Design and implementation of high voltage DC generation system based on push-pull inverter integrated with Cockcroft-Walton

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ABSTRACT

High-voltage DC generation is essential for industrial, medical, and scientific applications, such as X-ray machines, particle accelerators, and electrostatic precipitators. Existing high-voltage DC generators face challenges such as high cost, complexity, and inefficiency. A simplified and cost-effective solution that can reliably generate high-voltage DC from a low DC power supply is needed. This paper discusses the design and implementation of a high-voltage DC generator with a low-voltage DC power supply input. The generator employs a push-pull inverter to transform the DC 12 V voltage into AC 400 V at a frequency of 20 kHz. A Cockcroft-Walton circuit, comprising a positive and a negative Cockcroft-Walton circuit, then steps up this voltage. The Arduino Nano microcontroller uses pulse width modulation (PWM) signals to control the system. This research aims to provide a reliable and economical high-voltage DC voltage generation system for various applications. We discuss the design process and hardware implementation in detail. We set the target output voltage of this hardware at 10 kV DC. MATLAB/Simulink simulation software verifies the performance of the proposed high-voltage generator, and hardware implementation validates its effectiveness. The proposed high-voltage DC generator's hardware tests successfully produced an output voltage of 14.12 kV DC.

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1. INTRODUCTION

High voltage has played an important role in the advancement of electrical technology. Commonly recognized are three types of high-voltage sources: alternating current (AC) high voltage, direct current (DC) high voltage, and impulse high voltage [1]. DC high voltage finds extensive use in testing and research endeavors due to the demand for robust DC power [2]-[4]. Presently, transformers are the primary means of implementing high-voltage DC [5]. DC high voltage is used in many areas of electrical engineering and applied physics, such as electron microscopes, X-rays, electrostatic precipitators, particle accelerators in nuclear physics, dielectric testing, and more [6], [7]. Despite advancements, existing high-voltage generation equipment encounters challenges concerning size, operation, cost, and efficiency. Notably, DC high-voltage generators, typically operating at a 220 V input voltage with a low frequency of 50 Hz [8], garner significant attention [9]. To get high-voltage direct current or HVDC output from lower input voltages, different techniques are used, such as step-up transformers [10], voltage doublers [11], [12], multiplier circuits [13], charge pump circuits [14], [15], switched-capacitor circuits [16]-[18], and boost or step-up converters [19]. A high voltage conversion ratio is becoming more and more important in many industrial and lab research settings. For example, it can be used as the first stage for batteries or photovoltaic sources [20], and it makes DC backup systems, uninterruptible power supply (UPS) devices, step-down inverters, and other things possible.

Conventional voltage multipliers often face challenges such as suboptimal efficiency and design complexity. Cockcroft-Walton is a popular choice among DC high-voltage applications [21]. The Cockcroft-Walton voltage multiplier is a cascaded voltage multiplier that is commonly used in a variety of applications because its components consist only of diodes and capacitors. This voltage multiplier converts the AC voltage at the input side into a higher DC voltage [22]. An inverter is required to convert the DC voltage into an AC voltage, which then undergoes multiplication, in order to increase the small input DC power voltage. Different applications can design inverters to operate with various voltage ranges and topologies [23].

A push-pull inverter is a type of DC-AC inverter technology that uses a transformer to convert voltage from a DC power source. The push-pull inverter's characteristic feature is the use of two switches to change the voltage on the transformer's supply side, causing it to function like it does in AC power and produce voltage on its output side [24]. Push-pull inverters are known for their advantages in producing sinusoidal waveform outputs and their ability to operate at high frequencies [25]. On the other hand, the Cockcroft-Walton circuit is a type of voltage multiplier that can increase voltage gradually using capacitors and diodes [26], [27]. We expect the integration of these two elements to yield a more efficient and reliable voltage multiplier system. There have been many developments in solving the problems of high-voltage generation using the Cockcroft-Walton. Some researchers have developed a high-voltage DC-DC converter with Cockcroft-Walton [5]. In [28], a combination of Cockcroft-Walton and Dickson charge pumps was used. A combination of the Cockcroft-Walton and Marx generators have been present in [29].

