Low cost pulsed electric field generator using DC-DC boost converter and capacitor diode voltage multiplier

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ABSTRACT

Traditional high-voltage pulse generators, like Marx generators often face challenges related to efficiency and complexity. In this paper, a solid-state multi-module high-voltage pulse generator that integrates capacitor-diode voltage multipliers (CDVM) with DC-DC boost converters and closed-loop voltage control is proposed to overcome these challenges. The system achieves high output voltage by coupling the pulsed output voltages of individual low-voltage DC sources in series across each module. The proposed design was modeled using MATLAB, and experimental testing was conducted on a single stage. Comparative analyses between time-domain parameters, proportional-integral (PI), and fractional order proportional integral derivative (FOPID) controllers were performed. Both MATLAB simulations and experimental validations demonstrate the effectiveness of this approach. The rise time, peak time, settling time, and steady-state error are all improved using an FOPID controller, decreasing from 0.32 to 0.31 seconds, 0.42 to 0.35 seconds, and 3.15 to 2.20 seconds, respectively. These findings indicate that a closed-loop FOPID controller enhances time-domain performance parameters more effectively than a PI controller for a two-stage DC-DC voltage multiplier.

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1. INTRODUCTION

High-intensity, short-duration electrical pulses are used to generate the electroporation pulses [1]. Electroporation is the process of forming pores in cell membranes, which can be either reversible or irreversible depending on the applied electrical pulse parameters such as electric field intensity and duration [2]. During irreversible electroporation, the pores created in the cell membrane do not reseal, whereas, in reversible electroporation, the pores may reseal when the electric field is turned off [3]. The biomedical, environmental, food preservation and processing industries employ reversible/irreversible electroporation depending upon the application [4]. Solid-state Marx generators are the most widely used high-voltage pulse generators [5]. They require numerous expensive and space-consuming semiconductor components to step up DC voltage [6]. Multiport DC-DC converters offer a cost-effective solution due to their compact design and reduced component count compared to multiple independent DC-DC converters [7].

At high voltages, switching voltage stress poses a significant challenge for DC-DC converters. High-voltage switches can introduce voltage stress due to their substantial forward voltage drop and ON-state resistance, adversely affecting overall efficiency. Insulated gate bipolar transistor (IGBT) is the primary semiconductor used for high-voltage applications [8]. However, IGBT suffers from significant switching losses, limiting their switching frequency to approximately 1 kHz [9]. Consequently, IGBTs are inefficient for multiport DC-DC converters. This system, therefore, employs a multiport DC-DC converter that ensures high efficiency, smaller passive components, and reduced voltage stress on semiconductors.

Our model utilizes hybrid renewable energy sources and converter topologies for efficient energy production. To balance electricity output and consumption within a power system, fuel cell stacks and photovoltaic solar panels are used in combination. The two most common methods for combining multiple input power sources are multiple-converter systems and multiple-port systems [10]. These methods allow for several input ports to share the output stage. Because fewer components will be needed, the cost will be lower, and the system's overall efficiency and power density will be improved.

Capacitor-diode voltage multipliers (CDVM) are small, have less weight, and have high efficiency [7]. As a result, it may be utilized successfully to produce strong pulsed electric fields (PEF) [11]. We propose a high-voltage pulse generator based on an uncontrolled CDVM and a DC-DC boost converter [12]. The proposed high voltage (HV) pulse generator may be used for PEF applications with the following key benefits:

- High system efficiency because no transformer is used;
- It is sufficient to use an AC input power source with low voltage and low frequency;
- It is possible to control the output voltage; and
- System expenses are reduced by using low-voltage capacitors and diodes to achieve high PEF.

2. PROPOSED PEF GENERATOR

The existing single-stage DC-DC voltage multiplier is shown in Figure 1. Using a boost converter, low-voltage DC is stepped up to a certain level and then applied to the load at its rated voltage. Due to voltage drop between diodes and losses in the capacitors, the single-stage DC-DC voltage multiplier that is used currently has poor efficiency. In applications needing higher output voltages, a substantial part of the input power may be wasted as heat. It also has low output power, poor control, and significant voltage stress [13]-[17].

The proposed DC-DC voltage multiplier incorporates photovoltaic (PV) and fuel cells, which are deemed efficient choices among other renewable energy sources [18]-[22], as illustrated in Figure 2. In such a system, the energy storage unit manages the mismatch power, absorbing the excess energy during light load conditions and supplying the energy shortage during high load conditions. Consequently, depending on the output of the renewable energy source and the amount of load, power flow may differ [23].

To lessen the ripple voltage of the open-loop system, a large step-up voltage multiplier is suggested. Figure 3 depicts the suggested circuit diagram for a two-stage DC-DC voltage multiplier with an open-loop system. The fundamental benefit of a two-stage voltage multiplier over a single-stage one is that it enables higher voltage multiplication without considerably raising the complexity of each stage individually. Also, it offers additional significance in terms of higher voltage output, reduced voltage stress, improved efficiency, and improved output regulation [24]. Figure 4 depicts a two-stage voltage multiplier DC-DC converter's closed-loop circuit diagram with proportional-integral (PI) and fractional order proportional integral derivative (FOPID) controller systems.

