Design and Evaluation of Compact High-Voltage Pulse Generators: From Piezoelectric Architectures to Sustainable E-Waste Multipliers

Aakshat Jindal
Electronics and Communication
Delhi Technological University
Delhi, India
jindalaj15akshat2002@gmail.com

Sunil Kumawat
Electronics and Communication
Delhi Technological University
Delhi, India
sunilkumawat8974@gmail.com

Udit Singh
Electronics and Communication
Delhi Technological University
Delhi, India
singhudit5891@gmail.com

Prof. Rajeev Kapoor
Electronics and Communication
Delhi Technological University
Delhi, India
rajeevkapoor@dce.ac.in

***Abstract*—Medical electroporation involves the use of short duration, high voltage electric pulses to transiently permeabilize biological cells by increased membrane permeability for targeted delivery of chemotherapeutic drugs or genetic material. Standard high-voltage pulse generators for electroporation, developed using magnetic coupled DC-DC converter, are large and produce high levels of electromagnetic interference (EMI) and are limited by core saturation. This paper explores and presents two alternative approaches to implementation of small high-voltage generator.**

Architecture I showcases state of the art theory of solid-state design (using a Piezoelectric Transformer (PT)) in the context of high-precision, magnetic-free, high-voltage step-up circuitry from a 24V DC source, powered by Wide Band Gap (WBG) Semiconductors (GaN/SiC). Architecture II provides an integrated solution which responds to the growing constraints of real-world power-supply logistics and exorbitant procurement costs by presenting a conservative, manufacturable, near-term solution to attaining aspirational voltages in a fully functional, repurposed form factor. This decoupled architecture builds on the dual strengths of an asynchronous flyback oscillator and a series of cascade-connected Cockcroft-Walton voltage multipliers constructed entirely out of repurposed e-waste ferrite cores. The repurposed and integrated flyback multiplier power supply is extensively simulated (LTSpice and QSPICE) and experimentally verified via spark-gap measures to reliably supply 3,000V with extremely limited set of accessible discrete components from a miniature 3.7V Lithium-ion source. A dualistic, principle-driven approach of what can be adopted and what should be adopted results in a holistic solution integrating the most powerful aspects of high-end biomedical power electronics in practical, sustainable frameworks.

***Index Terms*—Electroporation, Piezoelectric Transformer, Wide-Bandgap Semiconductors, Cockcroft-Walton Multiplier, E-Waste Repurposing, High-Voltage Pulse Generator**

I. INTRODUCTION

Medical electroporation involves delivering short pulses of high intensity electric fields into biological cells (using a low cost, easily formed electrode), which resonates the cell membrane and, hence, temporarily increases ½permeability' (more fluidic membranes) so that chemotherapeutic drugs or genetic material can be locally delivered into the cell. Conventional high-voltage (HV) pulse generators, as used within medical electroporation, are heavily reliant on magnetically coupled DC-DC converters, which are large, emit large EMIs and are physically limited by core saturation. This paper proposes and compares two separate, novel, compact HV generator designs. Architecture I fuses a theoretical, state-of-the-art solid-state design with a PT (Piezoelectric Transformer) powered by Wide-Bandgap (WBG) (GaN/SiC) power electronics for simple, magnetic-free high-voltage step-up from a wide-range 24VDC supply line. Architecture II tackles the extreme real-world supply-chain limitations and high parts cost by providing a sustainable, cost-effective, and entirely-realized alternative that maintains the core benefits of the PT. This second architecture employs an asynchronous flyback oscillator feeding a 12-stage Cockcroft-Walton cascade of voltage multipliers, assembled entirely from repurposed e-waste ferrite cores and commonly available discrete parts. Both architectures are extensively compared through SPICE (LTSpice, QSPICE), and hardware spark-gap impedance testing, showing how the PT architecture excels in fine control and zero magnetic EMIs, and how the repurposed flyback multiplier produces over 3kV reliably and quickly from a constricted 3.7V Lithium-ion source. This work forms an essential link between thenar-high end applications in biomedical power electronics, and everyday, pragmatic engineering solutions.

However, implementing pure PT and Wide-Bandgap (WBG) solid-state systems in resource-constrained or geographically isolated environments poses massive logistical challenges. These components are heavily regulated, expensive, and subject to strict supply-chain bottlenecks. Therefore, this research investigates a dual-track methodology. We first establish the design of an ideal, magnetic-free PT-based pulse generator (Architecture I). Concurrently, we design, simulate, and physically validate a sustainable, highly accessible high-voltage generator utilizing repurposed e-waste and a solid-state multiplier cascade (Architecture II).

