fed parallel-resonant inverter has been proposed in [12]. It employs a parallel inductor across the output of the high-voltage transformer; therefore, the secondary is required to compensate the operation of the ozonizer. In [8], [9], a current-fed parallel-resonant push-pull inverter was presented. The use of high-frequency power supplies allows for an increase in the power density applied to the ozonizer and an increase in ozone production while reducing the voltage level for the discharge inception. However, it is little difficult to control the ozone yielding linearly. When a voltage-source inverter is applied to ozone generation system, a clamping inductor is essential because the discharging tube is equivalent to a capacitor. In these circuit configurations, the linear control of the ozone quantity is very difficult when the value of the capacitance is small. To control the rate of ozone yielding linearly, the most

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Received 20 April 2013; Accepted 20 May 2013

important factor is to control the amplitude of the supplied voltage as precise as possible.

In this paper, a cascade multilevel inverter is proposed to control the quantity of the ozone with a stability and high precision. The proposed inverter consists of several full-bridge inverter modules and a cascade transformer. The amplitude of the output voltage is determined by the secondary turns-ratio of the cascade transformer and switching combinations of the full-bridge modules. The performance of the proposed ozone generation system is verified by computer-aided simulations and experimental results based on a 200 [W] prototype.

2. The Principle of Ozone Generation

Ozone is an unstable molecule composed of three oxygen atoms. It comes from original oxygen by means of the energy of ultraviolet or electromagnetic rays. Therefore, the formation of ozone is written as [19]

$$3O_2 \rightarrow 2O_3 . \tag{1}$$

The solubility of ozone is higher than that of oxygen, but it largely depends on temperature and pressure. In the case of silent discharge method, the efficiency of ozone generation is different from ozone’s solubility. The ozone density is about 10-35 [g/m^3] in air, and 50-150 [g/m^3] in oxygen, respectively. The most widely used for ozone generation is the passage of an oxygen-bearing gas through an electrical discharge. In this process, the major reactions that result in the formation of ozone are given as [19]-[21]

$$O_2 + e^- \rightarrow 2O + e^- \tag{2}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{3}$$

where M is the compound such as O, O_2, and O_3. Fig. 1 shows a structure of the silent discharge (SD) ozone generating tube. The surface of the manufactured ozone tube is wrapped by aluminum for uniformity of electrodes.

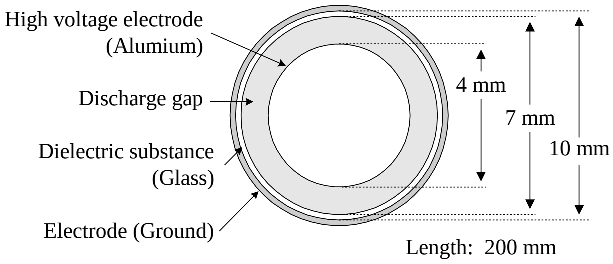
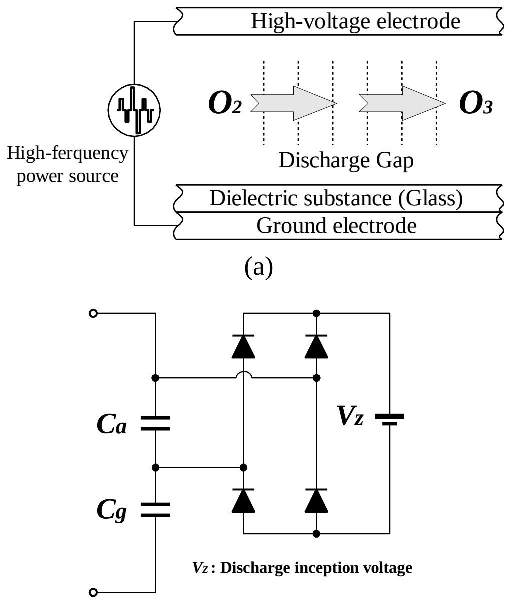


Fig. 1. Cross-sectional view of the silent discharge ozone tube.

Fig. 2 (a) shows the internal structure of the silent discharge type ozone generating tube. Fig. 2 (b) shows its electrical equivalent circuit. Here, C_a means the equivalent capacitance in air, and C_g is the equivalent capacitance by means of the glass. V_Z is the discharge inception voltage. These parameters are determined by the air gap of the discharge tube, width of the glass wall, geometry structure of the discharge tube, and the condition of gas [3], [6], [7]. In the silent discharge tube, the quantity of ozone is determined by



(a)

(b)

Fig. 2. Equivalent circuit of the silent discharge ozone generation tube. (a) Internal structure of the ozone tube. (b) Electrical equivalent circuit.

$$N_o = K \cdot A \cdot \left(\frac{V_Z}{K_g} - V_Z \right) \tag{4}$$

where K is the proportional constant obtained by experiments. A is the effective area of the electrodes. K_g is the effective length between the discharge-gap and the glass wall.