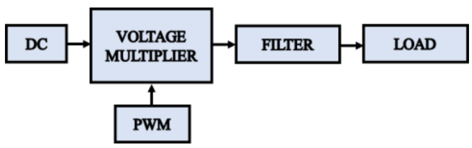


Figure 1. Diagram showing current single-stage DC-DC voltage multiplier

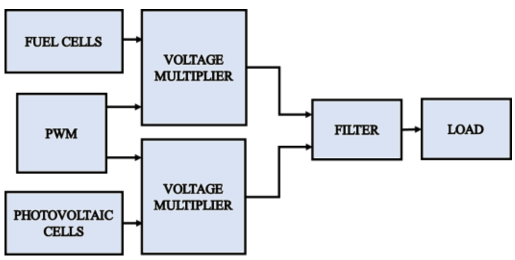


Figure 2. Schematic of envisioned dual-stage DC-DC voltage multiplier

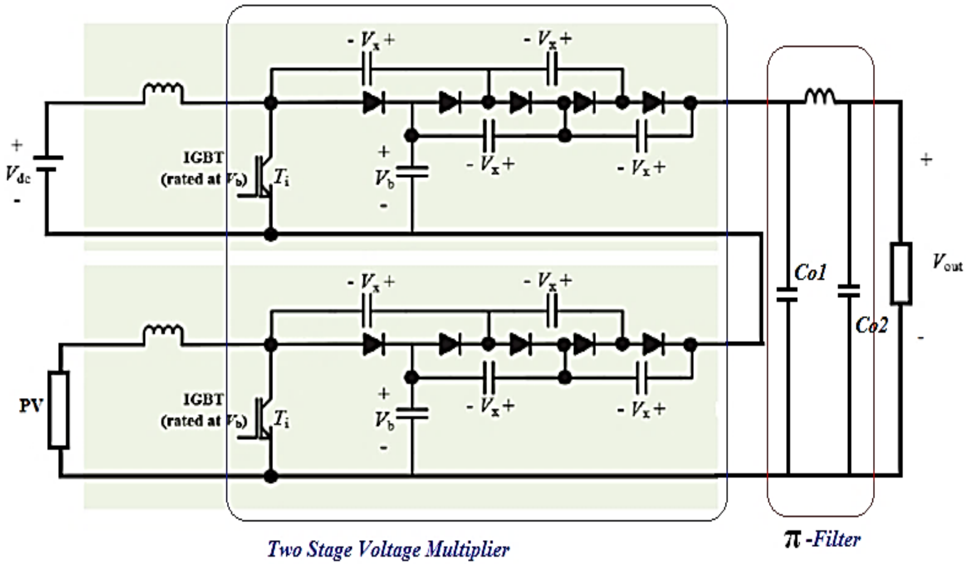


Figure 3. Proposed circuit for a two-stage voltage multiplier DC-DC converter system

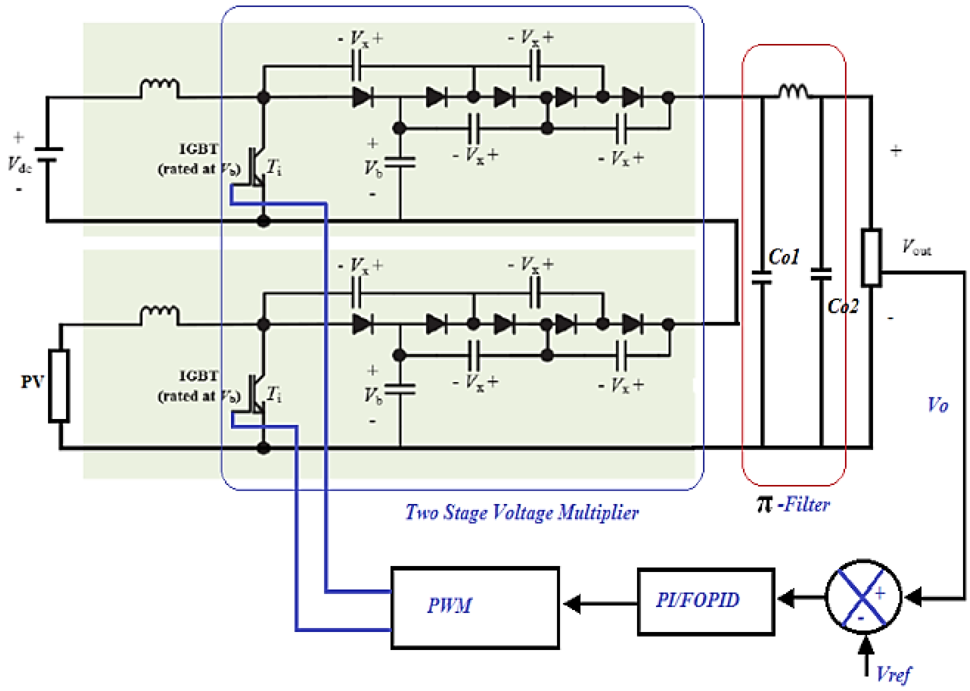


Figure 4. PI and FOPID controller system-equipped circuit schematic for proposed two-stage voltage multiplier DC-DC converter

3. METHOD

The input DC voltage is chopped using an IGBT switch. Each stage will produce a pulsed output voltage that has a large voltage magnitude (V_{out}) and a brief time duration, which corresponds to the IGBT switch's turn-on time (T_{on}). The magnitude of the overall pulsed output voltage must be kept constant and equal to the sum of the magnitudes of the pulsed output voltages at each stage. To ensure smooth functioning, synchronization between switches should be maintained. A diode placed across each stage's output may help you skip that step if there is any discrepancy between the switches or if the stage has failed or been deactivated. Both stages' pulsed output voltages are connected in series. Since there are n stages and V_{out} is the output voltage at each stage, the overall pulsed output voltage has the magnitude $n*V_{out}$.

