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DEVELOPMENT OF HIGH-VOLTAGE HIGH-FREQUENCY POWER SUPPLY FOR OZONE GENERATION

NACERA HAMMADI[1], MANSOUR ZEGRAR[2], SAID NEMMICH[1], ZOUAOUI DEY[1], SIDI-MOHAMED REMAOUN[1], BOUREGBA NAOUEL[3], AMAR TILMATINE[1,*]

[1]APELEC Laboratory, Djillali Liabes University of Sidi Bel-Abbes, Algeria
[2]University of Science and Technology of Oran, Mohamed Boudiaf. Oran, Algeria
[3]University of Mascara, Institute of Hydraulics, Mascara, Algeria.
*Corresponding Author: atilmatine@gmail.com

Abstract

A high-voltage high-frequency power supply for ozone generation is presented in this paper. Ozone generation is intended to be used in air and in water disinfection. A power stage consisting of a single-phase full bridge inverter for regulating the output power, a current push-pull inverter (driver) and a control circuit are described and analyzed. This laboratory build power supply using a high voltage ferrite transformer and a PIC microcontroller was employed to energize a dielectric barrier discharge (DBD) ozone generator. The inverter working on the basis of control strategy is of simple structure and has a variation range of the working frequency in order to obtain the optimal frequency value. The experimental results concerning electrical characterization and water treatment using a cylindrical DBD ozone generator supplied by this power supply are given in the end.

Keywords: Dielectric barrier discharge, ferrite transformer, high-frequency, high-voltage, inverter, ozone generation, power supply.

1. Introduction

Ozone (O_3) is considered as an excellent powerful oxidizer and germicide. Its disinfection potential is significantly higher than chlorine and other disinfectants [1-2]. Nowadays, ozone is widely used for disinfecting and oxidizing in substitution of chlorine, due to the latter's by products such as smell, bad taste and carcinogenic agents resulting from it [3-5]. Indeed, ozone produces much less by-products and ozone itself is transformed into oxygen within a few hours [6].

Applications of ozone technology are various and could be found in disinfection, water and air purification, medicine and so on [7-8].

The aim of the present work is the development of a simple high frequency high voltage power supply (HF-HVPS) for a DBD ozone generator, consisting in a power stage, a current push-pull inverter (driver) and a control circuit, where the output frequency could be easily regulated using PIC16F84Amicrocontroller [9-10]. A laboratory experimental bench of water treatment was carried out to study disinfection efficiency of an ozone generator supplied by this power supply.

Commercial ozone power supplies are expensive but the main feature is that this type of power supply works on the basis of resonance between the HV transformer and the capacitive DBD load. Thus, a commercial supply may work with one specific configuration of ozone generator of which its capacitance produces a resonance with the HV transformer. The proposed topology of the ozone power supply is aimed to be used with any ozone generator. In addition, it can be used for research purpose as laboratory supply needs to be versatile in order to change several factors and in particular by adjusting the frequency for obtaining resonance with any ozone generator. The proposed power supply was also tested for treatment of infected water.

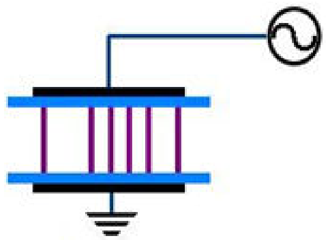
2. Description of the power supply

Since ozone cannot be stored, it must be generated on site. High voltage electric discharges are widely used in industry and the dielectric barrier discharge (DBD) method is considered as the most efficient way to produce ozone (Fig. 1) [11-12]. Oxygen is injected to pass through a small discharge gap between two high-voltage electrodes, one of them or both being covered by a dielectric layer in order to avoid sparks taking place [13-17]. The reason for the different configurations of dielectric is due to the multiple applications of the DBD. For example, in the case of waste gases sterilization and ozone generation, at least one electrode is covered by a dielectric. While for DBD new-generation lamps, the gas in the lamps is completely isolated from the metallic electrodes, which are covered with a dielectric layer. In this way, gas contamination is prevented and the lifetime of the lamps is enhanced [18].