In this paper, we discuss the design of high-voltage DC generator hardware with a low DC power supply input. This research designs a high-voltage DC generator that not only has a low input voltage but is also portable, efficient, easy to make, and economically affordable. This hardware design uses DC input voltage from batteries connected to a push-pull inverter. The push-pull inverter converts DC voltage into AC voltage and integrates with the Cockcroft-Walton circuit to boost voltage at each stage through the use of capacitors and diodes. We design a high-voltage DC generator that integrates a push-pull inverter, a Cockcroft-Walton circuit, and the Arduino Nano microcontroller's pulse width modulation (PWM) signals. We aim to produce a more efficient, better, affordable, and reliable voltage multiplier system solution to meet high voltage needs in various application contexts. This paper also demonstrates the implementation of the proposed high-voltage DC generator hardware. MATLAB/Simulink simulations verify the effectiveness of this circuit. We discuss in detail the design and manufacturing process of the high-voltage DC generator hardware. We present hardware results to further validate the performance of the proposed combination of a push-pull inverter with a Cockcroft-Walton voltage multiplier circuit.

2. THE PROPOSED HIGH DC GENERATION SYSTEM

Figure 1 shows the block diagram of high-voltage DC-generating proposed system. The schematic block diagram illustrates the designed high-voltage DC generation system, which integrates a push-pull inverter with a Cockcroft-Walton voltage multiplier. The designed system consists of a DC voltage source and a power circuit that includes a push-pull inverter, transformer, and Cockcroft-Walton voltage multiplier circuit. The controller circuit comprises an Arduino microcontroller that regulates the metal-oxide-semiconductor field-effect transistor (MOSFETs).

A 12 V DC voltage serves as the primary power source, which enters the push-pull inverter circuit and is converted into an alternating current (AC) voltage source. This low-rated DC voltage undergoes processing in the inverter using a step-up transformer, converting it into a high-voltage of approximately 400 V. This voltage is then utilized as the input for the Cockcroft-Walton voltage multiplier circuit. As a control circuit, an Arduino Nano microcontroller is utilized to generate PWM signals. A fixed switching frequency of 20 kHz with a duty cycle of 47 % is established. The PWM signal is transmitted to the gate driver and MOSFET.

2.1. Push-pull inverter

A push-pull inverter is a type of electronic circuit used to convert direct current (DC) power into alternating current (AC) power. It operates by alternately switching two transistors (usually bipolar junction transistors or MOSFETs) on and off in a push-pull fashion. The key principle behind the push-pull inverter is its ability to generate AC output by driving the load alternately in opposite directions. This is achieved by dividing the input DC voltage into two halves and applying them to the primary winding of a center-tapped transformer.

Figure 2 shows a push-pull inverter circuit. During the first half of the cycle, transistor S1 conduct while transistor S2 is cut off. This allows current to flow through one half of the primary winding, inducing a magnetic field in the transformer core. As a result, a positive voltage is induced in the secondary winding, creating the positive half-cycle of the AC output. During the second half of the cycle, the role of the transistors reverse. Transistor S1, which previously conducted electricity, is now cut-off, while transistor S2, which was previously cut-off, now turn on. This causes current to flow through the other half of the primary winding, inducing a magnetic field with opposite polarity in the transformer core. Consequently, a negative voltage is induced in the secondary winding, producing the negative half-cycle of the AC output. One of the main advantages of the push-pull inverter is its efficiency, as it utilizes both halves of the input DC voltage waveform to generate the AC output. Additionally, it offers good voltage regulation and can provide relatively high output power.