Each stage utilizes a DC-DC boost converter that is regulated to provide a stable output voltage. To accomplish this, one can measure the output voltage (V_{out}) at every stage and then compare it to the reference value. The voltage error is sent to PI controllers to calculate the boost converter duty cycle. The duty cycle of the boost converter is compared with a high-frequency triangle wave to generate the gate pulses for the boost converter's-controlled switch (T).

3.1. Proportional integral controller (PI)

Two output signals were produced by the PI control scheme: one proportional to the error signal and the other proportional to the error integral. The proportional integral controller output is obtained by (1) and (2).

$$c(t)\ \alpha\ (e\ (t) + \int e(t)dt) \tag{1}$$

$$c(t) = K_c[\ e\ (t) + \frac{1}{\tau i}\int e\ (t)dt] \tag{2}$$

Where, K_c is the proportional constant gain and τi is the integral constant time. The Laplace transform of equation gives as (3) and (4).

$$c(s) = K_c[\ (s) + \frac{1}{\tau i.s}(s)] \tag{3}$$

$$\frac{c(s)}{E(s)} = K_c[\ 1 + \frac{1}{\tau i.s}] \tag{4}$$

3.2. Fractional order PID control (FOPID)

The fractional order proportional integral derivative (FOPID) controller is a fractional calculus-based version of the IO proportional integral derivative (IOPID) controller. The much more popular method of FO controller is the $PI^{\lambda}D^{\mu}$, which consists of an integrator of value λ and a differentiator of value μ, where λ and μ can be any true number. The mathematical expression for $PI^{\lambda}D^{\mu}$ the controller is as (5).

$$c(t) = K_c\ e\ (t) + K_I D^{-\lambda} e\ (t) + K_d D^{\mu} e\ (t) \tag{5}$$

Where, D^{μ} is Caputo's fractional derivative of value 'μ' with respect to variable 't'. The TF of the FOPID controller is as (6).

$$\frac{c(s)}{E(s)} = K_c + K_I S^{-} + K_d S^{\mu} \tag{6}$$

The generalized TF of this FOPID controller is as (7).

$$c(s) = K_p + \frac{K_i}{S^{\lambda}} + K_d S^{\mu} \tag{7}$$

In which K_p represents the proportional constant gain, K_I represents the integration constant gain, K_d represents the derivative constant gain, and $c(s)$ represents the controller output.

4. SIMULATION RESULTS AND DISCUSSION

MATLAB/Simulink is utilized for modeling and simulating a closed-loop PI and FOPID controller system with a high step-up voltage multiplier DC-DC converter system. This part displays the results of different systems. Figure 5 depicts a circuit schematic of a two-stage voltage multiplier DC-DC converter featuring a source disturbance mechanism. As indicated in Figure 6, the DC input voltage is 58 V, while the voltage across the R-load is 1400 volts, as illustrated in Figure 7. The R-load has a current flow of 3.8 A, as depicted in Figure 8. Figure 9 demonstrates an output power of 3900 W.

The circuit schematic in Figure 10 illustrates a DC-DC converter with a closed-loop PI controller system that operates as a two-stage voltage multiplier. As depicted in Figure 11, the DC input voltage is 58 volts. As shown in Figure 12, the voltage drop across the resistor R-load is 1200 V. In Figure 13, the current flowing through the resistive load is 2.5 A. Figure 14 displays the output power at 3000 W.