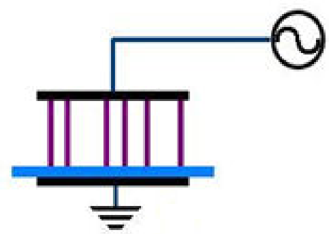
These devices are usually supplied by a high-voltage, high-frequency power supply, since high frequency decreases the necessary power to be used and increase the ozone production rate [19-21]. Thus, the power density applied to the discharge surface is increased as well as the ozone generation rate, for a given surface area, while the necessary voltage is decreased. The increase in the frequencies up to several kilohertz is now feasible using power electronic switching devices, such as MOSFETs [22-24].

The power supply comprises a control circuit stage for generating a high frequency square signal and a power block composed of four MOSFETs controlled by the square signal (Fig. 2). Input voltage is decreased to 6V using a step-down transformer 220/6 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 a microcontroller circuit, 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 MOSFETs (IRF740) controlled by the square signal, thereby obtaining an adjustable high voltage output.

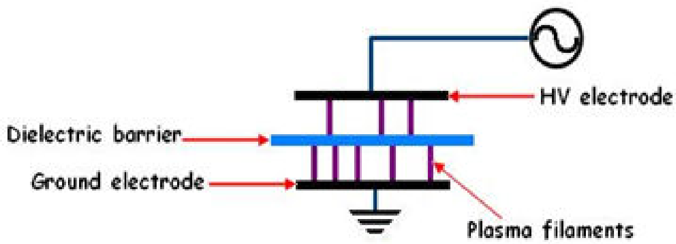
The main circuit of the ozone generation power supply is shown in Fig. 3. The switches used are MOSFETs, in parallel with diodes necessary to prevent MOSFET from conducting a reverse current.



(a) The dielectric is located on each electrode.



(c) The dielectric is located on one of the electrodes.



(b) The dielectric is located between the two electrodes in the gas.

Fig. 1. Dielectric barrier discharge with a gas gap.

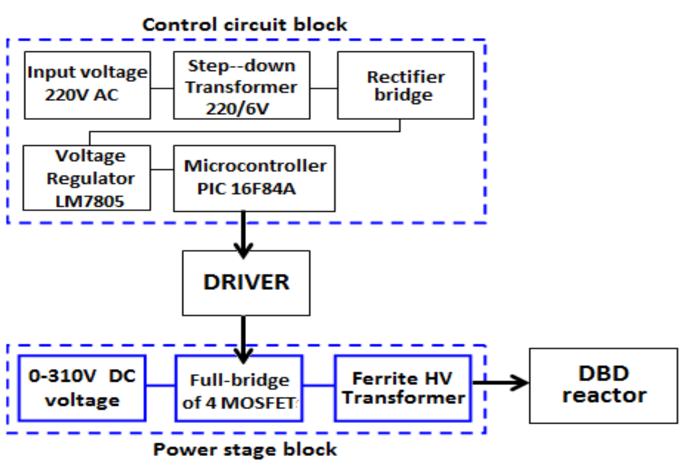


Fig. 2. Block diagram of the high voltage supply.

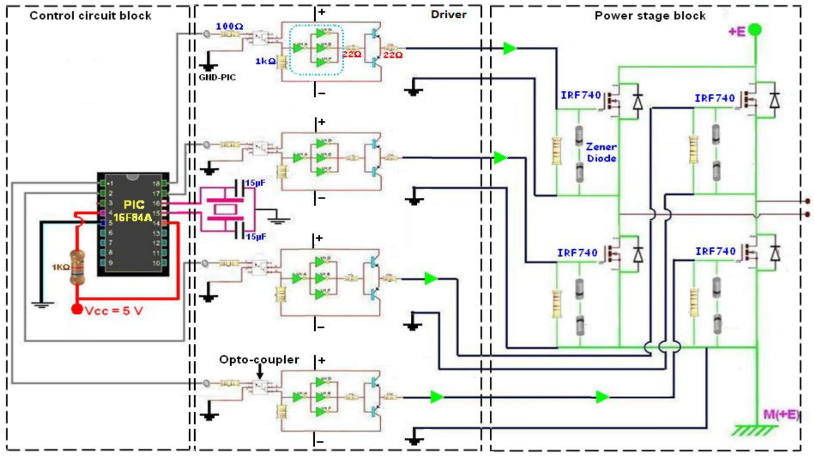


Fig. 3. The proposed system of ozone generation power supply.

