Microcontroller Based High Power Microwave Generator (HP-MWG) Control Board for Applications in Agriculture

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Abstract— This paper presents the design and implementation of a microcontroller-based control system for a High-Power Microwave Generator (HP-MWG), developed for agricultural and medical applications such as pest eradication, food disinfection, and sterilization. The system operates at a fixed frequency of 2.5 GHz and delivers up to 800 watts of power using a pulsed-mode magnetron oscillator. The duty cycle is adjustable, allowing for precise control of energy output tailored to specific application requirements. Electromagnetic energy is transmitted to specialized treatment chambers through a custom-designed microwave waveguide assembly. Three types of metallic exposure chambers—designated as types A, B, and C—are used to prevent radiation leakage, with volume capacities ranging from 500 cm³ to 180,000 cm³. The design also accommodates open-field deployment scenarios. System operation is governed by an Arduino-based control board that interfaces with key components, including pulse waveform generation, LED indicators, timing circuits, and power selection modules. The control system supports both local and remote (wired) operation and features real-time status monitoring via integrated display panels. An onboard electromagnetic radiation sensor ensures safe operation and compliance with environmental standards. This integrated solution offers precise, efficient, and remotely accessible high-power microwave treatment for a wide range of agricultural and medical applications.

Keywords: High-Power Microwave Generator (HP-MWG); Microcontroller-Based Control System; Pulsed Magnetron Oscillator; Electromagnetic Radiation; Agricultural Applications; Arduino Control Board; Microwave Treatment Chambers.

I. INTRODUCTION

Interest in the effects of high-frequency electromagnetic waves (EMWs) on biological materials dates back to the 19th century [1]. One of the most pressing challenges in agriculture today is the significant crop damage caused by harmful pests, which adversely impacts both yield and quality. Among environmentally sustainable solutions, the use of electromagnetic waves has emerged as a promising non-chemical approach to insect control [2]. Similar techniques have been extensively explored for food safety, pest disinfection, and crop preservation through controlled microwave heating [3–5]. The primary interaction of EMWs with biological matter is thermal in nature, whereby absorbed energy induces localized heating. This phenomenon has been effectively applied for bacterial inactivation in food products and for soil disinfection to eliminate pest infestations. In such applications, the use of high-power microwave systems is crucial to achieving the desired biological effects [2]. In response to these challenges and opportunities, a collaborative research initiative has been launched between the College of Agriculture, Zagazig University (Zagazig, Egypt), and the Higher Institute of Engineering, Shorouk Academy (Cairo, Egypt). The central goal of this initiative is to explore and advance the growing applications of microwave technology in agriculture—particularly in enhancing crop productivity through non-invasive, energy-efficient, and scalable treatment systems.

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II. Materials and Methods

A. Microwave Generator Description

Electromagnetic waves span a broad range of frequencies, each serving distinct roles across communication, industrial, medical, and scientific fields. The frequency spectrum is illustrated in Figure. 1, highlighting key divisions from low-frequency radio waves to high-frequency gamma rays. This study focuses on the microwave region of the spectrum, which extends from approximately 300 MHz to 300 GHz. Specifically, the proposed system operates at a frequency of 2.45 GHz, designated within the Industrial, Scientific, and Medical (ISM) band—a globally recognized range for non-communication applications. This frequency is widely used in industrial and food applications due to its efficient dielectric heating capability [4, 6, 7]. Microwaves at this frequency are non-ionizing and interact primarily with polar molecules, such as water, by inducing molecular rotation and friction. This interaction generates localized heating, which is exploited in various applications including disinfection, pest control, and microbial reduction in agricultural and food-processing environments. Figure. 2 illustrates a simplified block diagram of the proposed system architecture. The Microwave Generator Unit employs a magnetron oscillator to produce high-power electromagnetic radiation, which is delivered in pulsed mode. The system features an adjustable duty cycle, allowing precise control over the total exposure energy. Microwave energy is transmitted through a waveguide into a dedicated Microwave Radiation Exposure Chamber, where the biological material is treated. The exposure chamber is constructed from metallic enclosures to ensure radiation containment and operational safety. This configuration enables efficient and targeted delivery of high-power microwave energy for biological applications. Additionally, the system supports both local and remote operation modes, offering enhanced safety, monitoring capabilities, and operational flexibility tailored to specific agricultural needs.

