A technical review of implemented pulsed electric field generators with different topologies

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ABSTRACT

Pulsed electric field technology (PEF) seeks application in a variety of industries, such as food processing, wastewater treatment, and biomedical engineering, as it provides a non-thermal substitute for conventional thermal pasteurization techniques. The PEF generators are an increasingly important component of this technology since it necessitates high voltage in the range of 2 kV/cm to 100 kV/cm in food processing to inactivate the microorganisms. Different PEF profiles are required based on different foods and the type of microorganisms present in it. The size of existing PEF producers and space limitations are the major challenges in this technology. Hence, there is a growing need to develop laboratory-scale PEF generators to study and analyze the PEF electrical profile for the specified applications. While the single MOSFET PEF generator is appropriate for high frequency applications, the series linked MOSFET PEF generator, one of the PEFs produced in our lab, is found economical. The voltage boosting concept is used to develop 1.62 kV pulses at 52 kHz from 120 V DC input. This paper majorly studies the circuit topologies, switching strategies, and output performances of PEF generators implemented in the laboratory.

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1. INTRODUCTION

Everyone yearns for highly nutritious food that is delicious and fresh at all seasons. But it is impossible for fresh food round the year due to seasonal changes. Heat involved in thermal food processing degrade the nutritional and organoleptic quality of food [1]. Pulsed electric field (PEF) is the most attractive non-thermal method providing safe and nutritious food. This innovative non-thermal food preservation technique inactivates enzymes and bacteria in food products by subjecting them to brief bursts of high voltage electric fields. The technique behind the PEF technology is known as electroporation, and it is profoundly helpful to fields like microbiology and the practice of biomedicine due to its control over cellular permeability [2]-[7].

The outcome of electroporation depends on the electric field that may result either reversible or irreversible electroporation. This electric potential depends on the waveform such as rectangular, exponential, and sinusoidal pulses, that determines and influences the transmembrane potentials. The geometry, size, and composition of the cell, as well as the medium conductivity, influences the electric field distribution across the membrane. Therefore, optimization is critical in ensuring the right electroporation effect without causing excessive damage to the cell [8]-[10]. Research shows PEF processes to inactivate microbes at low temperatures, minimizing the deleterious heat effects on food [11], [12].

The literature review on this method clearly shows that there is no specific PEF profile to inactivate the microorganisms [13], [14]. PEF also finds applications in waste treatment, gene therapy, cell fusion, drug delivery, and cancer treatment [15], [16].

Therefore, the PEF generators become a vital part of the electroporation system, and they are of many types [14]. Despite their effectiveness for various applications, classical PEF generators have several drawbacks. Existing PEF generators are often expensive, bulky, and lack the flexibility to adjust key parameters such as pulse width, frequency, and voltage range with precision. This limits researchers' ability to explore diverse application scenarios and conduct cost-effective feasibility studies [13], [14], [17]. Therefore, there is a need for a compact, cost-efficient, and versatile laboratory-scale PEF generator that can reliably produce controllable high-voltage pulses for experimental purposes. Modern PEF generators address these issues by improving energy efficiency, enhancing control over pulse parameters, and offering greater scalability and affordability. But the PEF generators can concentrate one or two parameters, and it is not possible to enhance each individual parameter. Thulasidas *et al.* [18] suggested an experimental set up to overcome the limitations of Marx generator and similarly the compactness is improved in [19], [20], and pulse width is reduced in [21]. This paper investigates small scale PEF generators aimed to reduce the cost, enhance the compactness and elevate voltage level. Due to diverse electrical parameters expected to inactivate the microorganism, three such kind of PEF generators are detailed in this article. The basic theory and the existing PEF generators are explained in section 2 and the implemented small scale PEF generators based on solid state devices are detailed in section 3.

2. DEVELOPMENTS IN PEF GENERATORS

Traditional food processing PEF generators generate high instantaneous voltage/current and hence require components to withstand high voltage and high current. Later, a few more electrical parameters such as pulse frequency, treatment time, pulse width, and treatment chamber design, have been found useful in the PEF food treatment. Improvements in PEF generators to meet specific demands at an affordable cost and size have been developed, which are suitable for PEF food processing. The electric field intensity can be increased by adjusting the distance between the food chamber electrodes. The chamber must be constructed such that the electric field developed inside the chamber should be homogeneous across the entire active region.