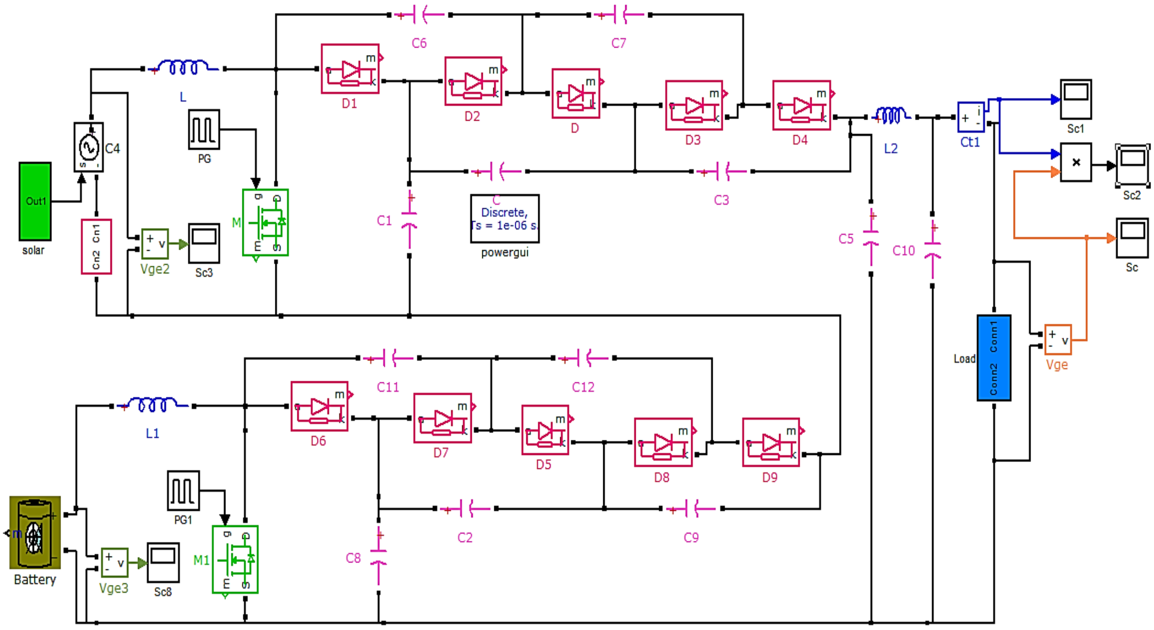


Figure 5. Schematic of a DC-DC converter with a two-stage voltage multiplier and source interference