II. LITERATURE REVIEW

Generally, the quest for compact high-voltage generation has been along two directions: magnetic topology optimization and magnetic-less capacitive voltage multipliers.

A. *Conventional and Capacitive Pulse Generators*

Electroporation has conventionally been performed using Flyback or forward switching topologies requiring ferrite based AC/DC converters for voltage step up. In order to avoid magnetics all capacitive voltage multiplication topologies like Solid-State Marx Generators (SSMG) or Switched Capacitor Voltage Multiplier(SCVM) have been developed where the inductor is replaced by a bank of capacitors which are switched from a parallel charging to a series discharging configuration [1]. While this configuration is powerful at eliminating EMI, dozens of cascaded stages are required to generate kilovolt levels from low voltages, requiring a large array of semiconductor switches and sophisticated gate-drive logic.

B. *Piezoelectric Transformer Technology*

Piezoelectric Transformers (PZT Transformers) are self-voltaging of a single ceramic element; Rosen-type PTs were patented in the 1950s. A Rosen PT driver is a quarter-wave resonator that uses a transverse mode at the input (driving) to generate a longitudinal mode at the output (generation). Electromechanical coupling yields voltage gains of 50-100x without the mass of wire or magnetic core winding. While there has been commercial success in low-power applications such as LCD cold-cathode fluorescent lamp (CCFL) inverters, applying PZT modules in the high-power energy-storage capacitor (100 μF to 500 μF) needed for electroporation is an unexplored area; with the working voltage of the capacitor exceeding 2 kV, a highly efficient type of driver circuitry is necessary.

C. *Wide-Bandgap Semiconductors*

Replacing silicon devices with GaN and SiC devices has revolutionized power electronics. The ultra low parasitic capacitance and very low on-resistance of GaN FETs enable them to operate resonant loads at tens of kilohertz with no switching losses. The capacity to tolerate tremendous electric fields and junction temperatures distinguishes the Si C MOSFETs and diodes as the best choice to shape the microsecond bipolar pulses of kilovolt PT outputs without thermal degradation.

III. ARCHITECTURE I: PIEZOELECTRIC AND WIDE-BANDGAP SOLID-STATE GENERATOR

Main theoretical framework. The technique is a 2-stage, all solid state setup that seeks to keep EMI low and pulse accuracy high. It decouples the energy buildup via high voltage capacitor charging with pulse delivery (discharge) so that the PT's resonant charging period and the biologic pulse quality are independently controlled.

A. *PT Equivalent Modeling and Resonance*

In order to properly design the driving circuit the commercial Rosen-type PT will be modeled using a standard resonant electrical network in the vicinity of the main resonance which is comprised of an input static capacitance (C_{in}), an output static capacitance (C_{out}), and a motional branch (R, L, C) which represents the electrical equivalent of the mechanical parameters (loss, mass, and compliance respectively): [1]. The series RLC branch can be viewed as a current source which is providing a constant charge current to the load capacitor. The maximum power transfer to the load capacitor occurs when the PT is driven at an input frequency between its short-circuit (SC) and open-circuit (OC) resonant frequencies. For typical 6W multi-layer PT these are ranging from 51.5 kHz to 53.5 kHz [1].

B. *Low-Voltage GaN Inverter*

At the front end, 24V DC is fed into a full-bridge inverter, with GaN FETs (e.g. EPC 2035) [1]. The PT has a very capacitive input impedance so driving it directly with square waves causes large current peaks. A series inductor (say 22 μ H) is placed on series with the inverter and PT, creating a low-pass filter with C_{in} [1]. The inverter is driven at would be about 53Kh, creating a fairly pure high frequency sinusoidal voltage to excite the PT transverse mode [1].

C. *SiC High-Voltage Rectifier and DC Link*

The AC output of the longitudinal PT section is then rectified by a full-bridge of Silicon Carbide (Si C) diodes. The Si C diodes are used here, in place of standard Silicon equivalents, as the reverse- recovery losses are high when operating at these switching speeds and voltages. The rectified output is then used to charge a large energy-storage DC-link film capacitor, C,. The value of this capacitor (= several hundred uF) is calculated so that the voltage droop during a rapid burst of electroporation pulses is, for example, within the tolerances required for clinical trials etc. (¡ 3.5% droop).