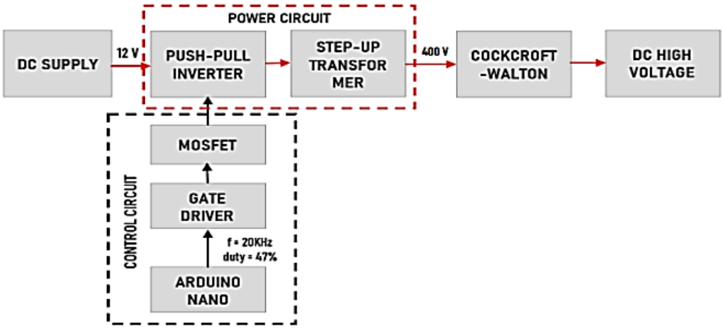


Figure 1. Block diagram of high-voltage DC generating proposed system

2.2. Cockcroft-Walton

The Cockcroft-Walton voltage multiplier, also known as the Greinacher multiplier and Villard cascade, is a switched-capacitor circuit that generates high-voltage from low input voltage. This circuit consists of multiple half-wave voltage multiplier units arranged in series. The successive voltage multipliers form a long chain of diodes and coupling capacitors. A part from the Marx generator, Cockcroft-Walton stands as the most favored solid-state high-voltage generator topology [30], [31].

The Cockcroft-Walton voltage multiplier is widely utilized in high DC voltage applications due to its advantages such as high-voltage amplification, reduced voltage stress on diodes and capacitors, compact circuitry, and cost-effectiveness. The Cockcroft-Walton voltage multiplier circuit is shown in Figure 3. The circuit involves several ladder stages each consisting of two capacitors and two diodes. This conventional configuration has proven to be effective as a DC voltage multiplier.

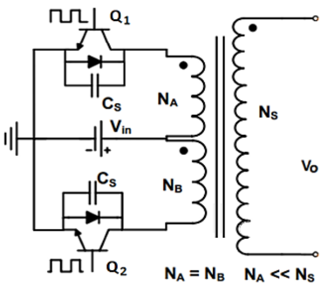


Figure 2. Push-pull inverter circuit

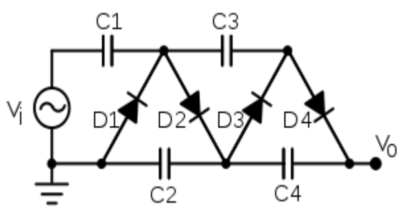


Figure 3. Cockcroft-Walton voltage multiplier circuit

3. METHOD

3.1. Design of push-pull inverter

Figure 4 illustrates the schematic model of push-pull inverter hardware circuit, comprised of three sections. The first section contains a power circuit constructed with two IRF3205 MOSFET components and a CT transformer. The second section consists of a gate driver circuit designed with the IC IR2110. The third section is the control circuit, utilizing the Arduino Nano microcontroller as the primary controller. This microcontroller, an 8-bit AVR microcontroller, offers high quality and low power consumption, capable of reaching up to 16 MIPS throughput at 16 MHz. It includes two 8-bit Timer/Counters, one 16-bit Timer/Counter with a separate prescaler, 6-channel PWM, and 8-channel ADC with 10-bit resolution. The circuit is operated with an input voltage of 12 V DC, which is connected to the primary winding of the transformer at the center tap terminal. The primary side of the transformer consists of two windings, 5 turns each, connected to the center tap. On the secondary side, the transformer has a single winding consisting of a total of 167 turns. As a result, the transformer has a gain of 33.4 times, allowing an approximate output voltage of about 400.8 V at the output terminal of the secondary winding, with an input voltage of 12 V. In order to calculate the output voltage value of the transformer, it is calculated using the (1), where is N_s the secondary winding, N_A is the primary winding.

$$Vo = \frac{N_S}{N_A} \times V_{DC} \quad (1)$$

To generate pulse width modulation (PWM) signals, an Arduino Nano is utilized. It is programmed to produce PWM signals with a duty cycle of approximately 47 % and 20 kHz of frequency. These PWM signals are then directed to the Gate Driver circuit for amplification, facilitating the driving of the MOSFETs.