2.1. Basic components of PEF generator

The traditional PEF processing system which is shown in Figure 1, is simple having a high voltage supply, a storage device, switch, and a treatment chamber [9]. PEF generators are classified as ON switches and ON/OFF switches. The ON switches like thyratron, ignitron, gas spark gaps, and trigatron provide the discharge path for the electrical energy from storage device to load. The classical ON switches have demerits like limited pulse frequency, more complexity in the triggering circuits, switching characteristics of the switches, and limited energy per pulse. The ON/OFF switches developed in recent years provide a flexible control on the electrical energy discharge. Insulated gate bipolar transistor (IGBT), Thyristor, and MOSFET are a few examples.

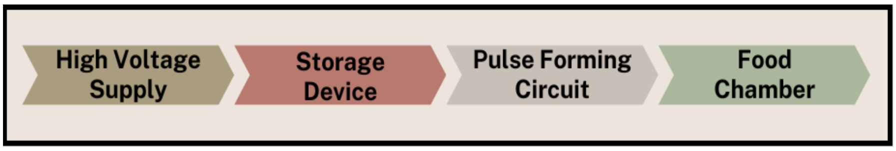


Figure 1. General block diagram of high voltage pulse generator

2.2. Basic high voltage circuits

Initially, the basic RC and RLC circuits are adopted in the PEF food processing as shown in Figures 2(a) and 2(b) respectively. The charging voltage can be increased up to 60 kV. The value of each component determines the shape of the generated pulse and so it is basically called a pulse forming a network (PFN). The simplest PFN is the RC circuit where the capacitor is charged to high voltage and then delivered to the food chamber. But the efficiency of RLC circuit is higher than the RC circuit, around 40-50% while the RC circuit has only 38% [22]. Though the circuit is simple, it has a few challenges like high supply voltage and therefore components should be designed to withstand the higher voltage. This makes the circuit bulkier.

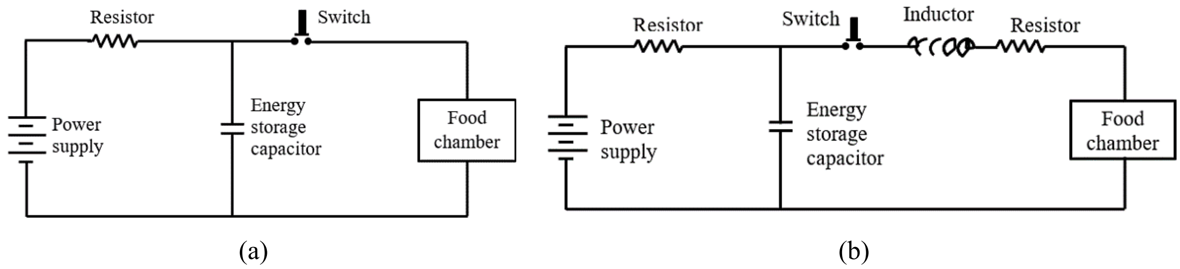


Figure 2. Typical high voltage pulse generator: (a) RC circuit and (b) RLC circuit

2.3. High voltage pulse generator based on Marx cells

Marx type generators have been developed as PEF generators where the higher output voltage is obtained without increasing supply voltage and the circuit diagram is shown in Figure 3 [23]. The capacitors are charged in parallel and the same capacitors are connected in series while discharging through the switches. Spark gap is used as active switches in the first version of Marx generators and these act as voltage limiting switches. Later, spark gaps are replaced by semiconductor switches like Thyristor, MOSFET, and IGBT, due to their advantages [23]. Based on the basic topologies and the application, the derived solid state PEF generators have been developed and few of them are illustrated in this article.

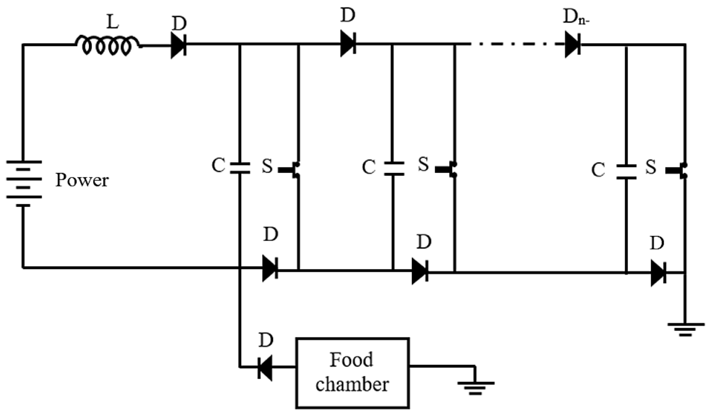


Figure 3. Marx high voltage pulse generator

3. HARDWARE IMPLEMENTATION OF PEF GENERATORS

Solid-state devices like MOSFETs provide high speed and fast switching of high voltages [10]. MOSFETs are available with higher switching frequency with less complex driving circuits. But the voltage/current rating of the individual MOSFET is limited to a few 100 V/10 A. So, this can be increased by connecting MOSFETs in series and parallel.

