

# Development of a Low-Cost Ozone Generator Supply – Optimization Using Response Surface Modeling –

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**Abstract - A high-voltage high-frequency power supply for ozone generator was developed and described in detail in this paper. The power supply comprises a power stage consisting of a single-phase full bridge inverter, a drive circuit and a control circuit. The ozone concentration depends on the voltage level, the signal frequency and the phase-shifted angle  $\alpha$  of the power supply; the response surface modeling was used to identify the optimal values of these factors for maximizing the ozone output and minimizing the power consumption.**

**Keywords - Ozone power supply, response surface modeling, optimization**

## I. INTRODUCTION

Ozone ( $O_3$ ), a powerful oxidizing agent obtained from molecular oxygen ( $O_2$ ), is widely used in replacement of chlorinated compounds in a variety of industry applications such as wastewater treatment, air treatment, and as a disinfectant[1-5]. Due to the small shelf life of ozone, it decomposes in a few tens of minutes at ambient temperatures and rapidly at higher temperatures[6]. Ozone production is achieved by several methods. One technique involves electrochemical reactions to produce ozone[7-9]. The second technique is based on the use of high-energy such as UV light, to convert oxygen to ozone[10,11]. The most employed approach utilizes electrical discharge, known as dielectric barrier discharge[12-20]. In this case, oxygen is passed through a plasma generated by an AC high voltage applied across electrodes, one of them being covered by a dielectric barrier in order to avoid sparkover discharge.

To increase the output of the ozonizer, this latter is fed by a high frequency power supply. It's well known that high frequency decreases the necessary power to be used and increase the ozone production rate. Therefore, ozone generators are usually supplied by a high-frequency power supply[21-23]. The power density applied to the discharge surface and the ozone generation rate are then increased, while the necessary voltage is decreased. The increase in the frequencies up to several kilohertz is now possible by using semiconductor switching devices, such as MOSFETs and IGBTs[24-26].

In general, resonant inverters with step-up ferrite transformer are employed[27-31]. An inductor is sometimes placed at the secondary or primary sides of the transformer to stabilize the flow of microdischarge in the chamber[30,31]. According to [32], a current fed full bridge inverter using a parallel inductor between the secondary side and the ozone chamber is developed. Construction of an ozonizer based on a single-switch resonant converter is indicated in [33],

The objective of the paper is the development of a low-cost ozone power supply, where the frequency and the voltage level are not dependent each other. The specific feature of the power supply used in this work is to vary the voltage level while keeping the value of the signal level constant and vice versa. Indeed, the power supplies generally used with ozone generators are based on the electrical resonance between the transformer inductance and the load capacitance for which the values of the frequency and of the voltage are interdependent. Moreover, the methodology of experimental designs was used for optimizing the values of the supply to give maximum ozone concentration with minimal power consumption.

## II. DESCRIPTION OF THE POWER SUPPLY

The power supply comprises a control circuit stage for generating a high frequency square signal and a power block composed of four IGBTs controlled by the square signal (Fig. 1). Input voltage is decreased to 9V using a step-down transformer 220/9 V, which is rectified and then fixed at a constant value of 5 V using a voltage regulator LM7805. This voltage (5V DC), used to power

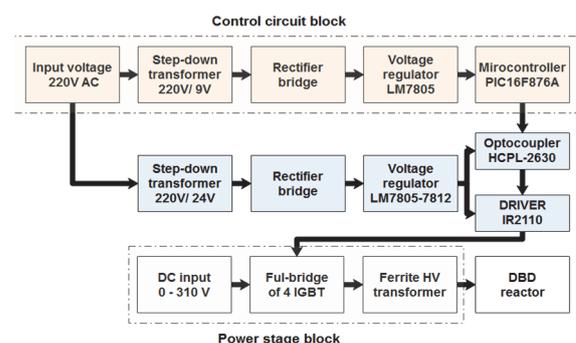


Fig. 1. Block diagram of the ozone power supply.