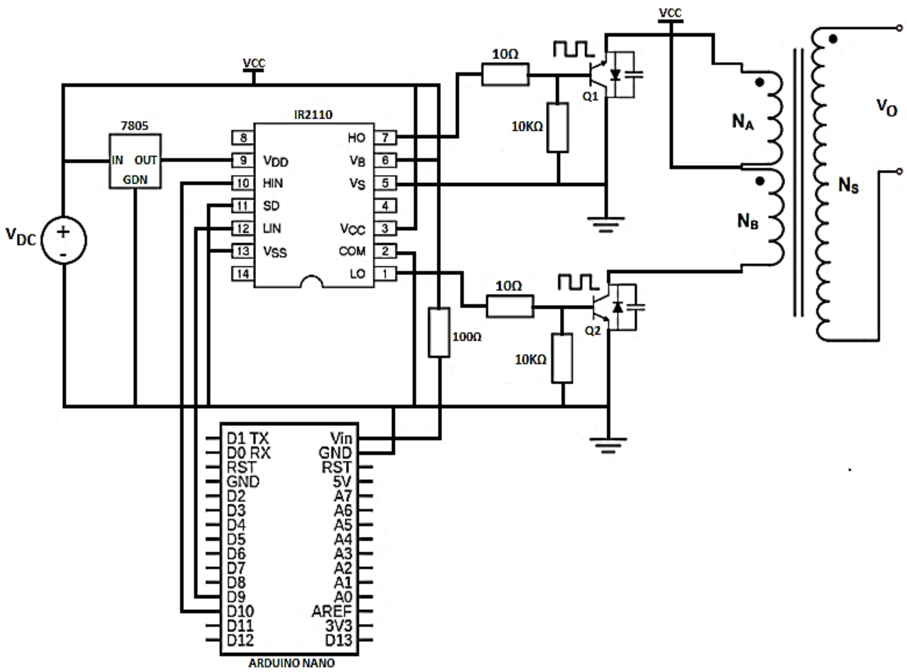


Figure 4. Schematic model of push-pull inverter hardware circuit

3.2. Design of Cockcroft-Walton

The designed Cockcroft-Walton circuit integrates two 20-level Cockcroft-Walton circuits with different outputs: one generates a positive output while the other generates a negative output. The Cockcroft-Walton circuit receives input voltage supply from a push-pull inverter. The Cockcroft-Walton hardware is assembled using FR207 diodes, with a total of 20 diodes employed. This particular type of diode is chosen due to the high-frequency AC output voltage from the inverter, which operates at a frequency of 20 kHz. The FR207 is a fast recovery 1000 V, 2 A Schottky rectifier diode with a maximum frequency capability of 25 kHz. The circuit utilizes capacitors of the 10μ F 3 kV type, with a total of 20 capacitors used. The circuit design utilizes 20 diodes and 20 capacitors for both the positive and negative circuits. By combining the positive and negative circuits of the Cockcroft-Walton will result in a 40 times voltage gain. Figure 5 depict the schematic model of Cockcroft-Walton hardware circuit.