The main components of the inverter chain are: control, driver and power stage blocks.

1. Control block: The generation of control signals is performed by aPIC16F84A microcontroller type circuit (Fig. 4). These signals are sent to the power switches through a galvanic isolation guaranteed by opto-couplers.
2. Driver: The interface must provide protection of the control circuit in case of problems on power circuit side. Galvanic isolation between control circuit (0V/5V) and power circuit (220V/1A) is then ensured.
3. Power stage block (inverter): The inverter uses IRF740 MOSFET package equipped with a freewheeling diode (Fig. 5). It converts DC into AC voltages by means of the PIC microcontroller. Since the reliability of MOSFETs decreases with increasing temperature, the heating produced in the semiconductor junctions has to be evacuated using sinks.

The overall power supply, without the step-up transformer, is shown in Fig. 6.

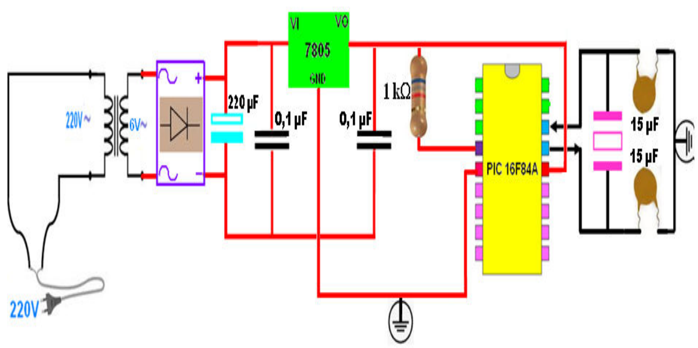
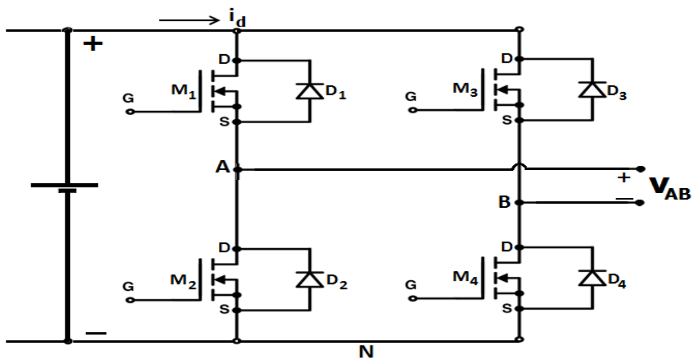
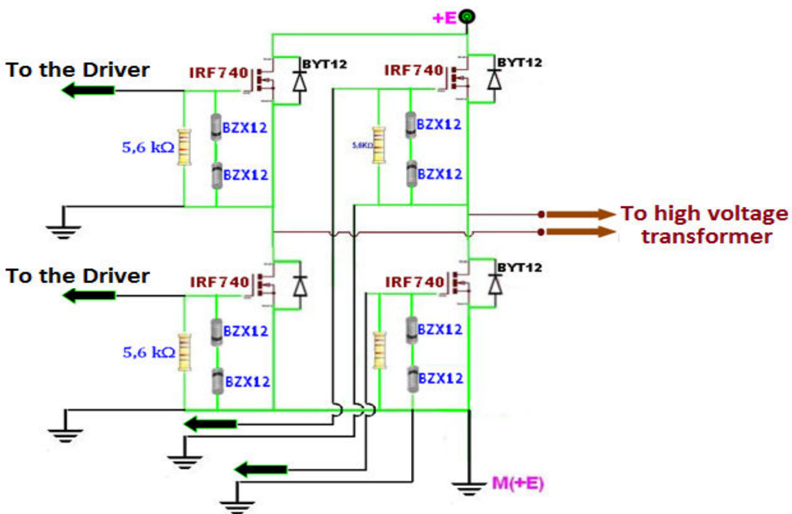


Fig. 4. Circuit diagram of the control block.