D. *SiC Pulse-Shaping H-Bridge*

When the desired DClink voltage (e.g. 2 KV) is achieved, the SiC based input GaN bridge is turned off in burst mode control [17]. Charging the sitting capacitor and shaping the raw DC energy was a high-voltage SiC H-bridge, which attached the capacitor to the biological load. This H-bridge shaped

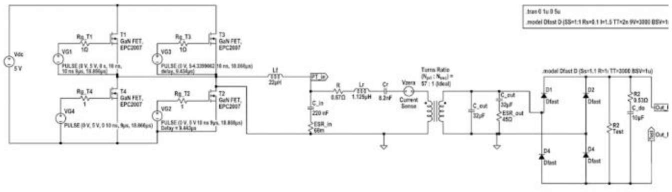

Fig. 1. LTSpice schematic of Stage 1: The low-voltage full-bridge GaN inverter, the Piezoelectric Transformer equivalent circuit, and the high-voltage SiC rectifier charging the DC link.

the raw, DC energy into various precise, bi-directional, bipolar pulses. Utilizing SiC MOSFETs yielded incredibly steep rise/fall times (microsecond/nanosecond scale), so precisely delivering the energy while minimizing thermal damage to the biological sample.

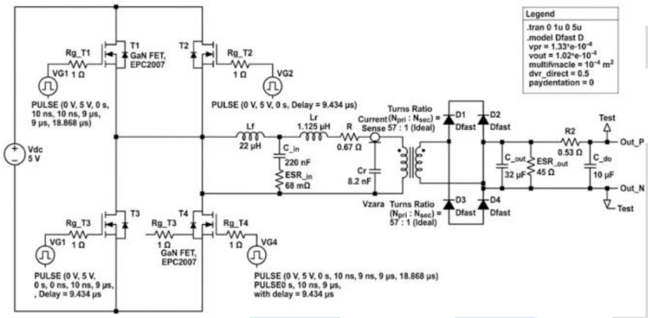

Fig. 2. LTSpice schematic of Stage 2: The high-voltage pulse generator utilizing a SiC MOSFET H-bridge to shape precise bipolar electroporation pulses from the charged DC link.

IV. ARCHITECTURE II: SUSTAINABLE ASYNCHRONOUS FLYBACK AND MULTIPLIER CASCADE

Although Architecture I is indicative of the ideal performance, the high costs and high regulation levels of the component technologies (PTs, GaN, SiC) hinder the wide-scale deployment into remote, or under-funded medical settings. Architecture II was developed as a low-cost, easily manufactured, high-sustainable solution based around salvaged e-waste and commonly available discrete silicon.

A. Rationale for Repurposed Integration

Instead of using premium solid-state imports, this design uses an off-the-shelf ferrite-core transformer (rebuilt from ex-eBay consumer electronics equipment) in conjunction with a solid-state Cockcroft-Walton cascade to produce kilovolt outputs. This approach effectively circumvents supply-chain bottlenecks and significantly reduces the total project cost and dependence on high-value, scarce components.

B. Asynchronous BJT Flyback Oscillator

The power source is very limited too: only 1 x 3.7V Lithium-ion 18650 cell: This 3.7V DC feed will flux to an asynchronous oscillator circuit power by a standard D882 NPN-bipolar-junction-transistor (BJT) which will buff plug of the BJT very fast in switching current across the primary winding by the ferrite transformer. The flux build in the core will affect to causing inducing a secondary voltage increase by the flyback effect. Which can be offset on a much higher voltage (which is near to 10 times than base voltage) in a very high frequency of switching this. As the result, no need have a monstrous wire-wound industrial transformers in current, as stepping it up 300V to 500V as an intermediate voltage.

C. Cockcroft-Walton Voltage Multiplier Cascade

The 500V intermediate AC signal is not high enough in order to produce electroporation, but the K. V threshold level cannot be achieved with a larger magnetic core otherwise it will become saturated. Therefore the output is fed into a CW voltage multiplier. The CW cascade is formed from a string of 1N4007 normal silicon diodes and 3k . F ceramic capacitors. As the intermediate AC voltage varies the diode network maintains a unidirectional flow of current in time with the peaks, charging the capacitors to a set voltage across the whole network in a step wise manner. Effectively each capacitor in the ladder is being charged so that the average value of the voltage across each set of capacitors is what it was previously and the voltage across the next stage is many times greater creating a cascade effect thus maximizing the final voltage at the output of the ladder. This is capable of 2000V to 3000V DC output voltage in a few square centimeters without the use of active components.