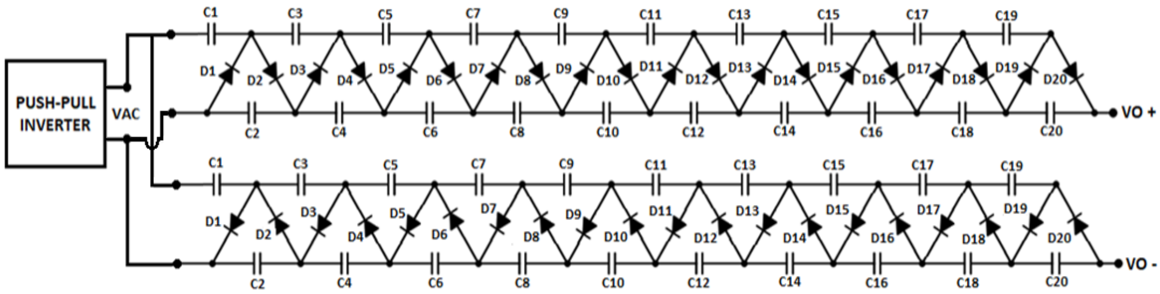


Figure 5. Schematic model of Cockcroft-Walton hardware circuit

4. RESULTS AND DISCUSSION
4.1. Simulation results

A comprehensive simulation using MATLAB/Simulink was conducted to evaluate the proposed high-voltage DC generator. The results were compared with those of a conventional Cockcroft-Walton circuit, which was supplied with an AC input voltage of 400.8 V RMS at 20 kHz. The voltage is measured at the output terminals of both the positive and negative circuits of the Cockcroft-Walton circuit, as well as the combined voltage of the two circuits.

Figure 6 illustrates the simulation model of the Cockcroft-Walton circuit with an AC input voltage. The output measurement voltage and the output voltage waveform of the Cockcroft-Walton simulation circuit with an AC input are shown in Figures 7(a) and 7(b). There are three waveforms displayed on one scope. The green waveform represents the output voltage value for the Cockcroft-Walton circuit with the positive circuit with a voltage of 7.09 kV, the blue waveform represents the output voltage value for the Cockcroft-Walton circuit with the negative circuit with a voltage of -7.06 kV, and the red waveform represents the sum of the output voltage values from the positive and negative circuits with a voltage of 14.15 kV.

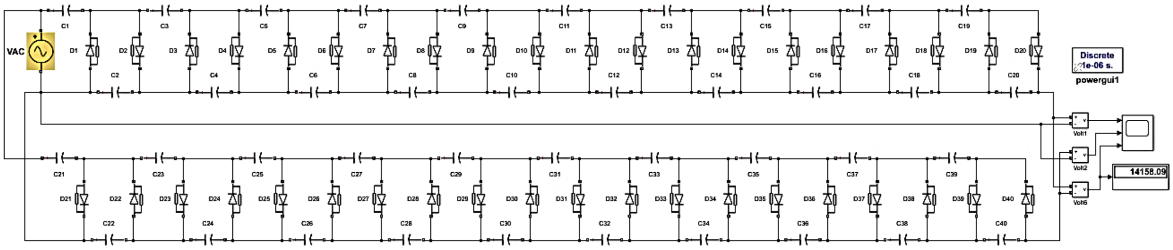
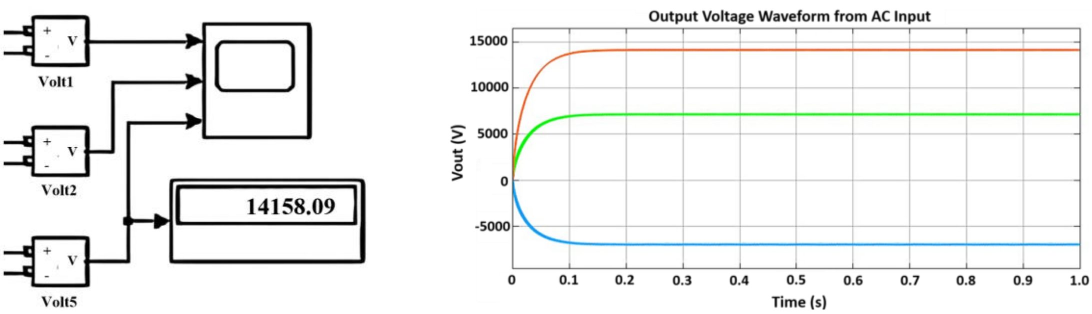


Figure 6. Simulation model of Cockcroft-Walton circuit with AC voltage input



(a) (b)

Figure 7. Output voltage of Cockcroft-Walton circuit simulation with AC voltage input in (a) measurement and (b) waveform

The performance of the proposed high-voltage DC generator circuit is evaluated using the model shown in Figure 8. The circuit is powered by a 12 V DC input. The push-pull inverter is designed to generate a square wave AC voltage with a peak of 400.8 V at a frequency of 20 kHz. The Cockcroft-Walton section includes two separate circuits that produce both positive and negative voltages.