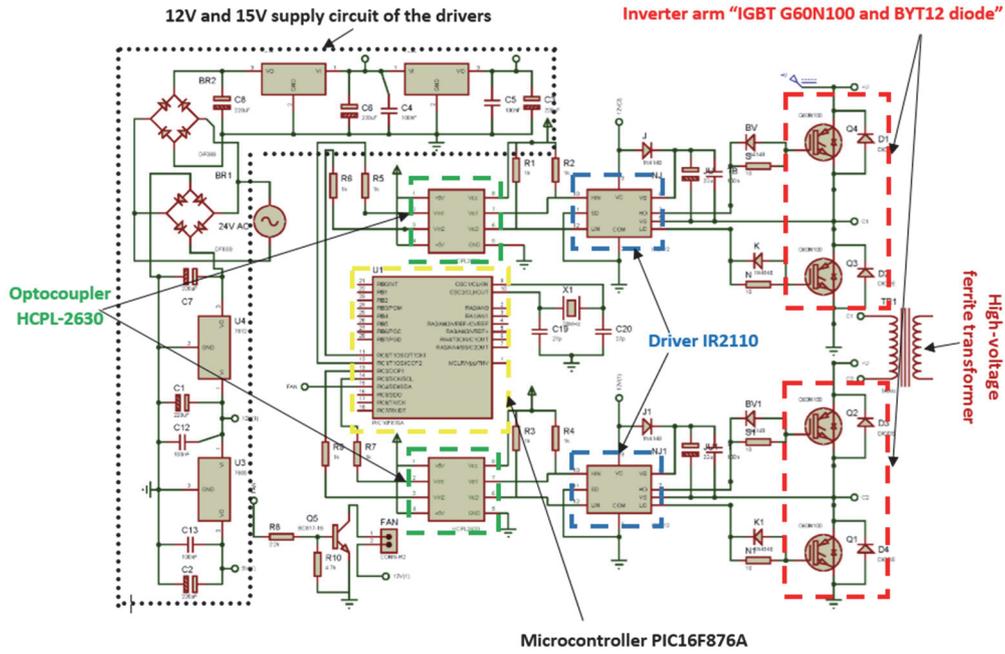


Fig. 2. The global electrical circuit of the ozone power supply.

a microcontroller circuit (16F876A), is transformed into a square signal of adjustable frequency. At the same time, a rectified and adjustable voltage (0-310 V), that feeds the primary of a step-up ferrite transformer of power 200 W, is transformed in a high frequency signal by the IGBTs (G60N100) controlled by the square signal, thereby obtaining an adjustable high voltage output.

The global electrical circuit of the ozone generator power supply is represented in Fig. 2. The isolation stage (HCPL-2630 optocouplers) is essential in order to protect the control device (16F876A) from possible faults in the power stage and thereby minimize damage to the control devices which can be expensive according to the range. Presently the majority of the electronic circuit isolation devices use opto-coupling devices due to the fact that these devices are affordable and more accessible. To activate or deactivate a IGBT, it is necessary to design or select a circuit that ensures the state transition in a short time (drive). The integrated driver circuit IR2110 meets

the above requirements. These integrated circuits can feed two IGBT in the same branch (inverter arm), which needs the use of 2 identical driver circuits to activate the system composed of 4 IGBT.

The output voltage of typical power supplies for ozone generators reaches levels of several kV[34], using a high voltage ferrite transformer. The ferrite core of the high voltage transformer operates over a wide frequency band, it is used in power applications where the operating conditions require a magnetic material with high permeability and low power loss. Moreover, their high resistivity (greater than  $10^6 \Omega \cdot m$ ) is an advantage for applications at high frequencies.