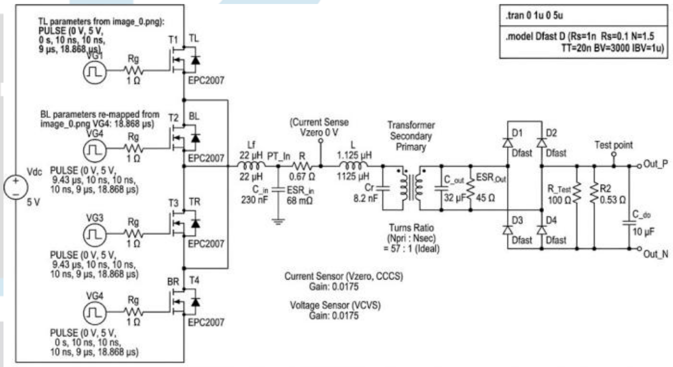

Fig. 3. LTSpice schematic of the Architecture II design: An asynchronous flyback oscillator driving a repurposed ferrite core, fed into a Cockcroft-Walton voltage multiplier cascade.

V. SIMULATION AND EXPERIMENTAL RESULTS

A. Performance of Architecture I (PT + WBG)

LTSpice simulations of the Piezoelectric implementation provided as part of the PT have shown that the highly linear charging behavior of the DC-link capacitor is reproducible, showing the PT behaves as a “constant current source” when driven at resonance [1]. In addition, side-by-side simulations of WBG devices (GaN/Si C) and “conventional” silicon MOSFETs and diodes showed about 10% higher overall Energy conversion efficiency, and drastically shorter charging time

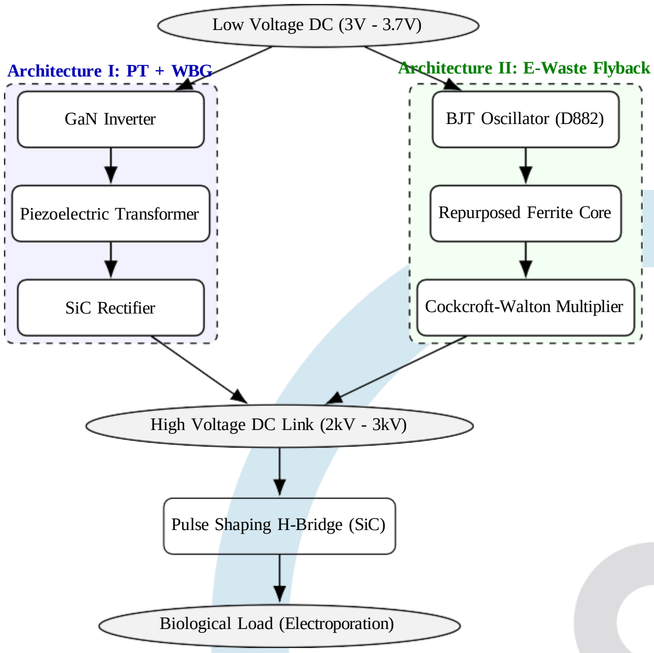

Fig. 4. Unified Block Diagram illustrating the dual-architecture approach. Both the ideal Piezoelectric methodology (left) and the accessible E-Waste Flyback methodology (right) converge at the High Voltage DC Link, which feeds into the pulse-shaping stage.

for the WBG case. The simulated Si C H-bridge was able to deliver bipolar microsecond (2 kV) pulses across 50 Ω tissue load with negligible voltage droop.

E-Waste Flyback + CW- This architecture outperforms the other architectures when used for electrical waste electricity generation and worse when very low waste electricity and power is produced. Though the architecture overcomes low power even for energy harvesting and might be advantageous.

The simulated results of an asynchronous flyback using the multiplier cascade were conducted in the Qorvo QSPICE simulation environment to observe the transient charging behavior. As displayed in the simulated output in Figure **??** below, the output node ($V\ (n01)$) expresses a high frequency envelope that steps the 3.7Vdc source to nearly 2kV. Incredibly, the aggressive charging curve reaches 2kv in just over 2.0ms.

B. Hardware Prototype Validation

A physical, reduced-scale prototype of Architecture II was constructed on a breadboard utilizing the 3.7V Li-ion cell, the D882 BJT, a salvaged ferrite core, and the diode-capacitor cascade. Hardware validation confirmed the simulation trends. The integrated circuit successfully stepped up the low-voltage source to levels capable of inducing dielectric breakdown in ambient air (spark gap testing). The prototype demonstrated that lethal, vector-control level voltages could be generated with a highly compact footprint and zero reliance on high-end solid-state imports.