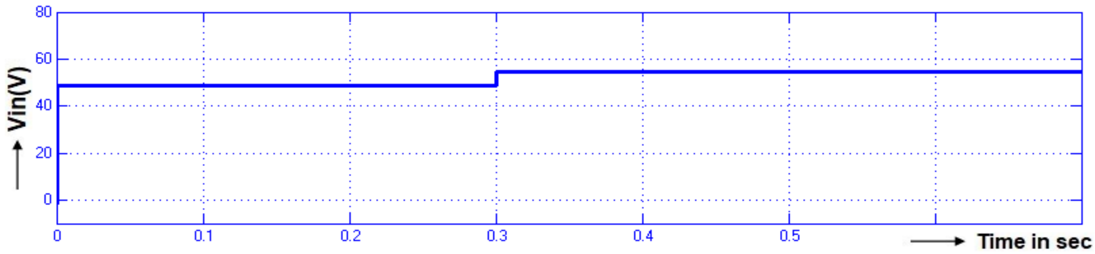


Figure 6. Input voltage

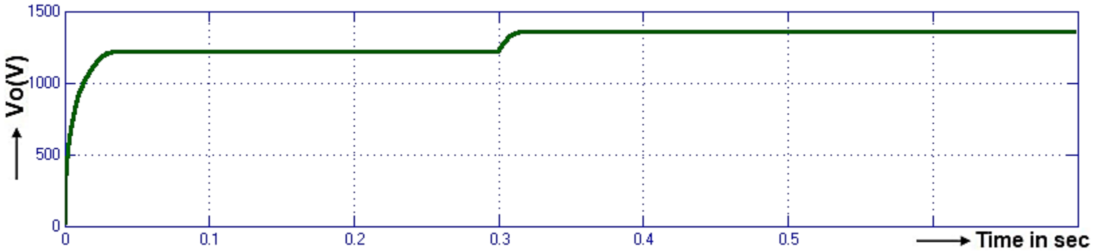


Figure 7. The voltage across a resistive load

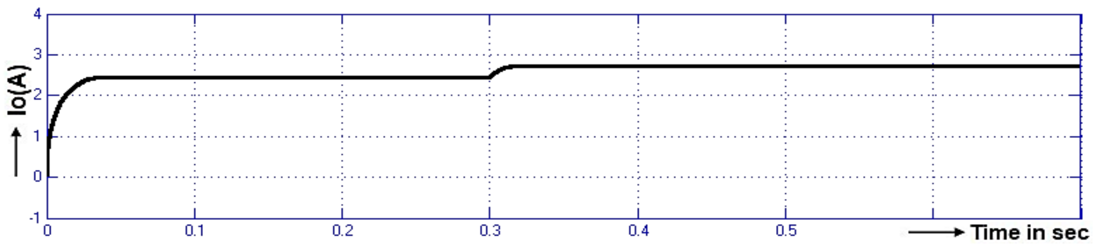


Figure 8. Current through a resistive load

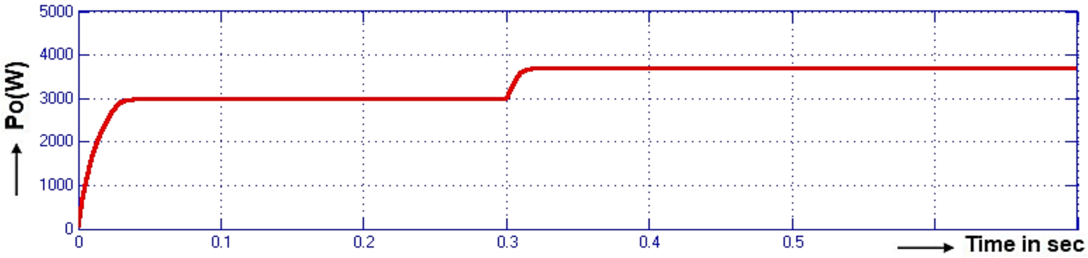


Figure 9. Output power delivered to resistive load

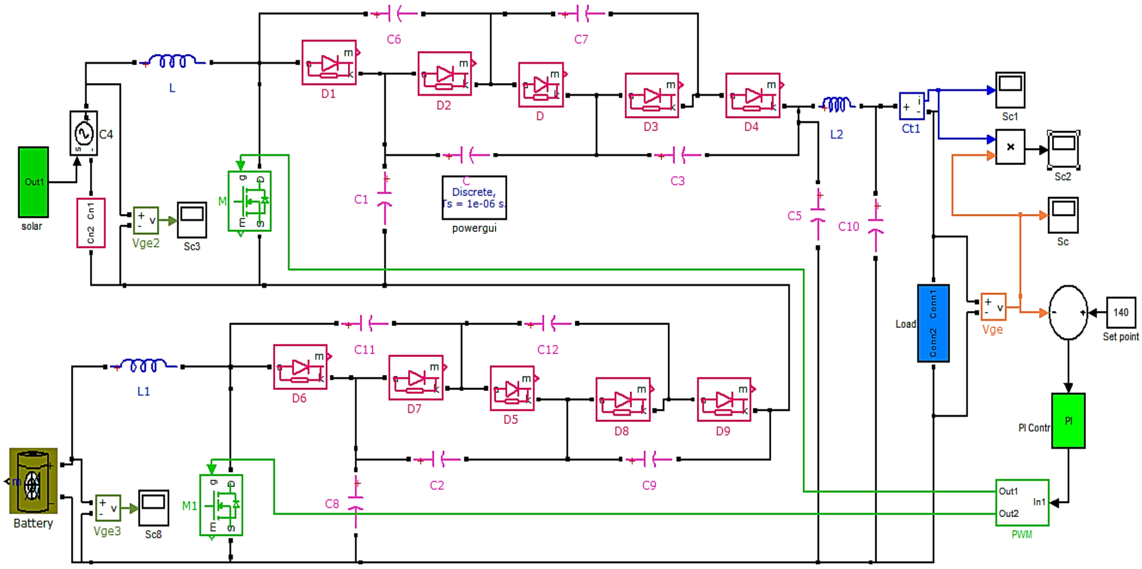


Figure 10. Schematic of a DC-DC converter with two stages, controlled by a closed-loop PI system