3. Ozone Generating System

3.1 Conventional ozone generating system

Fig. 3 shows a configuration of generally used high-frequency inverter for ozone generation. It consists of a full-bridge inverter, a resonant inductor, and a step-up transformer operated in high frequency. The primary voltage of the transformer V_i has three different values of

$+E$, 0, and $-E$ according to the switching states. Neglecting the winding resistance and the leakage inductance of the primary of the transformer, V_t synthesizes $+aE$, 0, and $-aE$, respectively. The turns-ratio (a) of the transformer is determined by the characteristic of the silent discharging tube. The circuit shows a simple configuration, however it is difficult to control the rate of ozone yielding with high precision.

3.2 Operational principle of the proposed inverter

Fig. 4 shows a circuit configuration of the proposed multilevel inverter for ozone generation. Fig. 5 shows a simplified block diagram of the proposed multilevel inverter. It consists of four full-bridge inverters and fourteen high-frequency transformers which have a series-connected secondary. Among full-bridge inverters, one is used for a PWM operation, and the other is an assembly of LEVEL inverters devoted to generate fundamental output voltage levels [23]. By employing a cascade transformer, it increases the number of output voltage levels, whereas it decreases the numbers of switching devices compared with the conventional multilevel inverters such as diode-clamped, flying capacitors, and cascaded H-bridge cell type. It also boosts low input voltage up to the discharging inception. Most of all, the leakage reactance of the cascade transformer provides a good resonant inductor.

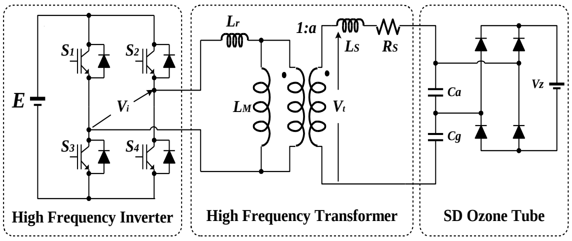


Fig. 3. Configuration of conventional ozone generator.

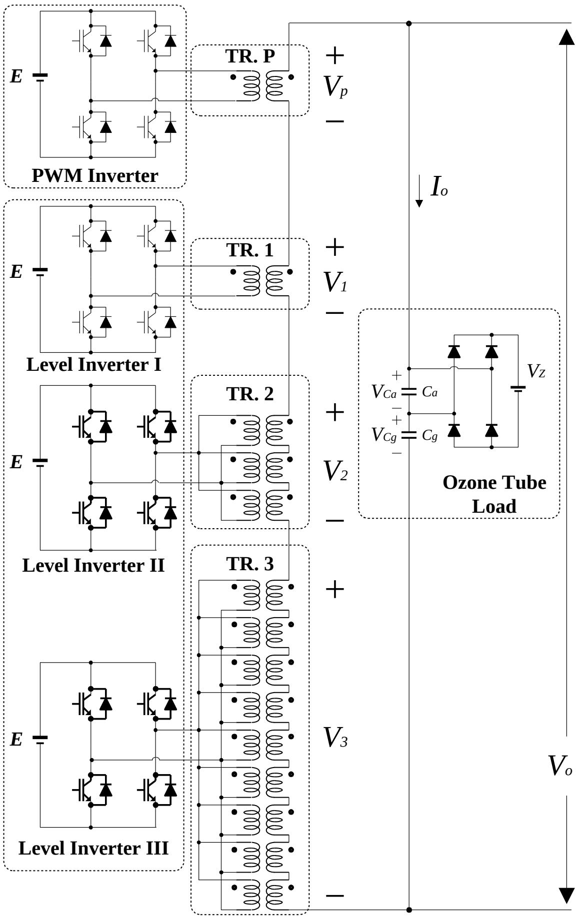


Fig. 4. Configuration of the proposed multilevel inverter.

In Fig. 4 and Fig. 5, it depicts a terminal voltage of PWM inverter (V_P), output voltages of LEVEL inverters (V_1, V_2, V_3), and a final output voltage (V_o). The number of fundamental output voltage levels is 27. It is synthesized by the sum of V_1, V_2 and V_3. Then V_P adds a pulse ($\pm aE$) on the fundamental level to control the amplitude of the output

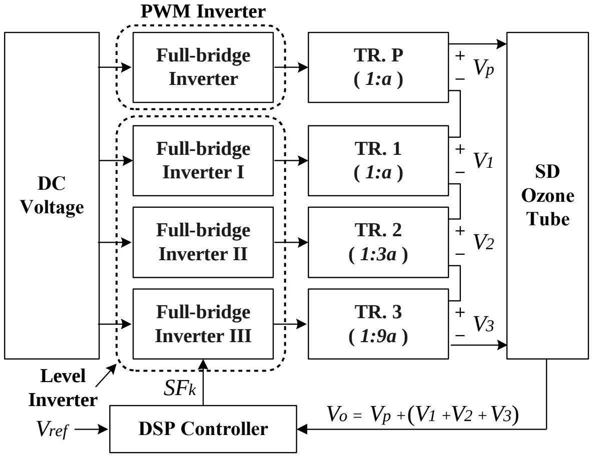


Fig. 5. Block diagram of the proposed ozone generator.