3.1. PEF generator based on series-connected MOSFETs

By using a series combination of power MOSFETs to support higher voltages, the PEF generator can be designed to generate the necessary voltage at a reasonable cost using mass-produced devices [24], [25]. Such type of PEF generator is economical and simulated as shown in Figure 4. The switching loss is reduced for series MOSFETs because the switches are simultaneously turned ON and OFF with voltage shared evenly. Also, since the voltage is shared dynamically across each device, thermal management is greatly handled. Regarding the component-level constraints, the capacitors must be able to withstand high voltage across the MOSFET, gate source voltage should never exceed 20 V, and each MOSFET's voltage rating limits stacking, and the collective stacked devices should withstand high voltage [24].

In this designed circuit, the source impedance maintained as 20 Ω plays an important role in fixing the waveshape of the output voltage. In the suggested circuit, which uses IRF740, 400 V, and 40 A are put in series to produce 500 V square pulses. It is important to leave a safety buffer for the maximum blocking voltage of the MOSFETs because the circuit components are not optimal. The hardware implementation is shown in Figure 5 with its output voltage [26]. The circuit is tested with 120 V as input and have measured 106 V as output. Together with the 74AC14 Schmitt trigger, the TSC426 driver IC activates the gate of the lowest MOSFET. The TSC426 converts TTL input into outputs with high voltage and current. The mass-produced switches are restricted because of the need for isolation between gates and the limited withstand voltage levels MOSFET power and trigger circuit. The synchronization of gate pulses must be properly maintained by choosing the external gate source capacitances.

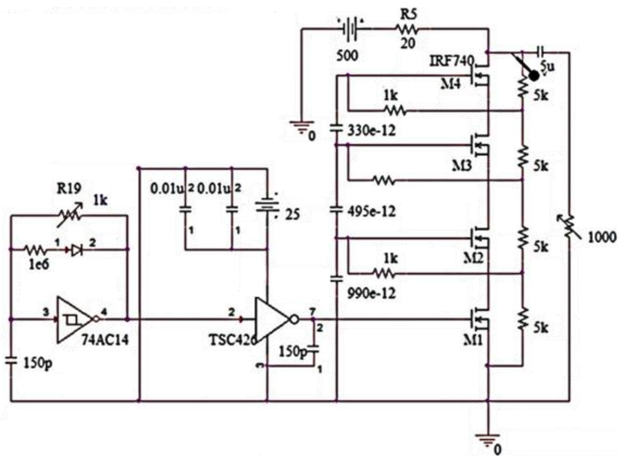
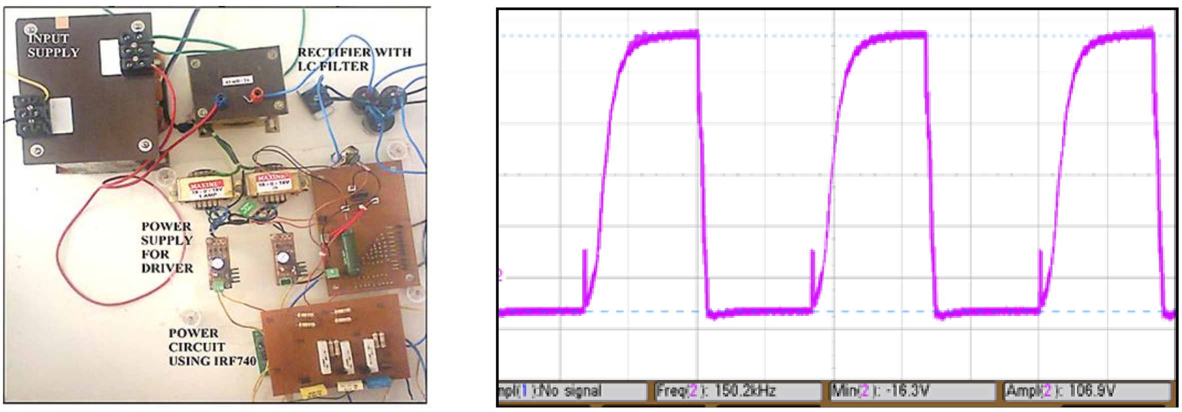