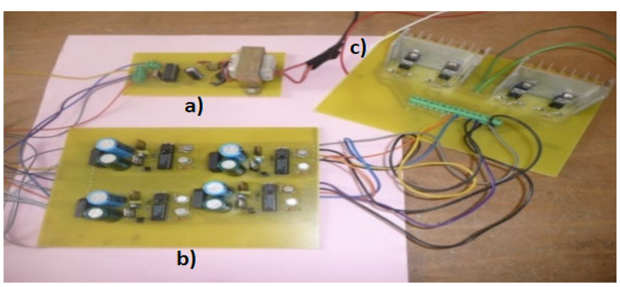


(a) Circuit of the inverter.



(b) Electric circuit of the inverter with specified used components.

Fig. 5. Electric circuit of the inverter.



(a). Circuit control ; (b). Driver ; (c). Inverter.

Fig. 6. Overall power supply without HV transformer.

3. Experimental setup

Several papers were written about the influence of the generator dimensions of cylindrical shape on the ozone generation efficiency [25]. The ozone generator used in this work is a conventional cylindrical DBD reactor like those employed in industry and research, with almost similar dimensions of the electrodes length and the gap discharge. The DBD ozone generator used in this work 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. 7). A discharge gap of 1.5 mm exists between the Pyrex glass tube and the stainless steel electrode. 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.

Fig. 7. Cylindrical DBD reactor.

3.1. Electrical characterization

The DBD ozone generator has been implemented and tested, using the experimental bench shown in Fig. 8. The ferrite-core HV transformer, energized by the inverter, supplies the ozone generator. A high voltage probe (Tektronix 6515A) and a digital scope (GW INSTEK GDS-840C) were used to visualize the output high voltage. For the present work, the maximum voltage applied to the MOSFETs Bridge is 120 V. The switching of the four MOSFETs is driven synchronously by the square wave signal issued from the driver. Four frequency values were tested (f=16 kHz, 20 kHz, 22 kHz, 25 kHz).

3.2. Ozone generation

The power supply and ozone generator were thereafter tested for water treatment, using an experimental laboratory bench described in Fig. 9. A first set of experiments was carried out with tap water to measure the ozone concentration dissolved in water. The contaminated water to be treated of volume 10 L is set in motion by means of a water pump with a water flow rate of 10 L/min. A Venturi system enables injection of ozone within the water loop and the ozonated water is reintroduced in the tank in a closed-loop system for a total duration of 10 min. The ozone generator is fed by an oxygen concentrator (NIDEK medical Nuvo Lite Mark 5), with a flow rate of 5 L/min, and supplied with a voltage V= 6 kV at a frequency of 25 kHz.

Water sample was taken at the output just before it falls in the tank. The experiments were carried out at constant values of ozone flow rate (5L/min) and applied voltage (peak value 6 kV), according to the signal frequency.

A second set of experiments was conducted to treat contaminated waste water (Fig. 10) taken from the wastewater treatment plant of Sidi-Bel-Abbes city in Algeria.

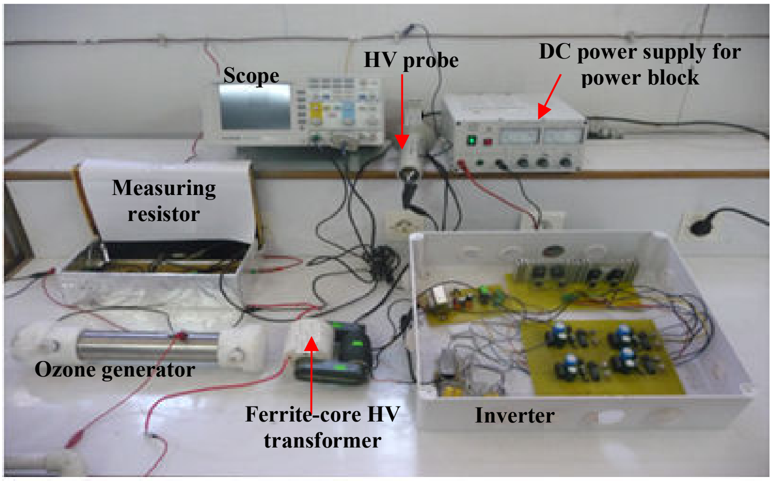


Fig. 8. The experimental bench.