### III. TOPOLOGY STRUCTURE AND PHASE-SHIFT CONTROL STRATEGY

In Fig. 3 is represented the topology of a series resonant power supply.  $V_{in}$  is a DC input power supply;  $T$  is as a step-up transformer;  $S_1 \sim S_4$  are the power switches (IGBT or MOSFET), and  $D_1 \sim D_4$  are the anti-parallel diode;

Phase-Shift Control (PSC) is a kind of PWM control strategy. In the control strategy, the driving signal of diagonal pairs switches in the inverter bridge legs ( $S_1, S_4$ ) and ( $S_2, S_3$ ) should have a stagger angle  $\alpha$ , which is called phase- shift angle, and the driving signal of the two switches ( $S_1, S_2$ ) and ( $S_3, S_4$ ) in the same bridge is complementary. So a zero voltage interval is inserted between the positive and negative edges of the inverter output voltage. The phase shifting angle  $\alpha$  is adjustable in the range of  $0^\circ \sim 180^\circ$ , and the duty ratio of the inverter output voltage can be varied by adjusting angle  $\alpha$ ; then the effective value of the output voltage can be changed, and power regulation is achieved ultimately. The principle of the PSC strategy is shown in Fig. 4, where  $V_{S1} \sim V_{S4}$  are

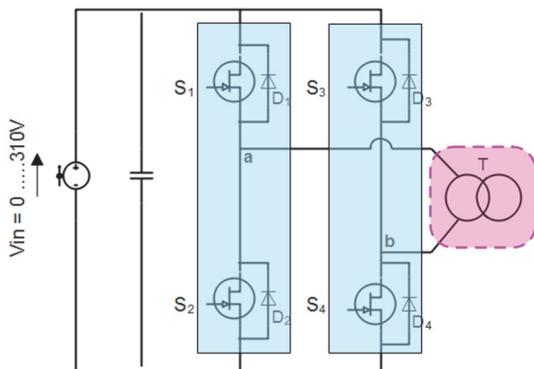


Fig. 3. Series resonant inverter for ozone generator.

the driving signals of the switches  $S_1 \sim S_4$ , and  $U_{ab}$  is the inverter output voltage.

#### IV. MATERIALS AND METHODS

The ozone generator used in this experimental work is a cylindrical Dielectric Barrier discharge (DBD) reactor similar to those generally employed in industry and research, with almost similar dimensions of the electrodes length and the gap discharge. It consists of a stainless steel outer ground electrode of internal diameter 47 mm and a glass tube of external diameter 44 mm having a same length of 30 cm (Fig. 5). The discharge gap between the glass tube and the stainless steel electrode is equal to 1 mm. An adhesive Aluminum tape, glued on the inside wall of the glass tube, was used as the high voltage electrode. Two openings are operated on the generator to enable the air inlet and the ozone outlet.

MODDE5.0 (Umetrics AB, Umea, Sweden) which is a Windows program for the creation and evaluation of experimental designs is used[35]. The program assists the user in interpretation of the results and the prediction of the responses. The optimization stage of an experimental procedure should enable the identification of the “set point,” i.e., the values of the control factors for which the response of the process is a maximum, is a minimum, or approaches a target[36-38]. For the present work, the maximization of the ozone concentration as well as the

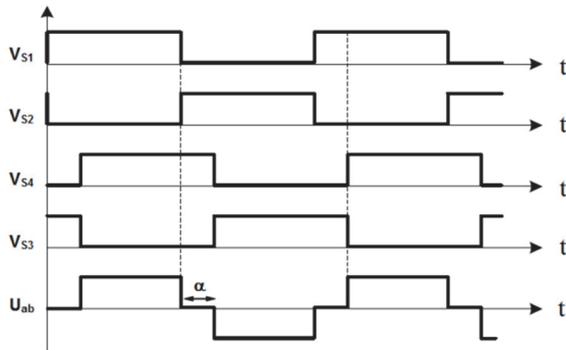


Fig. 4. Principle of PSC.