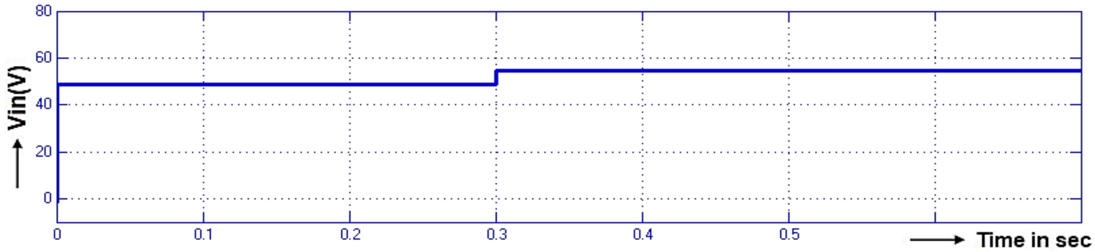


Figure 11. Input voltage

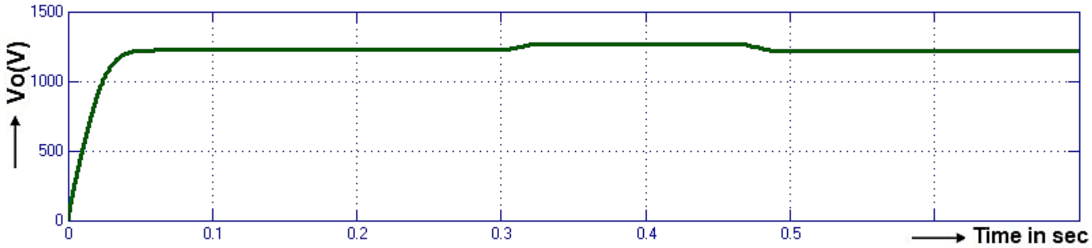


Figure 12. The voltage across a resistive load

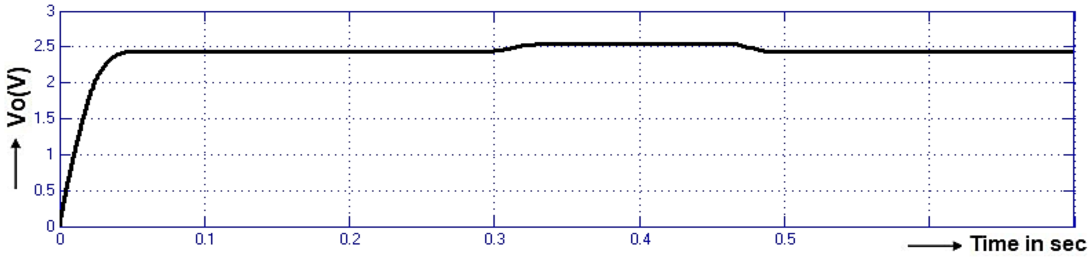


Figure 13. Current through a resistive load

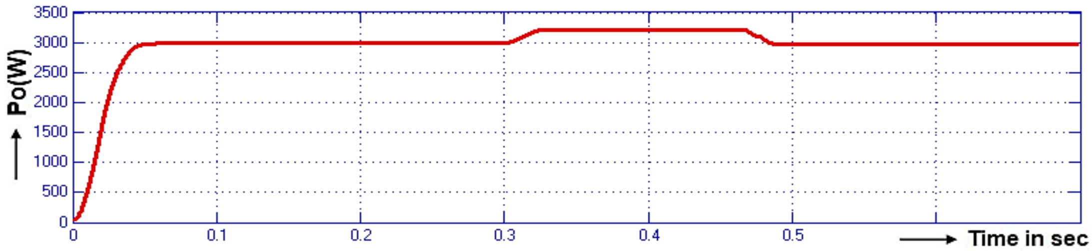


Figure 14. Output power delivered to resistive load

Figure 15 shows the schematic of a two-stage voltage multiplier DC-DC converter with a closed-loop FOPID controller system. The DC input voltage is 58 volts, indicated in Figure 16. As per Figure 17, the voltage drops over the resistor load is 1200 volts. Based on Figure 18, the R-load carries a current of 2.5 A. As illustrated in Figure 19, the load can deliver a maximum power of 300 W.

Table 1 compares the time domain parameters of a two-stage voltage multiplier DC-DC converter for closed-loop PI and FOPID controllers. It is clear from the table that the FOPID controller outperforms the PI controller in a two-stage voltage multiplier DC-DC converter. Figure 20 displays a contrast between PI and FOPID. Several measurements are considered, such as time to increase, time to reach the highest point, preparation time, and error in a stable state.

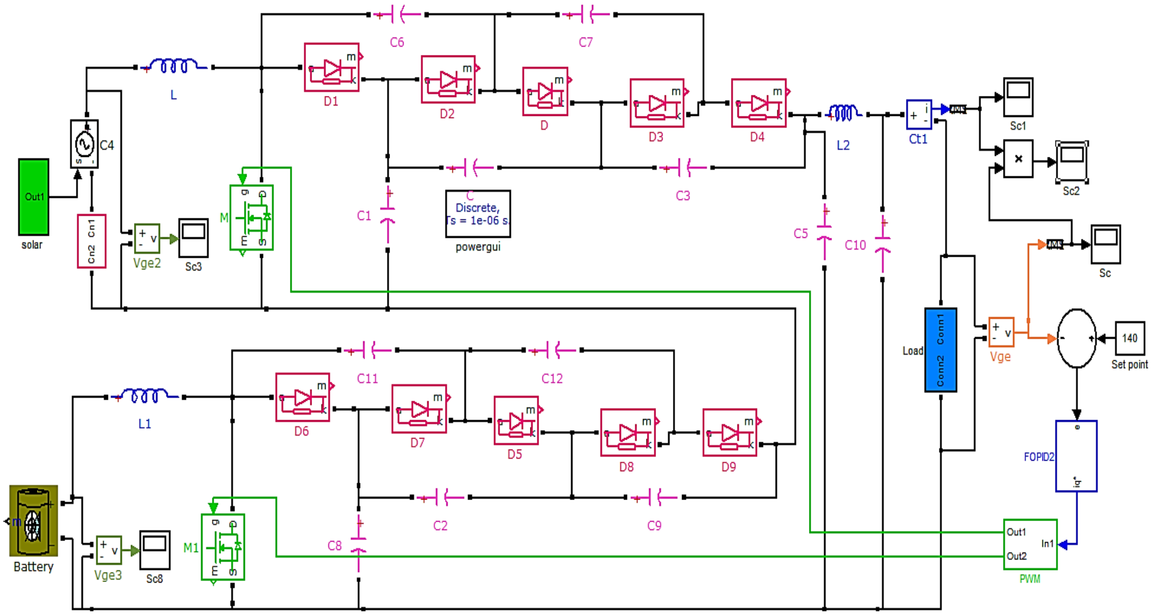


Figure 15. Schematic for a feedback-controlled FOPID controller on a voltage multiplier DC-DC converter with two stages