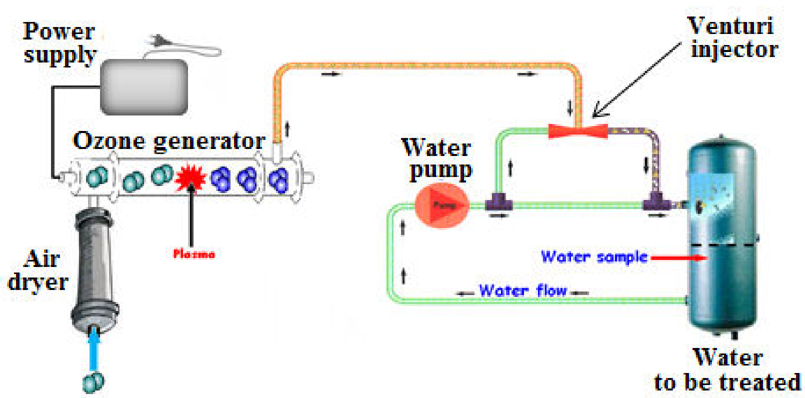


Fig. 9. Descriptive representation of the water treatment process using ozone.

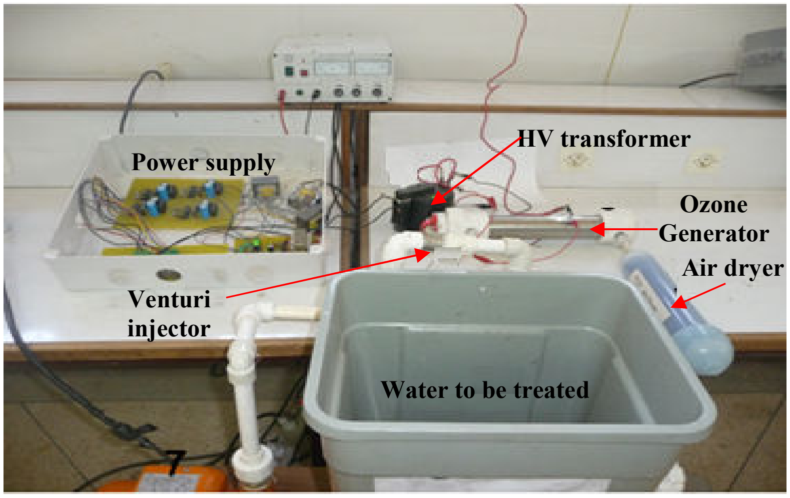


Fig. 10. The experimental bench for ozone water treatment.

4. Results and Discussion

The voltage developed by typical power supplies for DBD reactor reaches levels of several kV [25], using a high voltage ferrite transformer. The ferrite core operates over a wide frequency band. They are used in power applications where the operating conditions require a high-frequency magnetic material with high permeability and low power loss. Moreover, their high resistivity (greater than $10^6\Omega$.m) is an advantage for applications at high and very high frequencies.

Fig. 11 illustrates the voltage waveforms at the input and the output of the high-voltage transformer. A DC voltage up to 120 V was applied in the primary winding of the transformer while the high-voltage was obtained in the secondary winding. Voltage of sinusoidal shape with values up to 6 kV (peak value) was obtained with the HF-HVPS. Spikes can be seen during the process in the input DC voltage waveform. These spikes are mainly due to the effect of transformer leakage inductance. Therefore, Zener diodes were used to maintain the voltage across switches below 400V, thus avoiding voltage breakdown in the MOSFETs. The maximum rating voltage of the IRF740 is 400V.