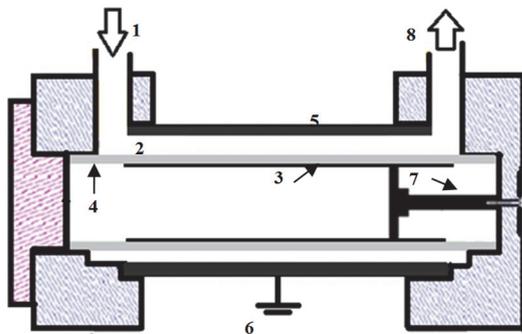


Fig. 5. Longitudinal cross section of the ozone generator (1) Oxygen inlet. (2) Gas gap for discharge. (3) Inner cylinder electrode (aluminum adhesive). (4) Dielectric barrier (glass). (5) Outer cylindrical electrode (6) Terminal to ground. (7) High-voltage terminal. (8) Ozone outlet.

minimization of the consumed power were chosen as criterion of evaluation.

Design of experiments methodology is useful for screening, optimization and robustness testing. Screening experiments are designed to identify the domain of variation of three factors, by performing classical “one-factor-at-a-time” experiments. The optimization stage of an experimental procedure should enable the determination of factor values for which the ozone concentration is a maximum and the consumed power is a minimum.

In this paper the experiments were carried out by considering the three most important parameters of the power supply, which are voltage  $V$ , frequency  $f$  and the phase shift angle  $\alpha$ .

The variation limits of voltage  $V$ , frequency  $f$  and phase shift  $\alpha$  are defined by following “one-factor-at-a-time” experiments.

Experiment 1.1. Variable voltage  $V$  (5-7.25 kV), at constant values of phase shift angle  $\alpha = 0^\circ$  and frequency  $f = 16$  kHz.  $V = 5$  kV corresponds to the minimal value of the voltage initiating the electrical discharge, while the maximum value  $V = 7.25$  kV was limited by the risk of electrical breakdown.

Experiment 1.2. Variable phase shift  $\alpha$  ( $0-160^\circ$ ), at constant values of voltage  $V = 6$  kV and frequency  $f = 16$  kHz.

Experiment 1.3. Variable frequency  $f$  (14.5-17.5 kHz), at constant values of phase shift  $\alpha = 0^\circ$  and voltage  $V = 6$  kV.

#### V. RESULTS AND DISCUSSION

##### A. Screening experiments

Obtained results of the screening experiments are given in Figs 6, 7 and 8. The ozone concentration  $C_{O_3}$  (mg/l) and power  $P$  (W) were considered as significant for the evaluation of the process and represented as function of the three control factors.

The following variation domains of  $V$ ,  $f$  and  $\alpha$  were then defined based on results obtained in this section:

$$V_{\min} = 5 \text{ kV}; V_{\max} = 7.25 \text{ kV}; f_{\min} = 15 \text{ kHz}; f_{\max} = 17 \text{ kHz}; \alpha_{\min} = 20^\circ; \alpha_{\max} = 80^\circ$$

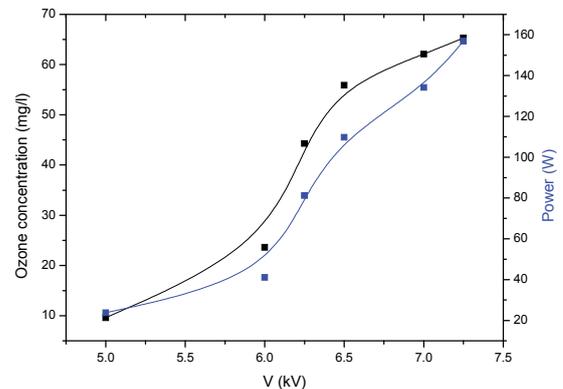


Fig. 6. Variation of the ozone concentration and the power as function of the applied voltage  $V$  ( $f = 16$  kHz,  $\alpha = 0^\circ$ ).