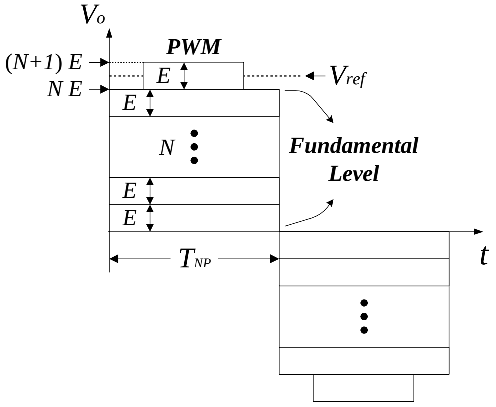


Fig. 6. The principle of the output voltage level generation.

voltage accurately as illustrated in Fig. 6.

Table 1 lists the output voltage levels obtained by the combination of transformers. The number of output levels (N) is normalized by

$$N = 3^{n-1} + 2, \qquad n = 1,2,3,\cdots. \tag{5}$$

Here n means the number of selected transformers in sequence. By applying proper switching functions to this configuration, the final output voltage level can be generated by the rate of an integer to an input voltage source (E).

Table 1. The number of output voltage levels obtained by the combination of transformers

Cascaded Transformers	PWM	LEVEL			
	Tr. P	Tr. 1	Tr. 2	Tr. 3	••• Tr. n
Turn-ratio	**1:a**	1:a	1:3a	1:9a	••• $1{:}3^{n-1}a$
No. of output voltage levels	**3-level**	**5-level**	**11-level**	**29-level**	**(5)**

Table 2 shows positive switching functions in order to synthesize 29 output levels, i.e., n=4 in (5). For the negative case, it is easily obtained by multiplying -1 to Table II. In the case of PWM inverter (SF_P), it plies between 0 and 1 modulating its pulse-width. It will iterate 0 and –1 for the negative output. Based on this basic idea, each switching function for the proposed inverter is given by C-language expressions. Here, all variables are assumed as an integer, and SF_n is the switching function of the full-bridge inverter; thus, it has three switching states, i.e., 1, 0, and –1, respectively. The switching function (SF_P) is written by

$$if\,(n>0) \quad then \quad SF_P = \langle 0 \leftrightarrow 1 \rangle \quad PWM\,. \tag{6}$$

$$if\,(n=0) \quad then \quad SF_P = 0\,. \tag{7}$$

Table 2. Switching functions for the positive output

Output level (n)	Switching Fuction				Terminal Voltage				Output Voltage
	SF_P	SF_1	SF_2	SF_3	V_P	V_1	V_2	V_3	V_o
0	0↔0	0	0	0	0	0	0	0	0
1	0↔1	0	0	0	0 ↔ aE	0	0	0	aE
2	0↔1	1	0	0	0 ↔ aE	aE	0	0	2aE
3	0↔1	-1	1	0	0 ↔ aE	-aE	3aE	0	3aE
4	0↔1	0	1	0	0 ↔ aE	0	3aE	0	4aE
5	0↔1	1	1	0	0 ↔ aE	aE	3aE	0	5aE
6	0↔1	-1	-1	1	0 ↔ aE	-aE	-3aE	9aE	6aE
7	0↔1	0	-1	1	0 ↔ aE	0	-3aE	9aE	7aE
8	0↔1	1	-1	1	0 ↔ aE	aE	-3aE	9aE	8aE
9	0↔1	-1	0	1	0 ↔ aE	-aE	0	9aE	9aE
10	0↔1	0	0	1	0 ↔ aE	0	0	9aE	10aE
11	0↔1	1	0	1	0 ↔ aE	aE	0	9aE	11aE
12	0↔1	-1	1	1	0 ↔ aE	-aE	3aE	9aE	12aE
13	0↔1	0	1	1	0 ↔ aE	0	3aE	9aE	13aE
14	0↔1	1	1	1	0 ↔ aE	aE	3aE	9aE	14aE

The switching function SF_1 is determined by

$$if\,[(n\%3=1)\,||\,(n=0)] \quad then \quad SF_1 = 0 \tag{8}$$

$$if\,(n\%3=2) \quad then \quad SF_1 = 1 \tag{9}$$

$$if\,(n\%3=0) \quad then \quad SF_1 = -1\,. \tag{10}$$

where % means the modulus operator, and || is the logical operator OR. And SF_2 is given as

$$if\,((n/3)\%3=0 \quad then \quad SF_2 = 0 \tag{11}$$

$$if\,((n/3)\%3=1 \quad then \quad SF_2 = 1 \tag{12}$$

$$if\,((n/3)\%3=2 \quad then \quad SF_2 = -1\,. \tag{13}$$

Finally, SF_3 is given as

$$if\,(n<6) \quad then \quad SF_3 = 0 \tag{14}$$

$$if\,(n\geq 6) \quad then \quad SF_3 = 1\,. \tag{15}$$

The switching function SF_3 takes a naught when the output level is lower than the sixth level. In contrast, it takes a unity when the command output level is higher than the sixth level. Using these switching functions, the final output voltage is defined as

$$V_o = a\cdot\left[SF_P + \left(SF_1 + 3SF_2 + 9SF_3\right)\right]\cdot E \tag{16}$$

3.3 Topological considerations of the proposed multilevel approach

A case where the proposed multilevel inverter is applied for the use of an ozone generation system, it has several promising advantages. First, it can convert power for high ac discharging voltage from relatively low dc voltage sources. Second, a galvanic isolation between the inverter system and the silent discharge tube by means of the cascade transformer increases the system reliability. Third, it can increase the output voltage levels with minimized number of switching devices compared with the conventional multilevel schemes such as a diode-clamped, a flying capacitor, and cascaded H-bridge cell method [27]-[32]. Fourth, it does not require an additional resonant inductor owing to the leakage reactance of the cascade transformer. Finally, it reduces *dv/dt* stresses on power switching devices resulted in low audio and RF (radio frequency) noise, EMI (electromagnetic interference) or EMC (electromagnetic compatibility) problems, although the upper PWM inverter is operated in high switching frequency.