Figure 4. Circuit diagram of series MOSFET



(a) (b)

Figure 5. Experimental set up of (a) series MOSFETs and (b) output voltage

The capacitance values for the designed circuit are 990 pF, 495 pF, and 330 pF, respectively. Though the complexity exists in the design of driver circuit in series connected MOSFETs, it is economical. The single power MOSFET could be used to achieve the necessary high voltage and at the same time, the driver circuit becomes simple. However, it needs unique, specially designed solid-state devices where specifications must be taken into account when the devices were being manufactured. The performance of the series MOSFETs can be evident in the balancing of voltage, high speed switching, the performance noted up to 1500 V, and finally the reliability of the series stack [24].

3.2. High voltage pulse generator using single MOSFET

When MOSFETs are connected in series, triggering them simultaneously can present several challenges and drawbacks. If not properly driven, some MOSFETs might not switch fully ON or OFF at the same time, causing unequal conduction, higher power losses, or slow switching transitions. Ideally, the voltage drops across each MOSFET should be equal, but in practice, due to device variations and the gate drive characteristics, the voltage can be unevenly distributed. If the voltage sharing is not properly balanced, some MOSFETs might experience excessive voltage stress, which could lead to breakdown or failure of those devices. So, it would be preferable to design a PEF generator with single MOSFET. The circuit diagram is given in Figure 6, in which a single high voltage MOSFET is selected and triggered properly [27].

This work concentrates on the main switch selection to get the required pulses with suitable driver by taking into account of the compactness. Therefore, an extremely fast RF MOSFET MOSFET-IXZR08N120B by IXYs has been chosen and it has a wide range of features that has over-dominated the use of other conventional MOSFETs. The cool MOS™ is the ideal solution to meet today's continuously increasing energy demands with appreciable price/performance ratio.

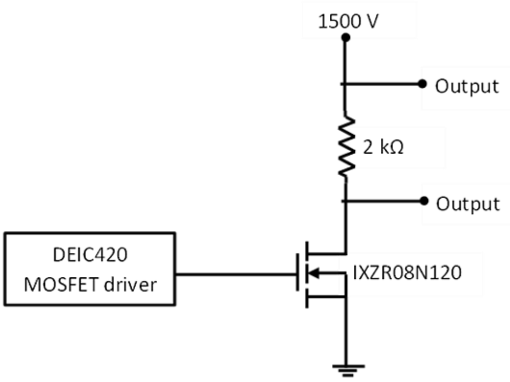
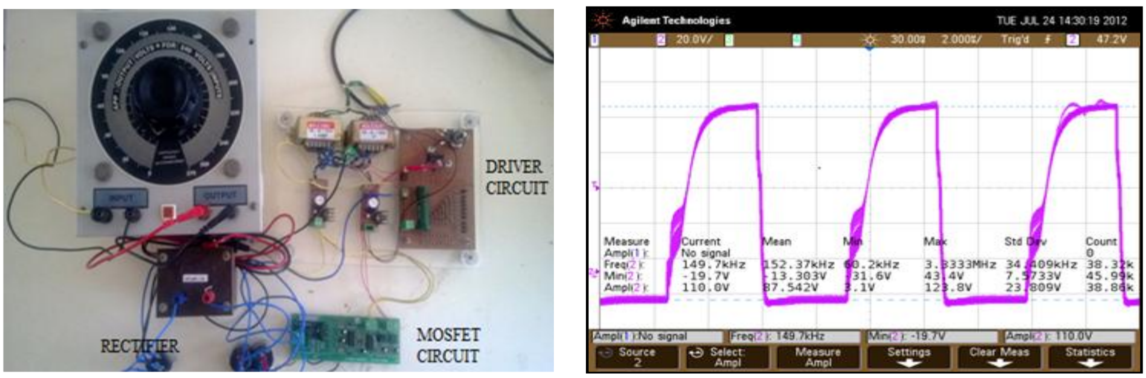


Figure 6. Circuit diagram of single MOSFET PEF generator

The DEIC420 driver runs on an 18 V supply. The pulsar tested at our laboratory at 120 V, the clock signal generated by MC74IC14, the implemented circuit, and the output of the compact pulse generator circuit is shown in Figure 7 [27]. In terms of output performance of the above MOSFET, the following were noted – high switching speed and frequency, current and voltage handling capability, very short pulse width due to fast response, and finally a compact and efficient operation [27]. As the voltage across the single MOSFET should be as same as the input voltage for the PEF application, the voltage stress on the MOSFET is higher which in turn requires a proper protective switch.