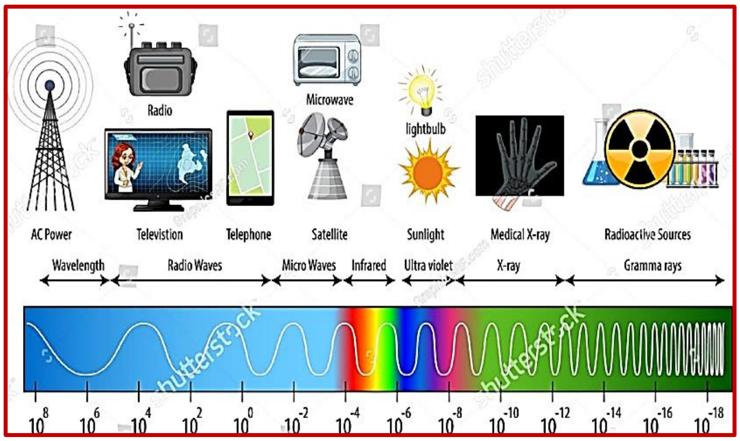

Figure 1. Frequency Spectrum

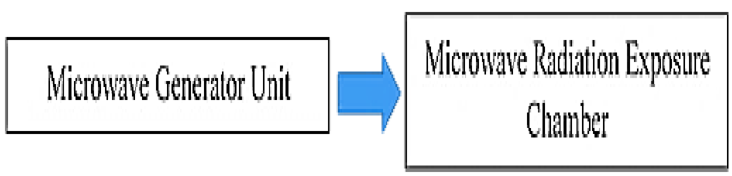

Figure 2. System Block diagram

B. Microwave Generator Unit

The microwave generation subsystem consists of a high-voltage power supply and a magnetron-based oscillator, engineered to deliver high-power microwave energy for biological treatment applications. The system utilizes a 4 kV DC power supply in conjunction with a magnetron oscillator capable of producing up to 800 watts of continuous microwave power. Operating in continuous wave (CW) mode, as depicted in Figure. 3, the magnetron ensures stable and sustained energy output. Microwave energy generated by the magnetron is transmitted to the treatment chamber through a waveguide transmission line. This begins with a magnetron launcher, shown in Figure. 4, which serves as the initial coupling interface, enabling efficient energy transfer from the magnetron into a rectangular waveguide. The guided energy is then directed to the exposure zone via a horn antenna, illustrated in Figure. 5, which functions as a wave radiator. The short horn antenna is carefully designed to uniformly radiate the electromagnetic energy within the exposure cavity, ensuring maximum treatment coverage and effectiveness. The waveguide assembly, connecting the magnetron to the horn antenna, was designed using CST Microwave Studio to achieve optimal impedance matching and efficient power transmission. Design methodologies and impedance-matching principles follow standard microwave engineering practices outlined in [6, 7]. The complete waveguide and horn structure were fabricated in an industrial facility located in 10th of Ramadan City, Cairo, Egypt.