In the cascade transformer configuration, the lowest located transformer (TR_3) should have higher turns-ratio than the upper ones; thus, the secondary voltage of the transformer becomes proportionally high. It is difficult to isolate between the primary winding and the secondary one because of the high voltage level. In this case, each transformer (TR_P, TR_1, TR_2, and TR_3) should be designed independently according to the corresponding capability; therefore, it causes the manufacturing cost to increase. To solve the problem, we used the identical transformer (1:a) and it is arrayed as shown in Fig. 4. Consequently, galvanic problems have been solved. In addition, fourteen small high-frequency transformers have relatively high leakage inductance. So the proposed inverter does not need an additional inductor for the resonance.

3.4 Digital microprocessor-based controller

Fig. 7 shows a block diagram of the microprocessor-based controller. The value of the capacitance in the ozone tube depends on the external conditions such as temperature and pressure, and it influences on the resonant frequency. Hence, the resonant frequency should be exactly sensed from the output voltage frequency. In the proposed controller, it removes the requirement of an additional high-voltage detecting sensor because the output voltage is sensed via the lowest located transformer.

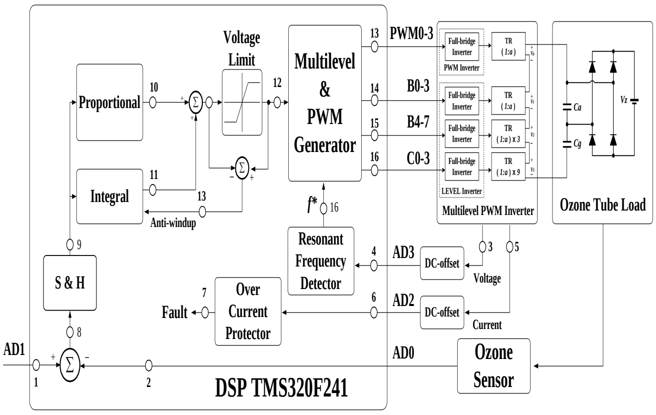


Fig. 7. Block diagram of control system.

In Fig. 7, the command value of the ozone quantity (1) given through AD1 is compared with an actual ozone quantity value (2) obtained by ozone sensor. The error (9) is given as an input of the PI controller. If the command value to the output voltage is out of the allowable range of the multilevel inverter system, the integrator maintains the present value by the anti-windup function. Using the output (12) of the PI controller, a desired output voltage level is selected, and the duty ratio for the PWM inverter is determined. The switching signals generated by the multilevel & PWM generator block are allotted to corresponding inverter switches through port C0-3 (16), and port B0-7 (14, 15), respectively. The PWM signal is given by port PWM0-3 (13). A case where the detected current (6) is beyond the preset limit value, the inverter system will be shunted down.

4. Simulation and Experiment Results

Fig. 8 shows photographs of 200 [W] ozone generating tube. The surface of the ozone tube is wrapped by aluminum for uniformity of the electrodes. To increase the power capability, the electrodes are connected in parallel, and the grass tubes are linked in series. Table 3 shows the specifications of the silent discharge type ozone generation tube, and the proposed multilevel inverter, respectively.

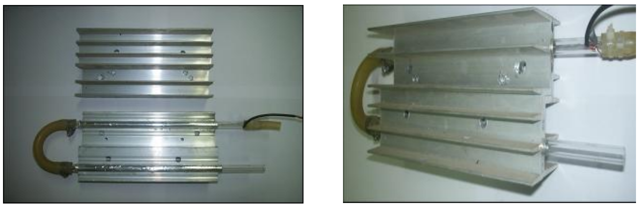

(a) (b)

Fig. 8. Photographs of the prototype ozone generating tube. (a) Before assembly. (b) After assembly.

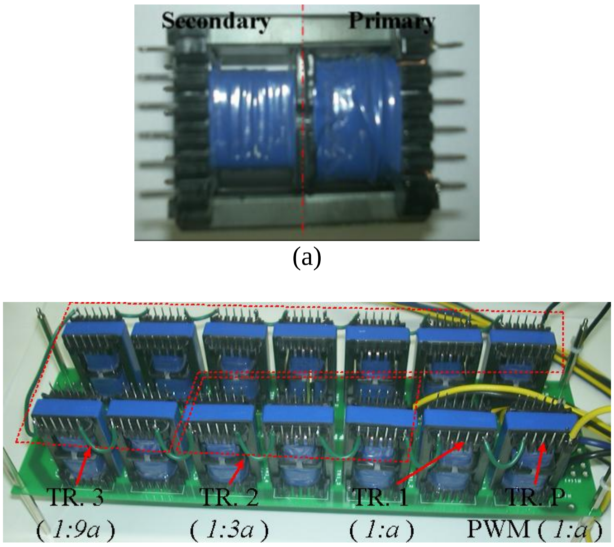
Table 3. Specifications of ozone generation system