(a) (b)

Figure 7. Experimental set up of (a) single MOSFET and (b) output voltage

3.3. Cascaded MOSFETS based PEF generator

Power devices can be driven in series using gate-side techniques that use dynamic clamping [4], [5], or optimize the driving circuit [6], [28], to synchronize the pulses and correct for the difference in switching time. Gate side voltage balancing, which includes dv/dt and di/dt control [3], [29], active overvoltage protection by dynamic clamp circuits [4], high precision gate drive timing, cascaded synchronization [28], and time-delay compensation [29], encompasses the new technique of connecting MOS devices in series. The proposed block diagram and the circuit diagram are shown in Figure 8 [30].

The drain of the power MOSFET M_1 is connected to the source of the power MOSFET M_2. In general, the gates of M_1 and M_2 are connected, and the same control signal is shared. But, in the proposed PEF generator, the gate of M_1 is separated from that of M_2 and they have their own control signal. The hardware circuit is developed and shown in Figure 9 [30]. A 20 Ω resistor is connected in series with a 10 µH ferrite core inductor as source inductor L_S. Additionally, the power MOSFET M_1's gate capacitance $C_{igs,1}$ and input capacitance of 10 nF are used in parallel.

The MOSFETs IRFP150 and IRF540 are used as driving MOSFETs and power MOSFETs M_1, M_2 respectively. The high di/dt rating of the source inductor and high switching frequency of 52 kHz enhance the pulse voltage magnitude from the given 120 V DC. At this pulse frequency, the pulse width and duty cycle are adjustable and 1.2 µs is used in our experiment. By applying PEF for 30 s, the colony forming units are tremendously reduced and the cell viability receded from 7 log to 1.1 log scales [30]. It is possible to change the control pulse width and frequency by simply reprogramming the PIC 18F2550.

Increasing the DC input voltage along the proper source inductor design is an alternative method of raising the output voltage. As a result, the constructed high voltage pulse generator makes it simple to modularize and alter the pulse parameters. The energy delivered per second increases with frequency and the capability of the output voltage is determined by the source inductor value [30].

(a)

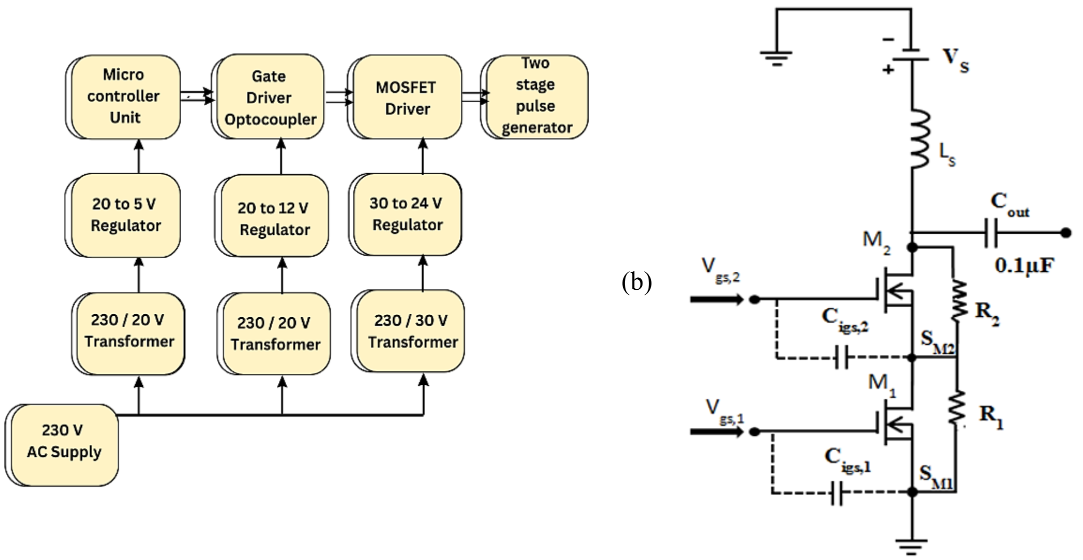
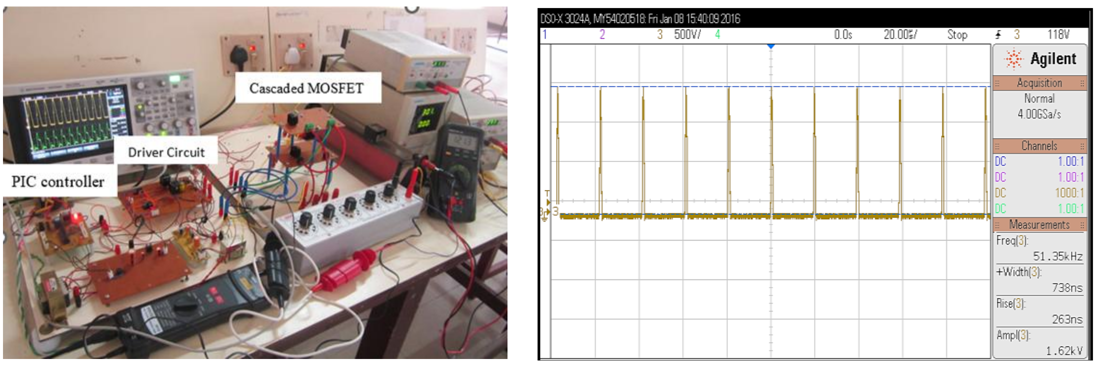