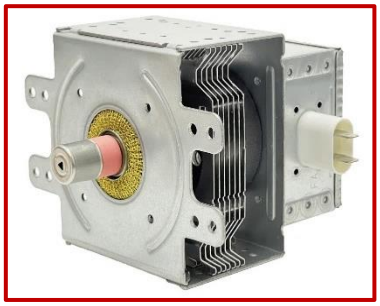

Figure 3. Magnetron Microwave Generator

Figure 4. Magnetron Launcher

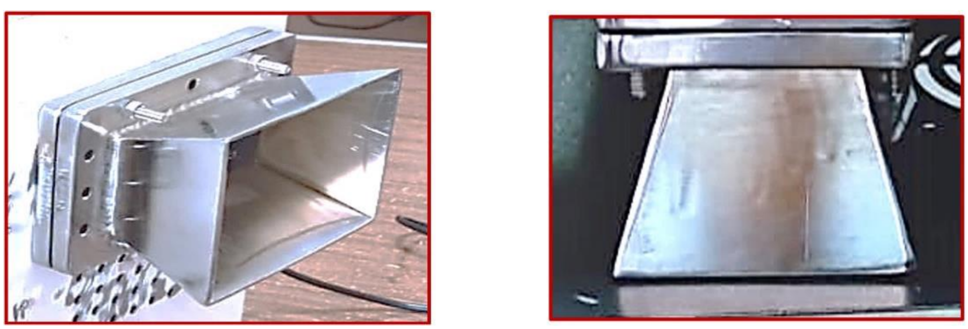

Figure 5. Short Horn Antenna

A test chamber was fabricated using a metallic Faraday cage, with dimensions illustrated in Figure. 6. To visually indicate the presence of microwave radiation within the chamber, a fluorescent bulb was placed inside, which glows when exposed to the emitted electromagnetic energy.

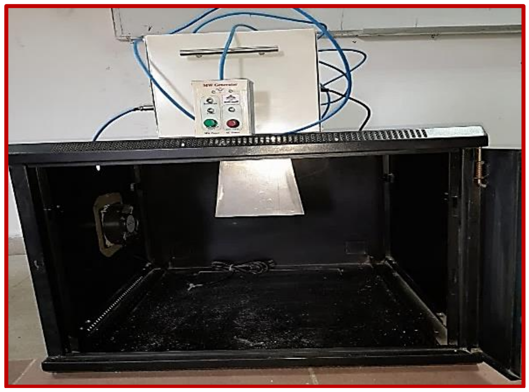

Figure 6. Radiation Exposure Chamber

C. Microwave Exposure Control

The control of microwave exposure levels is based on the amount of energy required to generate the desired thermal effect induced by microwave radiation. The physical principles of microwave-induced thermal heating have been well detailed in modern studies on dielectric heating and energy distribution [8, 9]. The applied energy is determined using Equation (1).

$$Q = P_o \times D \times N \times T = P_o \times D \times T_s \qquad (1)$$

Where Q is the total microwave energy (in joules), P_o is the maximum output power of the magnetron (in watts), D is the duty cycle, T is the duration of one magnetron operation cycle (in seconds), N is the number of cycles, and T_s is the total system operation time, calculated as $T_s = N \times T$.

The duty cycle D is defined as the ratio of the magnetron's active operation time (T_{on}) to the total cycle period T, as illustrated in Figure. 7. It is expressed by Equation (2).

$$D = {}^{T_{ON}}/_{T} \qquad (2)$$

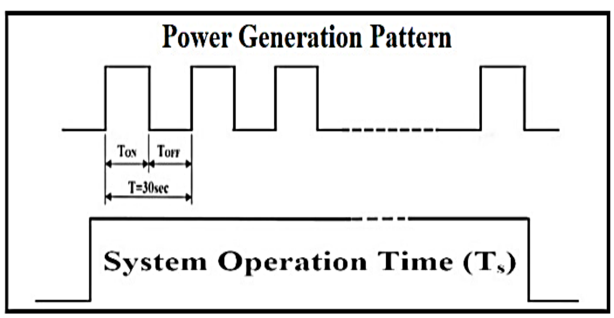

Figure 7. Power Generation Pattern

To facilitate user interaction and energy configuration, the system includes an intuitive energy setting panel (Figure. 8) supported by predefined operational presets detailed in Table 1. These presets define energy levels based on different duty cycles and exposure durations, enabling flexibility across agricultural treatment requirements. The microwave generator specifications are illustrated in Figure. 9, showing how operational parameters scale with energy output. Further, the energy setting interface is visualized in Figure. 10, providing a user-friendly layout for selecting treatment parameters.