Figure 9 (a) and (b) illustrate the output measurement voltage and the voltage waveform of the Cockcroft-Walton simulation circuit using the proposed high-voltage DC generator as the input. The green waveform indicates the output voltage of the positive section of the Cockcroft-Walton circuit, which is 7.34 kV. The blue waveform shows the output voltage of the negative section, measuring -7.11 kV. The red waveform represents the combined output voltage of both the positive and negative sections in total 14.45 kV. The output voltage of the Cockcroft-Walton circuit, powered by the AC voltage input and the push-pull inverter input, is measured at various gain levels. The results of these measurements, along with the corresponding calculations, are presented in Table 1. The output voltage of the Cockcroft-Walton voltage multiplier circuit is calculated as (2):

$$V_{out} = nV_{peak} - nV_{drop} \quad (2)$$

Where n is the number of stages, V_{peak} is the peak input voltage, and V_{drop} is the drop voltage of the diode.

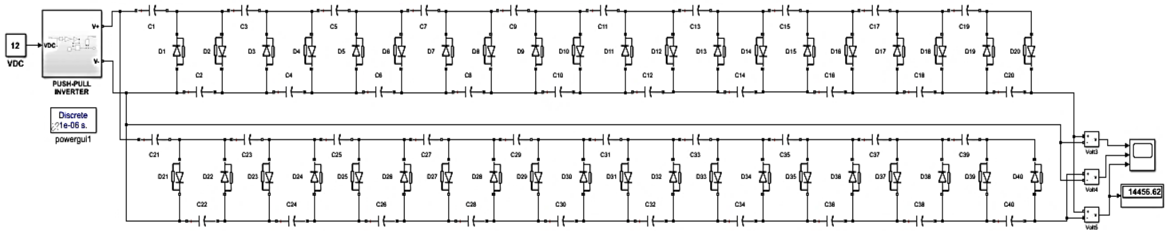
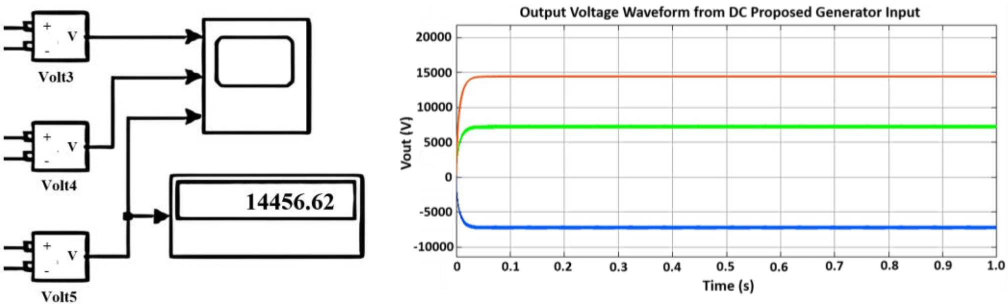


Figure 8. Simulation model of the proposed high-voltage DC generator circuit



(a) (b)

Figure 9. Output voltage of Cockcroft-Walton circuit simulation with the proposed high-voltage DC generator in (a) measurement and (b) waveform