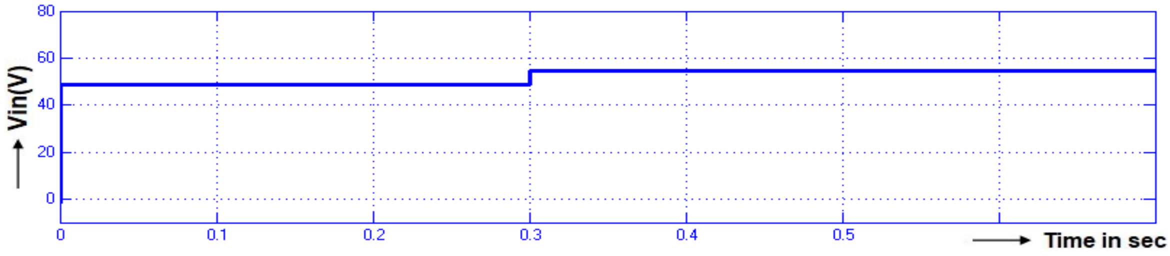


Figure 16. Input voltage

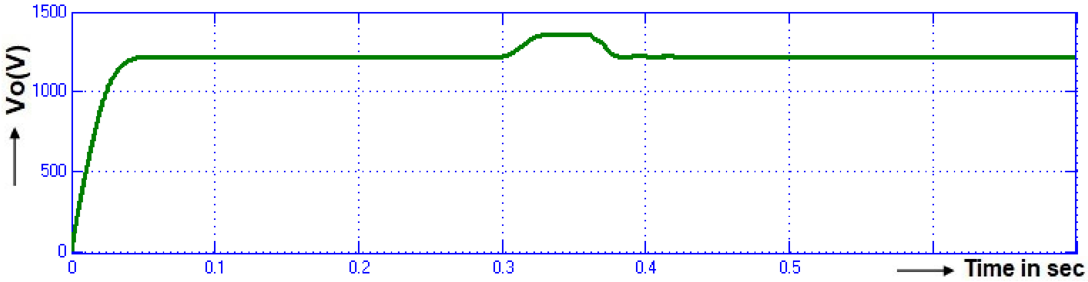


Figure 17. Electric potential difference over a resistive load

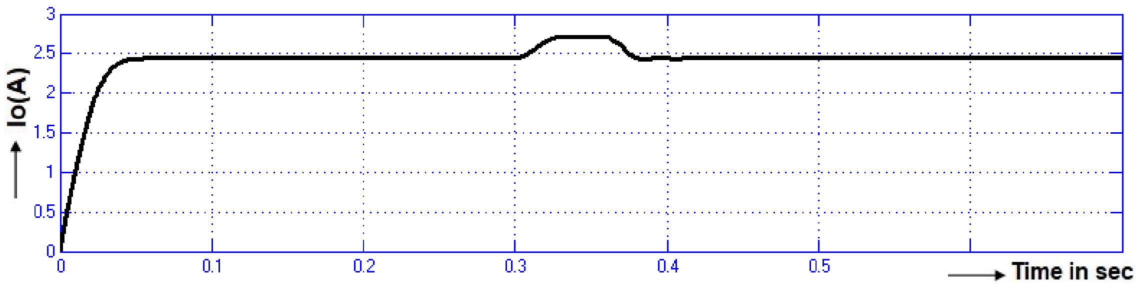


Figure 18. The flow of electric current in a resistive circuit

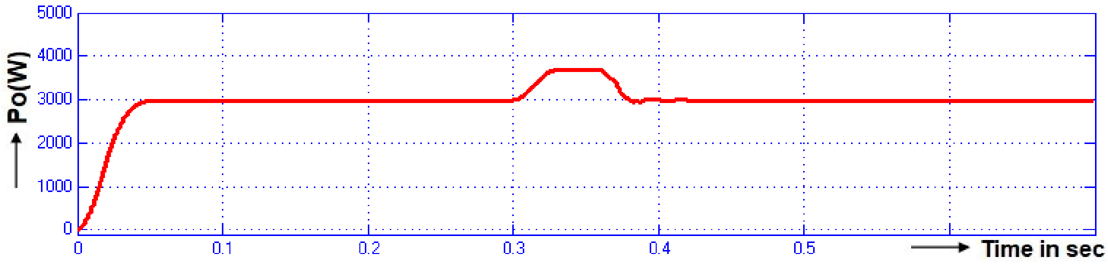


Figure 19. Output power delivered to resistive load

Table 1. Time domain parameter comparison

Controller	Rise time (s)	Peak time (s)	Settling time (s)	Steady state error (V)
PI	0.32	0.42	0.48	3.15
FOPID	0.31	0.35	0.39	2.20

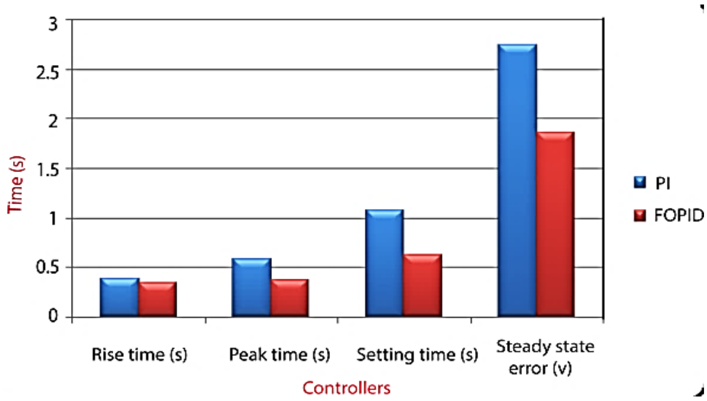


Figure 20. Comparison analysis for PI and FOPID

5. HARDWARE RESULTS AND DISCUSSION

A two-stage capacitor-diode voltage multiplier is a circuit designed to increase the voltage level from a low DC input. It consists of multiple stages of diodes and capacitors that work together to generate a stepped-up DC output voltage. The proposed system is validated through experimental testing, and the experimental setup of the hardware implementation of the circuit is illustrated in Figure 21(a). The operation of the two-stage capacitor-diode voltage multiplier prototype is as follows.