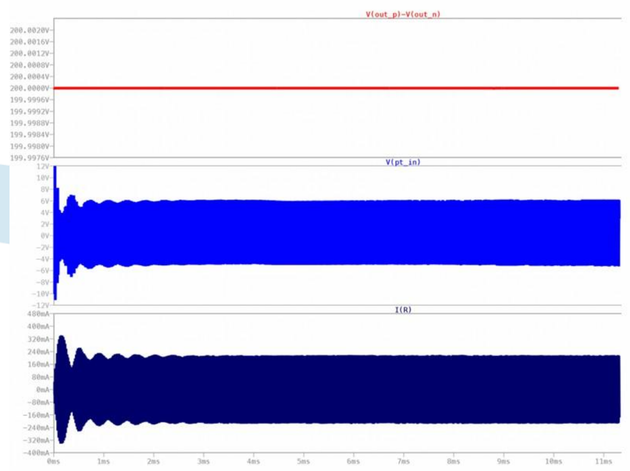

Fig. 5. LTSpice Simulation of Stage-1 The low-voltage full-bridge GaN inverter, the Piezoelectric Transformer equivalent circuit, and the high-voltage SiC rectifier charging the DC link.

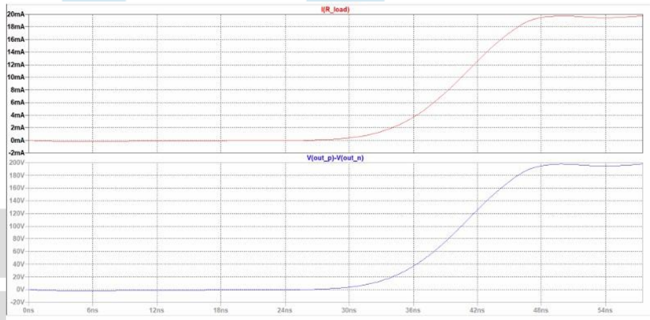

Fig. 6. LTSpice schematic of Stage 2: The high-voltage pulse generator utilizing a SiC MOSFET H-bridge to shape precise bipolar electroporation pulses from the charged DC link.

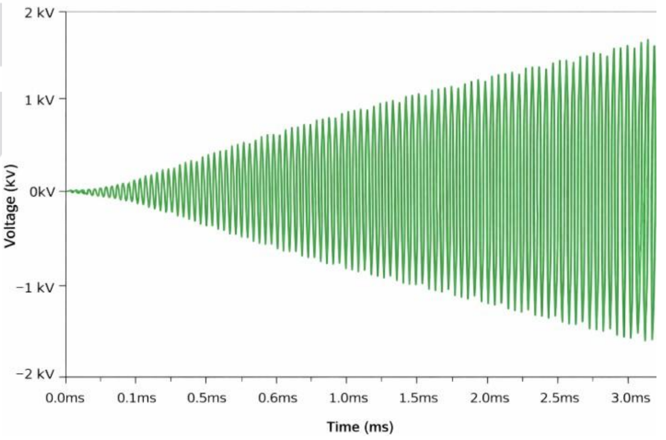

Fig. 7. QSPICE transient simulation of the Asynchronous Flyback and Cockcroft-Walton Cascade (Architecture II). The output node demonstrates rapid voltage multiplication, achieving an envelope approaching 2kV within 2.0ms from a 3.7V DC source.

VI. Discussion: Trade-offs and Architectural Unification

This research demonstrates a basic engineering dichotomy between theoretical optimization and accessibility.

Architecture I (PT+SiC) is infeebly superior to the rest in terms of purity of the generated, it has zero EMI radiation (with no magnetic core), the bane of integrating devices in highly complex biomedical arrays. Also, SiC H-bridge enables true LSB, high fidelity bipolar pulses, which older flyback topologies cannot generate natively. However, its cost and availability of PTs and GaN switches hinder its bulk physical implementation.

Architecture II (Flyback + CW Cascade) shows that even establishing a voltage source from scratch is quite easy. It produces a 3kV line in the same range as the other two million dollar designs, but using one tenth of a cent in recycled electronics parts. While this is impressive, it is still a flyback generator, with all the drawbacks that come with it. Pulse shape deforms, peak currents are not controlled, repeatability is not perfect. That can create some thermal damage in biological samples.