Figure 8. Energy setting panel

Table 1. Energy Setting Choices

D (Power ON Time %)	Operation Time (minutes) * and + similar levels, different conditions		
	5 Minutes	**10 Minutes**	**30 Minutes**
30% (9 sec)	77 KJ	* 155 KJ	+ 464 KJ
60% (18 sec)	* 155 KJ	310 KJ	929 KJ
80% (24 sec)	206 KJ	+ 413 KJ	1238 KJ

Microwave Power and Energy Levels	Controllable average power in range : 10% to 100%, in 10 steps
	Exposure Energy in 10 selectable time values 1 to 180 minutes. Or user specified times to attain the required exposure microwave energy
	System can be operated either by the on box key board or by a distant 6 meter wire keyboard

Figure 9. Microwave Generator Specifications

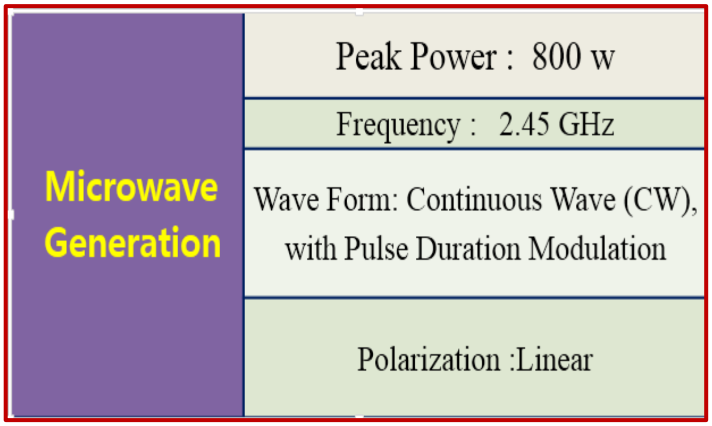

Figure 10. Energy Setting

D. Microwave Radiation Treatment Chamber Operation Manual

Power Source: 220 V AC, 50 Hz, 1 kW. The operational steps are outlined in Table 2.

Table 2. User Operation Manual

Step	Action	Using Generator Panel	Using Remote Box
			
1	Mains ON	220V AC Red Lam Lights	X
2	Power ON	Press the Red Switch: ON / OFF "Ready" Blue Lamp Lights	
3	Radiation ON	Press "Start" Button Green "Timer ON" lamp lights And Yellow "Radiation ON" lamp lights ON or OFF for the specified periods repeatedly during the timer operation set time (as long as the timer green lamp is lighting)	
4	Forced or Emergency RF Radiation Stop	Press the Red Switch: ON/OFF (Emergency OFF) Blue "Ready", Green "Time ON", and Yellow "Radiation ON" lamp are turned OFF.	
5	Restart again	Repeat Step 3	

E. The Integrated System

Two key components of this project are the LED drivers and the opto-coupler with a triac circuit. The Arduino board is programmed using the Arduino IDE software. The LED drivers control the visual indicators, providing real-time feedback on system status. The opto-coupler, in conjunction with the triac circuit, converts the microwave generator (MWG) pulse waveform into a 220 V AC output. This output powers the high-voltage transformer, magnetron, waveguide launcher, and horn antenna, forming the core of the microwave energy delivery system. The overall electronic control system, including the integration of LED indicators, opto-couplers, and triac circuits, is structurally presented in the block diagram of the system control electronics (Figure. 11), offering a comprehensive view of the hardware-software interaction.