Multilevel Resonant Inverter	
Turn-ratio (a)	0.42
Output voltage	0 ~ 10 kV
Output frequency	8 ~ 12 kHz
Leakage inductance	1.68 mH
Silent Discharge Ozone Tube	
Diameter	10 mm
Length	200 mm
Width	1.5 mm
Quantity of generated ozone	$0 \sim 10^3$m /hr

Fig. 9 (a) shows a configuration of the high-frequency transformer having *1:a* turns-ratio. To ensure the galvanic isolation between the primary winding and the secondary one, two cores of EI4035 are employed and assembled separately. Fig. 9 (b) shows the cascade connection of the transformer. Fourteen transformers are connected to synthesize maximum 29 output levels including PWM outputs.

Fig. 10 shows a configuration of the experimental board. The controller using a TMS320F241 and the power stage are composed on a single board. The power stage is consisted of four full-bridge inverter units.

Fig. 11 shows simulation results of the proposed multilevel inverter. In the simulation, a 9-fundamental level is synthesized by the LEVEL inverter units, and the duty ratio of the PWM inverter is set to 0.5. Fig. 11 (a) shows the output voltage of the multilevel inverter (V_o) without the ozone tube load. Fig. 11 (b) shows voltages across C_a and C_g, respectively. Fig. 11 (c) shows voltage across the ozone tube (V_o), and the output current (I_o) is shown in Fig. 11 (d). When the voltage level of V_a is equal to the discharge inception voltage (V_Z), the current flowing through the discharging tube is dramatically changed.



(a)

(b)

Fig. 9. Photograph of cascade transformer. (a) Structure of a transformer. (b) Cascade transformer for multilevel synthesizing.

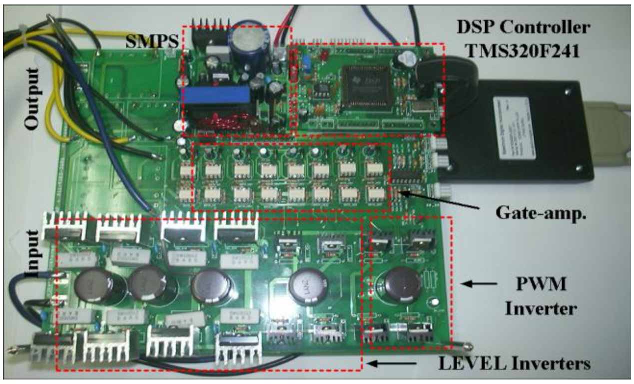
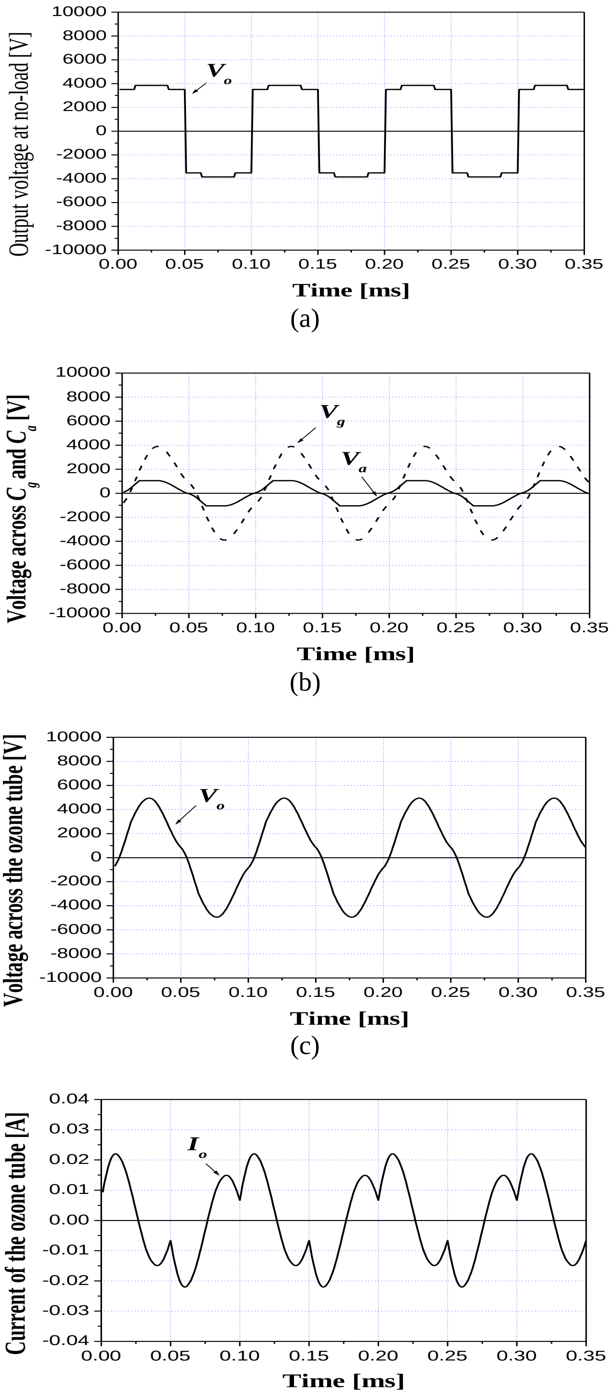


Fig. 10. Configuration of the proposed ozone generating system.