Fig. 12 represents the variation of the high voltage obtained at the output of the ferrite transformer (Peak value), according to the input DC voltage of the MOSFETs bridge, for different values of the frequency. The natural resonance frequency was about 25 kHz when the load is in the normal discharging conditions that are obtained once the micro-discharges occur in the reactor corresponding to current pulses as seen in Fig. 13. Such power supply is of resonant type which delivers a high output voltage when resonance occurs between the transformer inductance and the load capacitance. Hence, among the analyzed frequencies, the optimal operation (i.e., minimal power consumption) was obtained at a resonance frequency f = 25 kHz, for which the output voltage is highest and the input DC voltage is lowest.

It could be seen that the frequency is a significant factor to obtain higher values of voltage, because the transformer which is an inductive load creates resonance with the capacitance of the ozone generator.

Furthermore, results of ozone concentration in water as function of the flow rate are illustrated in Fig. 14 and results obtained after a microbiological analysis both before and after treatment of the waste water sample are given in Table 1. "Norms" reported in column 2 means "**standards**" corresponding to criteria of disinfected water.

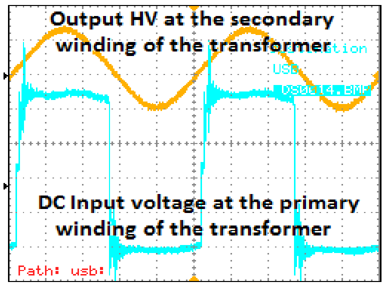


Fig. 11. Voltage waveforms obtained at primary side (Top, 5kV/div) and secondary side of the transformer (Bottom, 5 V/div). Horizontal scale: 10µs/div.

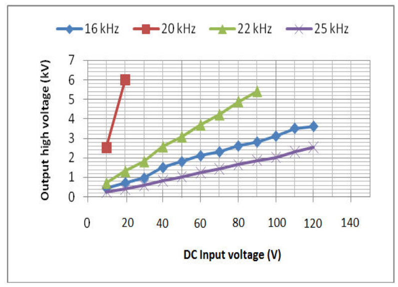
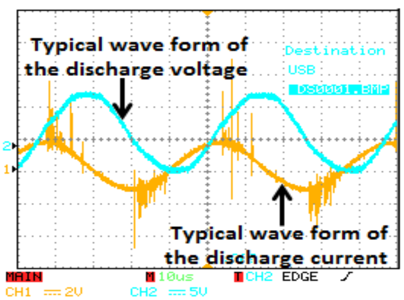


Fig. 12. Variation of the output high voltage according to DC input voltage of the inverter, for different values of the frequency.



Applied voltage = 6 kV
Voltage signal: 5 kV/div., Current signal: 2V/div., 10µs/div.

Fig 13. Typical wave forms of the voltage and the discharge current in the cylinder-cylinder configuration.

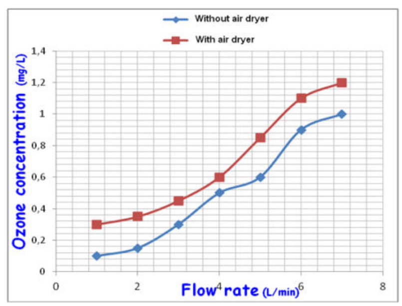


Fig 14. Variation of the ozone concentration in water according to the flow rate.

22 °C and 37 °C are the temperatures of development or propagation of aerobic bacteria on the solid culture medium which is the laboratory agar. The detection and enumeration of these germs are carried out at two different temperatures to target both psychrophilic microorganisms at 22 °C and those mesophilic at 37 °C. They are standard measurement practices in the laboratories for analyzing water disinfection rate.

Table 1.Obtained results after bacteriological and physicochemical analysis.

	Norms	Before treatment	After treatment
Aerobic germs at 37°C	20	60	35
Aerobic germs at 22°C	$<10^2$	10	10
Coliforms	10	1100	28
Fecal coliforms /100ml	Abs*	03	00
Streptococci D/50ml	Abs	1100	1100
Clostridium sulphite-reducers at 46°C/ml	Abs	Abs	Abs
Clostridium sulphite-reducers at 46°C/20ml	Abs	Abs	Abs

*: “Abs” means “Absence of microorganisms”

The reduction of ozone production in humid air is primarily attributed to the removal of O by H_2O molecules (Fig. 14). Moreover, different from the O_3 destruction mechanism by NO in dry air, the destruction of O_3 in humid air is primarily caused by OH radicals.