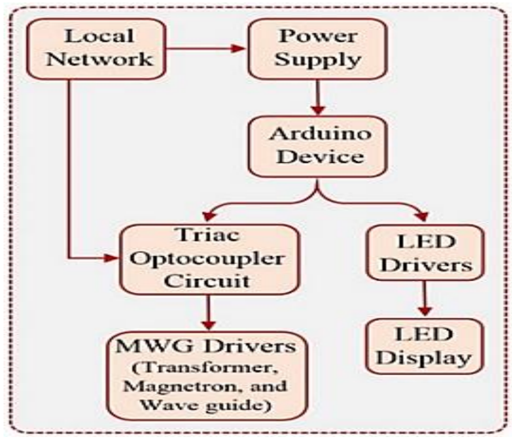

Figure 11. Block Diagram of the system control electronics

F. Microwave Generator Control Board Circuit Diagram

The circuit is designed to generate high-frequency pulses that regulate the radiated energy in a gradual and controlled manner, tailored to meet the specific requirements of agricultural applications. The energy output is adjusted by modifying the generator's operating cycle to a periodic interval of 30 seconds, with selectable duty cycles ranging from 10% to 100%. This configuration allows the system to operate for durations between 1 and 180 minutes, enabling fine-grained energy modulation with a variation ratio of up to 1:1850. The circuit is engineered for reliable performance in both indoor and outdoor environments, using components that are locally sourced and readily manufacturable. The microwave generator system, powered by an Arduino UNO R3 microcontroller, is configured to transmit pulsed signals to the opto-coupler input via a triac circuit, as illustrated in Figure. 12. The Arduino's "5V" pin is connected to toggle switches (S1 and S3), which activate or deactivate the system's electrical circuit. When either switch is turned on, the circuit is energized; when turned off, the circuit is disabled. The "0" pin of the Arduino is linked to push buttons (S2 and S4). When either button is pressed, the input registers a LOW signal, causing the MWG output to toggle ON and OFF in pulses. Arduino pins 1, 2, and 3 are connected to LED drivers, serving as indicators for power status (ON/OFF), timer activity, and MWG pulse generation, respectively. Pins 4 (D3), 5 (D2), and 6 (D1) are connected to the duty cycle selector switch (S6), allowing selection among three predefined pulse patterns: 9 sec ON / 21 sec OFF, 12 sec ON / 18 sec OFF, and 18 sec ON / 12 sec OFF. Pins 7 (T3), 8 (T2), and 9 (T1) are connected to the timer selector switch (S5), corresponding to operating durations of 2, 10, and 15 minutes. Finally, pin 13 is connected to an opto-coupler-based circuit [10] using a MOC3063 IC and a BTA41-600B triac switch [11], which controls power delivery to the microwave generator driver module—including the high-voltage transformer, magnetron, waveguide launcher, and short horn antenna. This design significantly reduces switching noise and minimizes electromagnetic interference (EMI) with nearby equipment [12].