Fig. 12 shows voltage across the ozone tube and output current according to the variation of the switching frequency. Fig. 12 (a) shows the response to a 5 [kHz] operating frequency. It shows an uncompleted resonance state. Fig. 12 (b) shows the response to 10 [kHz] switching frequency in resonance. In this case, the ozone yields 10 [m^3/hr]. Fig. 13 (a) shows the output voltage and current in order to generate 1 [m^3/hr], and Fig. 13 (b) shows for generating 3 [m^3/hr] ozone.



(a)

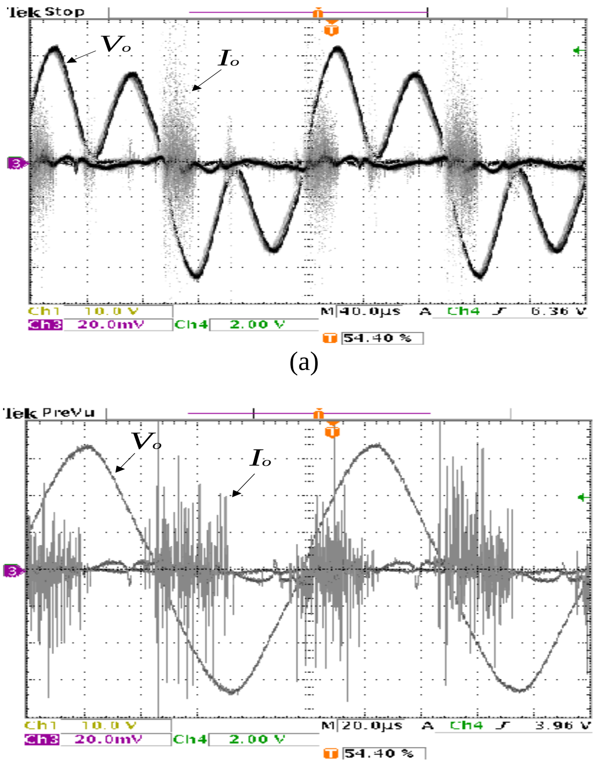
(b)

(c)

(d)

Fig. 11. Simulation results. (a) Output voltage at no-load. (b) Voltage across C_a and C_g. (c) Voltage across the ozone tube. (d) Output current.

Fig. 14 shows the characteristic of measured output voltage as a function of the dc input voltage, and it was compared with the calculated one. In the proposed multilevel approach, the output voltage is synthesized by the sum of the PWM output and the LEVEL inverter outputs. We can find that a good approximation is obtained using the theoretical response.



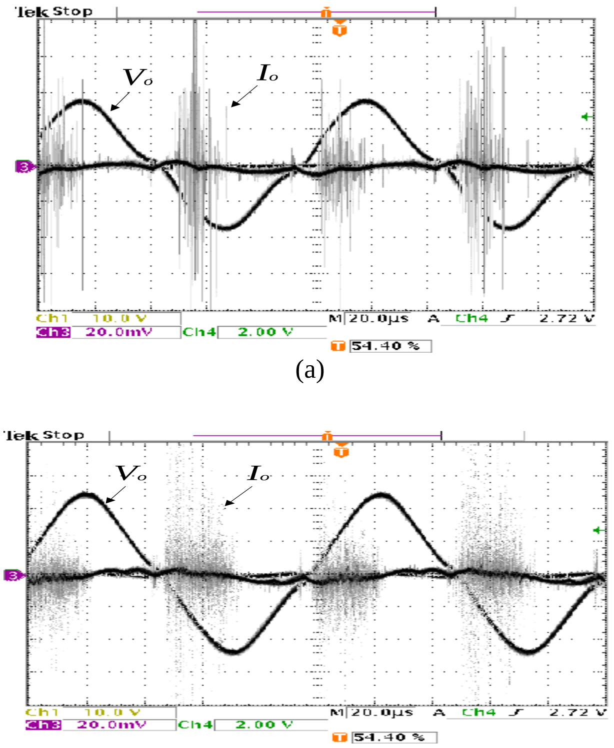
(a)

(b)

Fig. 12. Experimental results of voltage across the ozone tube and output current at different switching frequency. (a) Response to a 5 [kHz]. (b) Response to a 10 [kHz].

Fig. 15 shows the switching frequency as a function of the dc input voltage. In both approaches, the frequency decreases when increasing the dc input voltage. This is due to the change in the equivalent capacitance and resistance of the ozonizer when the supplied power is increased. In the case of conventional push-pull inverter [8], there is no ozone generation at low power level about 7 [kHz] range. However, the proposed approach can generate ozone linearly regardless of power levels. The switching frequency ranges from 11 [kHz] at low power level to 8.5 [kHz] at full output power. For higher power level, the resonant frequency decreases due to the effect of the equivalent resistance of the ozonizer.