Obtained results reported in table 1 demonstrate that production of ozone using DBD reactor is an effective way for the treatment of wastewater; the contaminant levels have decreased significantly. Due to its high oxidation potential, ozone oxidizes cell components of the bacterial cell wall. Once the ozone enters the cells, it oxidizes all essential components (enzymes, proteins, DNA, RNA), breaking thus the cell.

The reference method for the analysis is to count the number of germs per ml of water by estimating the:

- Total germs at 22 °C = number of aerobic bacteria at 22°C obtained after incubation at 22 ° C during 72 hours.
- Total germs at 37° C = number of aerobic bacteria at 37°C obtained after incubation at 37° C for 48 hours.

This process was favorable for aerobic mesophile bacteria (37 °C) with respect to aerobic bacteria psychrophilic (22 °C), because this latter is already lower than the normal standard as shown in Table 1. On the other hand, a decrease of almost 50 %, from 60 to 35 (germs / 100ml), is noticed for aerobic mesophile bacteria (41.66%). The value reached is close to the standard limited which is equal to 20 germs/100 ml.

In addition, the total coliforms are a group of bacteria commonly found in the environment and vegetation. Total coliforms do not cause disease in general, but their presence indicates that the water may be contaminated by harmful microorganisms. The improvement is so important for coliforms because these microorganisms are fecal indicators of primary importance. According to the obtained results, the total coliforms decrease abruptly from 1100 to 28 (coliforms/100ml) which corresponds to an inactivation rate of 97.45 %. This inactivation rate shows that total coliforms are very sensitive to ozone.

In addition, the exposure conditions for an efficient inactivation are a major factor influencing the survival of microorganisms. Thus, the effectiveness of water disinfection treatment depends strongly on the ozone concentration and the contact time with water. No reduction of fecal streptococci was observed in our experiments because a greater contact time is required [26]. The contact time between ozone and water is an important factor because microorganisms suspended in polluted water requires longer contact time with ozone for complete inactivation [27].

Fecal streptococci are generally considered as good indicator of fecal contamination. Their persistence in various types of water may be superior to that of other indicator organisms, particularly because of their resistance to disinfectants [28]. According to the model of Chick-Watson, the inactivation level depends on the contact time [29]. In this work, the inactivation of fecal streptococci by ozone is related to the contact time between the considered microorganism and the disinfectant, which is a few minutes in this case. The inactivation depends also on the pH and the temperature of the water to be treated. These three factors help to gradually improve the decrease speed of fecal streptococci. Recent studies on the inactivation of fecal streptococci by ozone show a decrease up to 97 % after a contact time of 120 min [30].

Increasing the temperature of the water to be treated can, on the one hand, reduce the stability of ozone and its solubility in water by increasing its decomposition rate, and on the other hand, increase the rate of reaction between the oxidant and microorganisms. Generally, the temperature increase lowers ozonation efficiency, by limiting the concentration of dissolved ozone. So the optimal temperature to ensure an efficient process is the ambient temperature, as the one considered in this work.

The sulfite-reducing anaerobes are not all indicators of fecal contamination. The relevance of the research of such indicators is the property that they have to sporulate, which makes them particularly resistant to disinfection treatment. However, in our case the contamination levels of such microorganisms were below the normal standards both before and after treatment.

5. Conclusion

In this paper, a single-phase full bridge inverter employing 4 semiconductor switches has been proposed to supply a DBD ozone generator. The converter has been analyzed and output characteristics have been obtained. The design and implementation of the complete power supply have also been shown. The power supply was successfully employed to supply an ozone generator, shown by analyzing both the obtained ozone concentration and the bacterial analysis of a waste water sample. These are preliminary results obtained with only one ozone generator. The disinfection rate would be greater when several units are mounted in series, in order to increase the ozone output, and by considering longer contact time. A mobile Skid comprising 20 ozone generators is under construction.

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