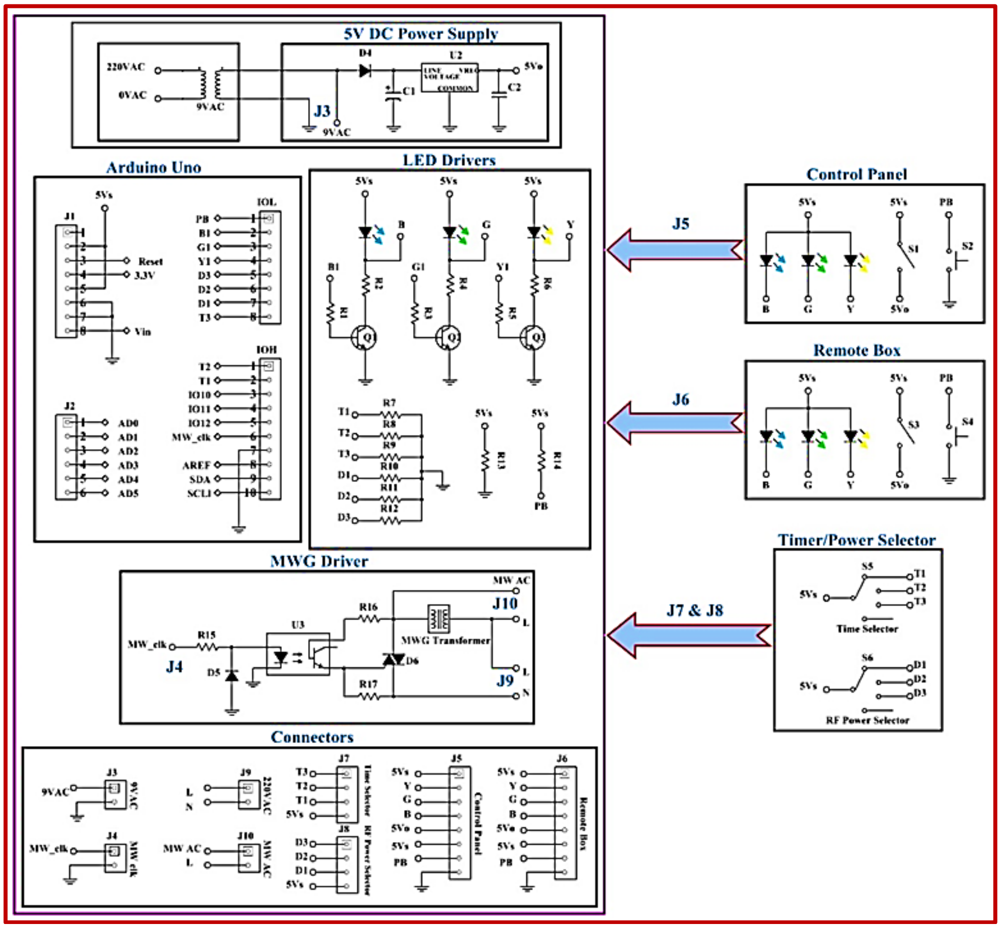

Figure 12. The connection between Arduino controller and electronic drivers

G. Agriculture Application

1. Agriculture Productivity Enhancement.

a. Agriculture insects and Pests killing.

b. Microwave Based Weed Control and Soil Treatment.

c. Fungus, Pests, Pathogens, and nematodes killing.

a) Agriculture insects and Pests killing is depicted in Figure. 13:

Figure 13. Agriculture insects and Pests killing

b) Microwave Based Weed Control and Soil Treatment is depicted in Figure. 14:

Previous studies confirm the effectiveness of microwave energy for pest control and soil sterilization [13], while recent advances extend these concepts to sustainable agricultural heating and energy-efficient greenhouse systems [14].

Figure 14. Microwave Based Weed Control and Soil Treatment

c) Fungus, Pests, Pathogens, and Nematodes Killing is shown in Figure. 15:

Figure 15. Fungus, Pests, Pathogens, and Nematodes Killing

The presence of fungi, pests, pathogens, and nematodes can severely compromise soil health, resulting in substantial reductions in crop yield.

2. Food Preservation

As illustrated in Figure. 16, food is exposed to microwave radiation to effectively eliminate bacterial contamination.

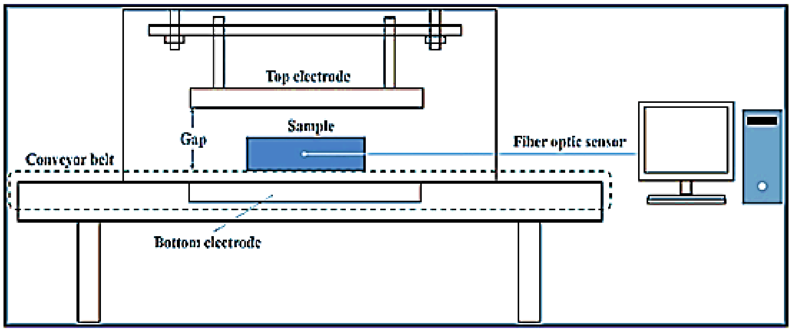

Figure 16. Food Preservation

H. Fabrication of MWG Control Board System

The MWG control board, opto-coupler with triac circuit, and the MWG driver—which includes the high-voltage transformer, magnetron launcher, waveguide, and horn antenna (as shown in Figure. 18)—were designed and programmed using the Arduino platform, with the complete system illustrated in Figure. 17.