Fig. 16 compares the rate of ozone yielding by using the proposed multilevel inverter with the conventional ozone generation system given in Fig. 3. At 10 [kHz] switching frequency, it investigates the relationship between the output voltage and the generated ozone quantity according to the duty ratio of the PWM inverter. A good linear characteristic of the rate of the ozone yielding is achieved in the proposed multilevel inverter. Since the proposed approach can control the amplitude of the output voltage accurately, it ensures high precision control of the quantity of the ozone generation.



(a)

(b)

Fig. 13. Experimental results of the output voltage and output current at the switching frequency of 10 [kHz]. (a) Ozone quantity = 1 [m^3/hr]. (b) Ozone quantity = 3 [m^3/hr].

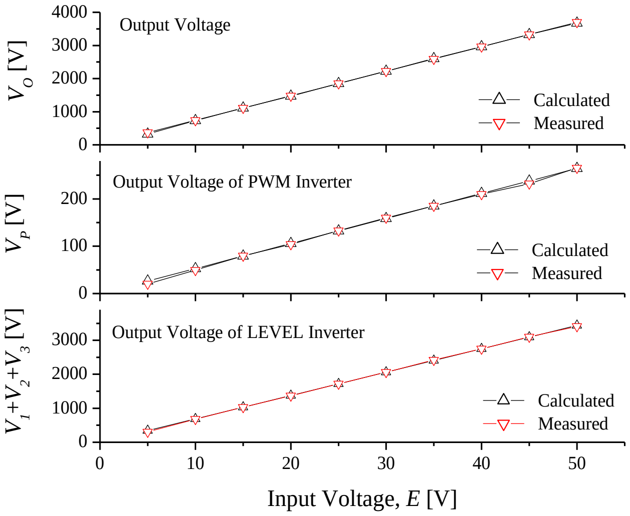


Fig. 14. Calculated and measured output voltage as a function of the input voltage.

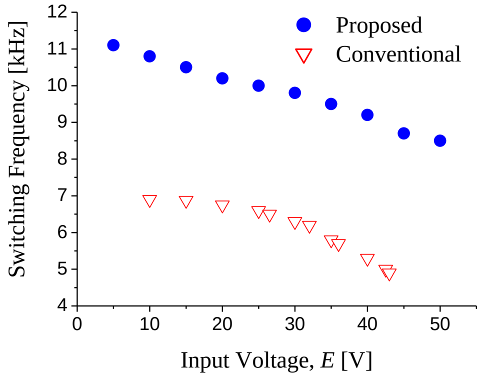


Fig. 15. Switching frequency as a function of the input voltage.

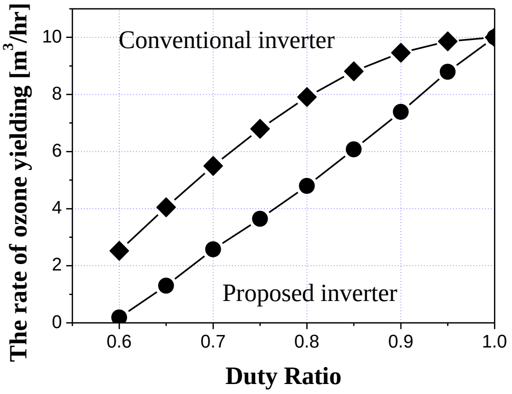


Fig. 16. Comparison of the rate of ozone yielding according to the duty ratio.

5. Conclusion

In this paper, a new multilevel resonant inverter is proposed to control the quantity of the rate of ozone yielding with a stability and high precision. It consists of four full-bridge inverters and fourteen transformers, which have a series-connected secondary. Among full-bridge inverters, one is used for a PWM operation, and the other is an assembly of LEVEL inverters devoted to generate fundamental output voltage levels. The validity of the proposed ozone generation system was verified through computer-aided simulations and experiments using a 200 [W] prototype.

Valuable achievements are summarized as:

(1) High precision and linear control of the rate of ozone yielding.

(2) Efficient power conversion for high ac discharging voltage from relatively low dc voltage sources by itself: it synthesizes a large number of fundamental output voltage levels with minimized switching devices.

(3) Increase of the system reliability owing to the cascade transformer: galvanic isolation between the inverter system and the silent discharge tube.

(4) No need of an additional resonant inductor owing to the leakage reactance of the cascade transformer.

Acknowledgements

This research was supported by Hanbat National University.

References

[1] D. Ibrahim, Marc A. Rosen, "Energy, environment and sustainable development," *Applied Energy*, vol. 64, no. 1, pp. 427-440, 1999.

[2] I. I. Inculet, "Method and apparatus for ozone generation and treatment of water," Canadian Patent 2 104 355, 1997.

[3] T. Muratal et al., "Polarity effect of silent discharge," *Ozone SCI. Eng*., vol. 17, no. 5, pp. 575-586, 1995.

[4] U. Kogelschatz and B. Eliasson, *Handbook of Electrostatic Processes*. New York: Marcel Dekker, 1995, ch. 26.

[5] *Design Guidline Manual for Ozone Systems*, M. A. Dimitrou. Ed., IOA Pan Ameerican Committee. Norwalk, CT, 1990.

[6] K. Urashima, T. Ito, and J. S. Chang, "The Effect of Ammonia on the reduction of NO_x in a combustion flue gas by super imposing space and silent discharges," *Trans. Ind. Electron. Eng. Japan*, vol. 115, no. 9, pp. 916-917, 1995.