5.1. Operation

- Stage 1: charging phase

A diode rectifier and step-down transformer are used to convert the 230 VAC voltage input into a 12 VDC power supply. Two-stage capacitor diode voltage multipliers (V_{M1} and V_{M2}) receive an input of 11.8 VDC. The inductor is charged with supply voltage when the switch is turned ON in the charging phase. When the switch is not turned ON, the stored energy in the inductor combines with the supply voltage, causing the current to charge the initial capacitor to the peak voltage of the input signal reduced by the forward voltage drop of the diode. Nevertheless, the important diode is reverse-biased, stopping the capacitor from discharging via the input source.

- Stage 2: voltage doubling phase

The initial capacitor is charged to a voltage just below the highest input voltage. It is then linked to the second-stage diode and capacitor setup. The second diode is turned on, and the second capacitor charges to the same voltage as the initial capacitor when the input voltage is positive. When the input DC voltage is negative, the second-stage diode is in reverse bias and the second-stage capacitor retains its charge.

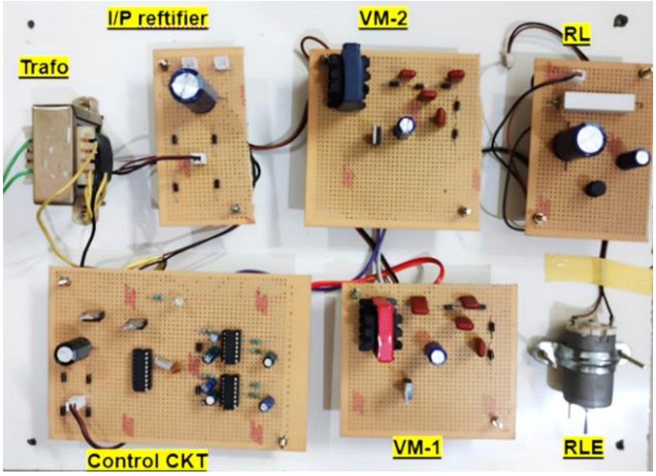
- Stage 3: output phase

The output voltage across the second-stage capacitor is approximately twice the peak input voltage of the source. Each stage of the voltage multiplier adds to the output voltage, effectively doubling it, in this case, to 70 V. Figure 21(b) indicates the output voltage across the RL load (single stage), Table 2 indicates the various components used to make the prototype, and Table 3 displays the various electrical parameters such as output power, ripple current, ripple voltage, and model output voltage.

The two-stage CDVM pulse generator generates a rectangular pulse output with voltage amplitude of 70 V and power of 50 W, derived from a 12 VDC input source. The output voltage is amplified by a factor of 5 compared to the input voltage. By implementing multiple stages, it is feasible to achieve significantly higher output voltages, potentially extending into the kilovolt range as obtained by other researchers [25]-[27].

In recent years, high voltage (HV) pulse generators for pulsed electric fields (PEF) in a variety of applications such as food processing, medical treatment, and scientific research, have gone through a series of significant developments. With literal translations, the innovative pulse technology of HV generators can be found in the fields of circuit design, structure, overall framework design, and its orientation. Below follow a few key areas for innovation:

- High system efficiency because no transformer is used.
- A low-voltage, low-frequency AC input power source is adequate.
- It is possible to control the output voltage.
- Utilizing low-voltage capacitors and diodes helps in cutting down system costs while maintaining a high PEF.



(a)

(b)

Figure 21. Hardware implementation of the proposed circuit: (a) experimental setup and (b) output voltage across RL load (single stage)

Table 2. Hardware components

Component	Specification	Component	Specification
Microcontroller	16F84A	Diode	1N4007
Driver IC	IR2110	Capacitor	100 mfd, 200 V
MOSFET	IRF540	Voltage regulators	7812, 7805
Capacitor	1000 nF, 400 V		

Table 3. Output power, ripple current, ripple voltage, and model output voltage

V_{in}(V)	V_o(V)	V_{or}(V)	I_{or}(A)	P_o(W)
11.8	70	2.20	0.018	50

6. CONCLUSION

The proposed model was simulated using MATLAB, comparing time-domain parameters for PI, and FOPID controllers. The implementation of a FOPID controller notably reduced the rise time from 0.32 to 0.31 seconds, the peak time from 0.42 to 0.35 seconds, and the settling time from 3.15 to 2.20 seconds. These results demonstrate that a closed-loop FOPID controller significantly outperforms a PI controller in the proposed circuit for a two-stage voltage multiplier DC-DC converter with a filter system. This study introduces an innovative high-voltage pulse generator that employs multiple modules, integrating a DC-DC boost converter and a capacitor-diode voltage multiplier (CDVM) for precise closed-loop output voltage control. The proposed generator offers distinct advantages, including the use of separate low-voltage DC sources, the capability to achieve higher output voltages, and improved capacitor voltage control, addressing the limitations of traditional Marx generators. The effectiveness of the suggested model was validated through both MATLAB simulations and experimental testing, confirming its potential as a robust solution for generating high-voltage pulses.

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