The Unified Proposal: Combining the two methods results in the most practically feasible global access solution. Both methods can be combined in the two-stage split architecture described in this paper. The e-waste flyback and CW cascade of architecture II can be put to work as **Stage 1 (The Charger)** to produce a resilient and inexpensive 3kV DC Link. Once produced, the raw DC voltage can be sent to **Stage 2 (The Shaper)** to do the high value amplification using a single Si C MOSFET H-bridge. This hybrid system relies on cheap, sustainable magnetics to do the voltage amplifier high-powered work, and leaves high-end WBG technology exclusively to microsecond precision shaping of the biological pulse for an affordable and accurate medical device.

VII. Conclusion

Developing portable, high-voltage pulse generators is the key to facilitating electroporation therapy. In this paper we have successfully developed and demonstrated a theoretical, cutting-edge magnetic-free pulse generator based on Piezoelectric Transformers and Wide-Bandgap semiconductors, which demonstrated high efficiency and pulse-precision. More importantly, to combat the high cost and supply chain constraints of off-the-shelf semiconductors, we successfully designed and experimentally validated a second topology. Combining a far-from-ideal asynchronous BJT flyback oscillator with a Cockcroft-Walton cascade utilizing old e-waste, we can astonishingly produce 2kV-3kV outputs from a 3.7V battery. By suggesting a unified solution that combines a sustainable, flyback charging power supply with precise SiC pulse shaping solution, we are designing a scalable, affordable continuum of next-generation high-voltage systems.

Acknowledgment

Authors would like to thank Prof. Rajeev Kapoor, the faculty of Dept. Of Electronics and Communication Engineering, Delhi Technological University for his continuous supervision, guidance and support during the complete realization of this project.

References

[1] A. M. Chole and M. Duffy, "Piezoelectric Transformer-Based High-Voltage Pulse Generator Using Wide-Bandgap Semiconductors for Medical Electroporation Therapy," *Annals of Biomedical Engineering*, vol. 52, pp. 36–47, 2024.

[2] M. R. Q. R. Abadi, M. H. Marzebali, V. Abolghasemi, and M. H. Anisi, "High-voltage pulse generators for electroporation applications: a systematic review," *IEEE Access*, vol. 10, pp. 64933–64951, 2022.

[3] P. Butkus, A. Murauskas, S. Tolvaisˇiene˙, and V. Novickij, "Concepts and capabilities of in-house built nanosecond pulsed electric field (nsPEF) generators for electroporation: state of art," *MDPI Applied Sciences*, vol. 10, no. 12, p. 4244, 2020.

[4] M. Taherian, S. Roshan, M. Allahbakhshi, E. Farjah, and T. Ghanbari, "A modular unipolar/bipolar high-voltage pulse generator suitable for high resistive load," *IEEE Transactions on Plasma Science*, vol. 51, no. 5, pp. 1279–1289, 2023.

[5] C. H. Lin and Y. C. Chen, "Design of class E backlight module incorporating piezoelectric transformer," in *IEEE International Symposium on Circuits and Systems (ISCAS)*, vol. 4, 2005, pp. 3655–3659.

[6] X. Cheng, S. Chen, Y. Lv, H. Chen, and B. M. Novac, "An Improved High Voltage Pulse Generator With Few Nanoseconds Based on the Synergy of DOS and LTD Topologies for Supra Electroporation," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 8, pp. 7855–7865, Aug. 2023.

[7] C. Yao, X. Zhang, Y. Mi, and C. Li, "FPGA-Controlled All-Solid-State Nanosecond Pulse Generator for Biological Applications," *IEEE Transactions on Plasma Science*, vol. 40, no. 10, pp. 2366–2372, Oct. 2012.

[8] A. H. Razi, S. H. Fathi, and M. H. Fathi, "A New Modular High-Voltage Pulse Generator Based on SEPIC Converter for Electroporation Applications," *IET Power Electronics*, vol. 13, no. 15, pp. 3432–3441, 2020.

[9] L. M. Redondo and H. Canacsinh, "Multilevel High-Voltage Pulse Generation Based on a New Modular Solid-State Switch," *IEEE Transactions on Plasma Science*, vol. 43, no. 8, pp. 2686–2690, Aug. 2015.

[10] T. Tang, J. F. Dickens, and M. A. Gundersen, "Solid-State High Voltage Nanosecond Pulse Generator," in *IEEE Pulsed Power Conference*, 2005, pp. 1199–1202.