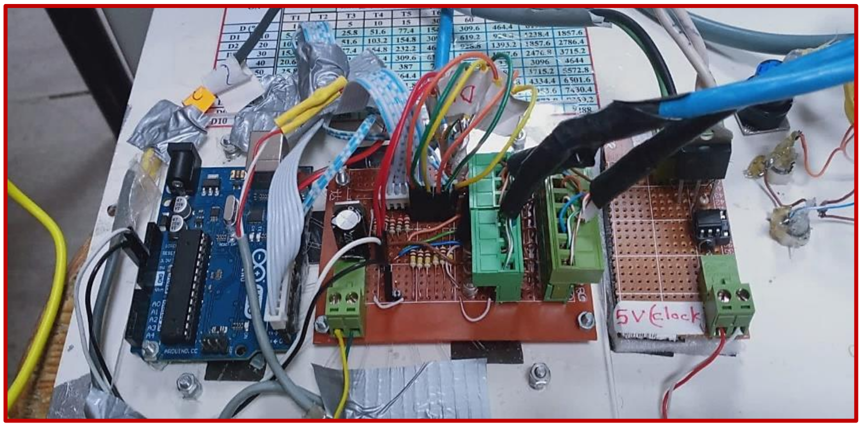

Figure 17. MWG Control Board System Fabrication

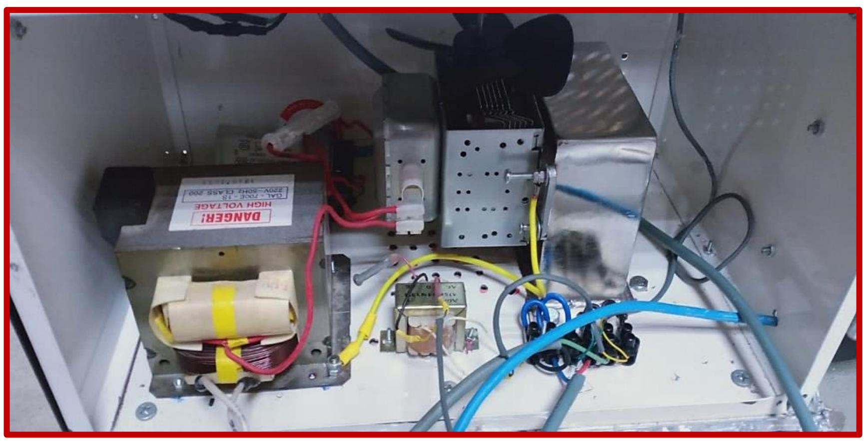

Figure 18. MWG Driver

V. CONCLUSION

In this work, a microcontroller-based HP-MWG control system was successfully designed, implemented, and tested for agricultural applications such as pest control, soil treatment, and food preservation. The system integrates a magnetron-based microwave source, a custom-designed waveguide and horn antenna, and an Arduino-controlled electronic interface to deliver precise and adjustable energy exposure. Through user-friendly energy setting panels and both local and remote operation modes, the system ensures flexibility, safety, and operational efficiency. The use of an opto-coupler with triac circuits enables effective pulse control while minimizing electromagnetic interference. Comprehensive testing demonstrated the system's capability to generate and direct high-power microwave radiation into secure treatment chambers, achieving targeted biological effects in a controlled manner. Furthermore, the design leverages locally available components, supporting cost-effective fabrication and deployment. This solution represents a scalable and energy-efficient tool that can support ongoing research and practical applications in sustainable agriculture and food safety, with the potential for adaptation in medical sterilization contexts. Future research can build upon emerging microwave-based green manufacturing and material processing technologies to enhance system sustainability and industrial applicability [15, 16].

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