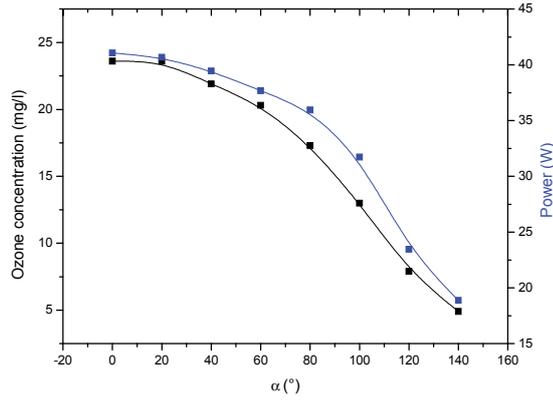


Fig. 7. Variation of the ozone concentration and the power as function of the phase shift  $\alpha$ . ( $f=16$  kHz,  $V=6$  kV)

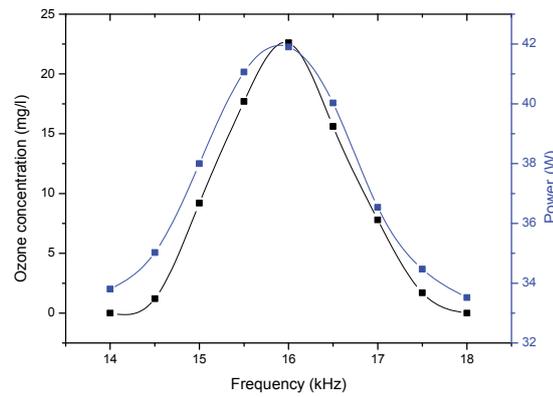


Fig. 8. Variation of the ozone concentration and the power as function of the frequency  $f$  ( $V=6$  kV,  $\alpha=0^\circ$ ).

### B. Set Point Identification

The identification of optimal values of the factors was carried out by using a central CCF design; the two levels “max” and “min” are the limits established in previous section for each of the three variables ( $V_{min}$ ,  $V_{max}$ ), ( $f_{min}$ ,  $f_{max}$ ) and ( $\alpha_{min}$ ,  $\alpha_{max}$ ). The central point ( $V_c$ ,  $f_c$ , and  $\alpha_c$ ) is calculated as follows:

$$V_c = (V_{min} + V_{max})/2 = \frac{5 + 7.25}{2} = 6.125 \text{ kV} \quad (1)$$

$$f_c = (f_{min} + f_{max})/2 = (15 + 17)/2 = 16 \text{ kHz} \quad (2)$$

$$\alpha_c = (\alpha_{min} + \alpha_{max})/2 = \frac{20 + 80}{2} = 50^\circ \quad (3)$$

The results of the design experiments are given in Table 1. Besides the ozone concentration  $C_{O_3}$  (mg/l), the power  $P$  (W) was also considered as a significant response and reported in the table.

The mathematical models of  $C_{O_3}$  (mg/l) and  $P$  (W) were obtained with MODDE 5.0 and plotted as shown in Fig.9. In Fig.10 are represented the iso-response contours obtained with the two present models.

TABLE 1: RESULTS OF THE CCF EXPERIMENTAL DESIGN.

Test N°	Voltage $V$ (kV)	Frequency $f$ (kHz)	Phase shift $\alpha$ (°)	Ozone concentration $C_{O_3}$ (mg/l)	Power $P$ (W)
1	5	15	20	0	16.57
2	5	17	20	0	24.24
3	7.25	15	20	62	141.83
4	7.25	17	20	50.9	158.13
5	5	15	80	0	17.69
6	5	17	80	0	26.85
7	7.25	15	80	58	156.36
8	7.25	17	80	45	163.89
9	6.125	15	50	16	43.03
10	6.125	17	50	7	45.41
11	5	16	50	9	26.54
12	7.25	16	50	61.7	153.68
13	6.125	16	20	25.2	42.75
14	6.125	16	80	16.1	43.27
15	6.125	16	50	24.1	43.51
16	6.125	16	50	24	43.24
17	6.125	16	50	24.2	43.52

Since the statistical criteria  $R^2$  and  $Q^2$  were close to the unit,  $R^2=0.988$  and  $Q^2=0.967$  for response  $C_{O_3}$  and  $R^2=0.995$  and  $Q^2=0.985$  for  $P$ , both models were validated and have been used for prediction and optimization analysis.