[7] R. Feng, G. S. P. Castle, and S. Jayaram, "Automated System for Power Measurement in the Silent Discharge," *IEEE Trans. Ind. Appl*., vol. 34, no. 3, pp. 563-570, 1998.

[8] J. M. Alonso, J. Garcia, A. J. Calleja, J. Ribas, and J. Cardesin, "Analysis, Design, and Experimentation of a High-Voltage Power Supply for Ozone Generation based on Current-Fed parallel-Resonant Push-Pull Inverter," *IEEE Trans. Ind. Appl*., vol. 41, no. 5, pp. 1364-1372, Sept./Oct., 2005.

[9] J. M. Alonso, J. Garcia, A. J. Calleja, J. Ribas, and J. Cardesin, "Analysis, design and experimentation of a high voltage power supply for ozone generation based on the current-fed parallel-resonant push-pull inverter," *in Proc. IEEE IAS'04 Conf*., vol. 4, no. 3-7, Oct. 2004, pp. 2687-2693.

[10] J. M. Alonso, A. J. Calleja, J. Ribas, M. Valdes, and J. Losada, "Analysis and design of a low-power high-voltage high-frequency power supply for ozone generation," *in Proc. IEEE IAS'01 Conf*., vol. 4, Oct. 2001, pp. 2525-2532.

[11] S. Wang, M. Nakaoka, and Y. Konishi, "DSP-based PDM and PWM type voltage-fed load-resonant inverter with high-voltage transformer for silent discharge ozonizer," *in Proc. IEEE PESC'98*, vol. 1, Fukuoka, Japan, 1998, pp. 159-164.

[12] S. Wang, Y. Konishi, M. Ishitobi, S. Shirakawa, and M. Nakaoka, "Current-source type parallel-compensated load resonant inverter with PDM control scheme for efficient ozonizer," *in Proc. IEEE Int. Power Electronic Conf.* (CIEP), Morelia, Mexico, 1998, pp. 103-110.

[13] J. M. Alonso, J. Cardesin, E. L. Corominas, M. Rico-Secades, and J. Garcia, "Low-power high-voltage high-frequency power supply for ozone generation," *IEEE Trans. Ind. Appl*., vol. 40, no. 2, pp. 414-421, March/April 2004.

[14] J. M. Alonso, M. Rico-Secades, E. Corominas, J. Cardesin, and J. Garcia, "Low-power high-voltage high-frequency power supply for ozone generation," *in Proc. IEEE IAS'02 Conf*., vol. 1, Oct. 2002, pp. 257-264.

[15] J. M. Alonso, J. Cardesin, J. A. Martin-Ramos, J. Garcia, and M. Rico-Secades, "Using current-fed parallel-resonant inverters for electrodischarge applications: a case of study," *in Proc. IEEE APEC'04 Conf.*, vol. 1, 2004, pp. 109-115.

[16] C. Boonseng, V. Kinnares, and P. Apriratikul, "Harmonic analysis of corona discharge ozone generator using brush electrode configuration," *in Proc. IEEE PES'00 Conf.*, vol. 1, Jan. 2000, pp. 403-408.

[17] J. M. Alonso, C. Ordiz, M. A. D. Costa, J. Ribas, and J. Cardesin, "High Voltage Power Supply for Ozone Generation Based on Piezoelectric Transformer," *in Proc. IEEE IAS'07 Conf.*, Sept. 2007, pp. 1901-1908.

[18] S. Masuda, K. Akutsu, M. Kuroda, Y. Awatsu, and Y. Shibuya, "A ceramic-based ozonizer using high-frequency discharge" *IEEE Trans. Ind. Appl.*, vol. 24, no. 2, pp. 223-231, March/April 1998.

[19] J. A. Robinson, M. A. Bergougnou, W. L. Cairns, G. S. P. Castle, and I. I. Inculet, "A New Type of Ozone Generator Using Taylor Cones on Water Surfaces," *IEEE Trans. Ind. Appl.*, vol. 34, no. 6, pp. 1218-1224, Nov./Dec. 1998.

[20] J. D. Moon, and S. T. Geum, "Discharge and ozone generation characteristics of a ferroelectric-ball/mica-sheet barrier," *IEEE Trans. Ind. Appl.*, vol. 34, no. 6, pp. 1206-1211, Nov./Dec. 1998.

[21] J. A. Dorsey, and J. H. Davidson, "Ozone production in electrostatic air cleaners with contaminated electrodes," *IEEE Trans. Ind. Appl.*, vol. 30, no. 2, pp. 370-376, March/April 1994.

[22] Y. Zhongming, P. K. Jain, and P. C. Sen, "A Full-Bridge Resonant Inverter With Modified Phase-Shift Modulation for High-Frequency AC Power Distribution Systems," *IEEE Tran. Ind. Electron*., vol. 54, no. 5, pp. 2831-2845, Oct. 2007.

[23] F. S. Kang, S. E. Cho, S. J. Park, C. U. Kim, and T. Ise, "Multilevel PWM Inverters suitable for the use of Stand-alone Photovoltaic Power Systems," *IEEE Trans. Energy Conver.*, vol. 20, no. 4, pp. 906-915, Dec. 2005.

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