Figure 8. Cascaded MOSFET based PEF generator: (a) block diagram and (b) circuit diagram



(a) (b)

Figure 9. Hardware implementation of (a) two stage PEF generator and (b) output voltage

4. DISCUSSION

For biological applications, reducing the pulse width and raising the pulse repetition rate could also boost energy efficiency. In the implemented series-connected MOSFET circuit, the feedback resistor can be changed to change the output pulse width. It is found that the pulse falls and rise times will not significantly alter when the pulse width is adjusted from 38 ns to 7 µs. The pulse width is one of the imparted parameters in PEF technology and different foods require different pulse widths as discussed in [10], [15], [16]. So, it would be better if a single source with variable pulse generation and single MOSFET PEF generator is developed. In the circuit, the DEIC420 driver runs on an 18 V supply, while the MCIC74AC14 runs on a 5 V supply. By changing the feedback resistor from 500 Ω to 100 kΩ, the pulse width could be changed to produce pulses that vary from 40 ns to 7 µs.

Grenier's high voltage pulse generator [31] made use of MOSFETs coupled in series. However, in order to generate the high voltage pulses, a large input voltage is needed. But, when the input voltage is between 30 and 120 V DC, the implemented cascaded MOSFET PEF generator generates a high output voltage between 400 V and 1.6 kV, respectively. The source inductor plays a major role to accomplish this. Additionally, by increasing the pulse length and frequency, more electrical energy can be transferred to the food product.

Solid-state PEF generators have demonstrated significant improvements over classical PEF systems in terms of precision, efficiency, and operational flexibility. By utilizing advanced semiconductor switching devices such as IGBTs and MOSFETs, solid-state designs enable precise control of pulse width, frequency, and amplitude, producing highly consistent pulse shapes with minimal jitter. This results in greater reproducibility and more uniform treatment outcomes. In contrast, classical PEF generators, which often rely on spark gaps, thyratrons, or mechanical switches, tend to exhibit variability in pulse timing and shape, limiting process accuracy. From a maintenance perspective, solid-state designs offer longer component lifetimes and lower servicing needs, while classical systems suffer from faster wear of discharge components. Moreover, solid-state PEF generators provide easy programmability for different treatment regimes, making them highly adaptable for research applications, whereas classical systems often require hardware modifications to change parameters. Overall, the improved reliability, compactness, and safety features of solid-state PEF generators contribute to better experimental control and reduced operational costs, while still achieving equal or superior process outcomes compared to their classical counterparts.

5. CONCLUSION

In conclusion, significant advancements in PEF generator technology have a growing demand across various industries, including food processing, biomedical engineering, and wastewater treatment. Additionally, innovations in modular designs and energy recovery systems have made these generators more adaptable and affordable, making them increasingly accessible for both research and industrial-scale applications. Furthermore, advancements in materials and design have contributed to systems that are more durable, reliable, and easier to maintain. As these technological improvements continue, PEF systems are becoming more viable for a wide range of applications, offering a non-thermal, environmentally friendly alternative to traditional processing methods. In this study, we have evaluated the circuit topologies and output performance of series connected MOSFETs, single MOSFET, and cascaded MOSFETs. Each of the generators have their own advantages and series connected MOSFETs is more economical than other two, single MOSFET PEF generator finds more compactness and cascaded PEF generator boosts minimum voltage to higher voltage.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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S. Jeroline Mary		✓			✓					✓	✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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