As seen in Fig. 9, voltage  $V$  is the most significant factor on both ozone concentration and power in comparison with frequency  $f$  and phase-shift  $\alpha$ . Furthermore, we notice that although effects of  $f$  and  $\alpha$  are small, the influence of the frequency is greater. Moreover, it seems that except the interaction between  $V$  and  $f$  for concentration  $C_{O_3}$ , there is no significant effect interaction between other factors.

As shown in Fig. 10, the effect of voltage  $V$  is considerably much higher in comparison with the effect of  $f$  and  $\alpha$ . Moreover, we notice that both ozone concentration and power are greatest for higher values of voltage  $V$  whatever the frequency value is. Therefore, the optimal values of the factors which should give the highest amount of ozone concentration for the smallest power consumption should be identified. The software MODDE.05 contains an optimization routine that is capable of simultaneously processing several responses, affected by different weighting coefficients. It has an optimizer tool which proposes the optimal values of factors by maximizing the ozone concentration and minimizing the power (Fig. 11).

According to this model, the optimum of the process should be obtained for  $V=7.15$  kV,  $f=15.4$  kHz and  $\alpha=20^\circ$  corresponding to  $C_{O_3}=61.7$  mg/l and  $P=133.7$  W.

## VI. CONCLUSION

A detailed description of an ozone power supply has been presented in this paper. The efficiency of ozone production is related to the factors of the power supply. An experimental procedure based on the RSM technique has been proposed for the identification of the optimal values of voltage, frequency and duty cycle ratio, for the

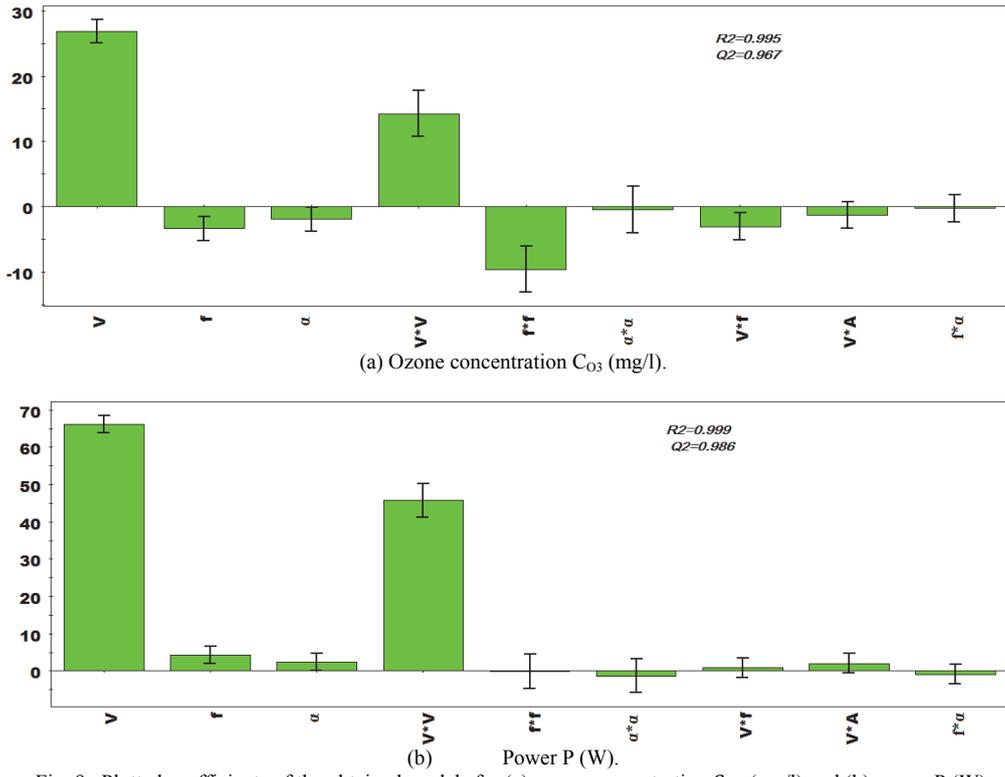


Fig. 9. Plotted coefficients of the obtained models for (a) ozone concentration  $C_{O_3}$  (mg/l) and (b) power P (W).

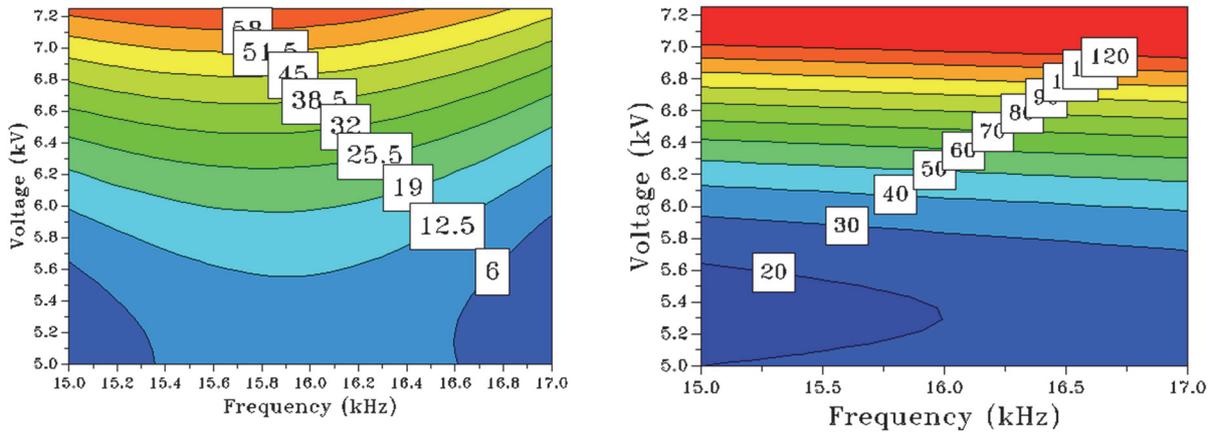


Fig. 10. Voltage-frequency response contour plots for (a) ozone concentration and (b) power.

	Response	Criteria	Weight	Min	Target	Max
1	CO3	Maximize	1	60.2646	66.755	
2	P	Minimize	1		60	150

Iteration: 5001		Iteration slider: <input type="text"/>					
	1	2	3	4	5	6	7
	V	f	$\alpha$	CO3	P	iter	log(D)
1	7.1826	15.2638	20.0018	62.0486	136.421	3370	-0.2052
2	7.1443	15.6337	20.0088	61.8712	133.641	2990	-0.2091
3	7.1433	15.714	20.0109	61.8572	133.997	5001	-0.2057
4	7.1458	15.5991	20.0326	61.8924	133.638	4660	-0.2109
5	7.1463	15.5898	20.2102	61.8843	133.685	3125	-0.2099
6	7.1443	15.6337	20.0088	61.8712	133.641	2990	-0.2091
7	7.1475	15.5688	20.0197	61.9117	133.674	4519	-0.2122
8	7.1986	15.1634	20.0215	61.948	137.934	3638	-0.1876

Fig. 11. Results of the optimization routine of MODDE 5.0.

maximization of the ozone concentration and the minimization of the power. Furthermore, the power supply is based on a compact ferrite-core high-frequency transformer instead of laminated core transformer; all the remaining material represents a set of electronic components. High frequency switching allows a significant reduction in the size and weight of the high voltage transformer. This reduction in size and weight leads to a compact design, which minimizes the installation and maintenance costs.

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