Table 1. The output voltage of the Cockcroft-Walton circuit simulation results

Gain	CW with AC supply (V)	CW with push-pull inverter (V)	Calculation (V)
4	1.529	1.858	1.593
8	3.014	3.928	3.186
12	4.465	5.921	4.778
16	5.888	7.703	6.371
20	7.292	9.242	7.964
24	8.679	10.556	9.557
28	10.054	11.686	11.150
32	11.425	12.684	12.742
36	12.791	13.594	14.335
40	14.158	14.456	15.928

4.2. Hardware results

To validate the effectiveness of the proposed high-voltage DC generator system, a hardware prototype has been developed. Figure 10 shows a complete prototype of the DC high-voltage generator, which integrates a push-pull inverter and a Cockcroft-Walton circuit. At the output of the Cockcroft-Walton circuit, a voltage divider is installed, comprising 10 of 2.2 MΩ resistors connected in series and 2 of 47 kΩ resistors connected in parallel. This voltage divider circuit has an R1 value of 22 MΩ and an R2 value of 23 kΩ. The function of this voltage divider is to convert the high-voltage output of the Cockcroft-Walton circuit into a lower DC voltage, making it measurable with a multimeter. The voltage attenuation achieved is 1/1000. The output of the voltage divider is calculated using the (3):

$$V_{divider} = \frac{R2}{R1+R2} \times Vo_{C-W} \tag{3}$$

Where $R1$ is 22 MΩ, $R2$ is 23 kΩ, and Vo_{C-W} is the output voltage from the Cockcroft-Walton circuit.

Figure 10 shows the results of testing the constructed high-voltage DC generator hardware. The output voltage shown by the multimeter is 1/1000 of the actual output voltage, indicating that the high-voltage DC generator output voltage is 14.12 kV with a DC input voltage of 12 V and a current of 0.65 A. The comparison of the simulation results, hardware measurement, and calculated output voltage for the proposed high-voltage DC generator is shown in Table 2.

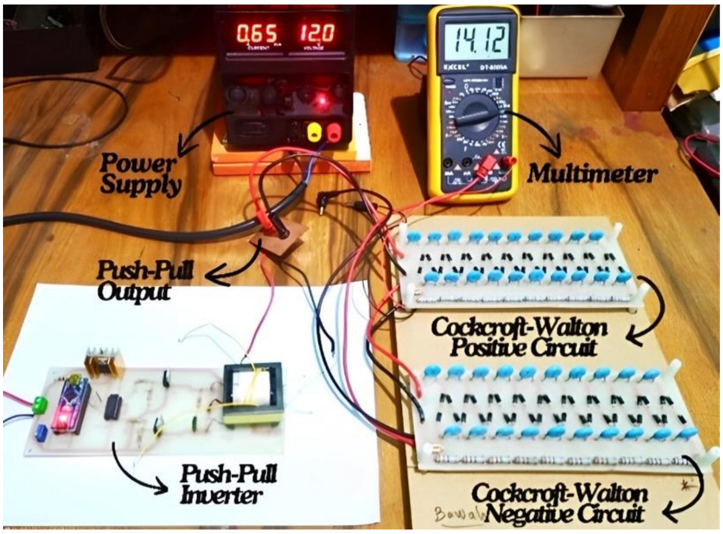


Figure 10. The high-voltage DC generator hardware

Table 2. Comparison of simulation, hardware, and calculated output voltage for the proposed high-voltage DC generator

Gain	Simulation result (V)	Hardware measurement (V)	Calculation (V)
4	1.858	2.210	1.593
8	3.928	4.140	3.186
12	5.921	5.930	4.778
16	7.703	7.570	6.371
20	9.242	9.050	7.964
24	10.556	10.390	9.557
28	11.686	11.570	11.150
32	12.684	12.600	12.742
36	13.594	13.460	14.335
40	14.456	14.120	15.928

5. CONCLUSION

This paper has presented the design and execution of hardware for a DC high-voltage generator, which integrates a push-pull inverter with a Cockcroft-Walton circuit. The control circuit was constructed utilizing an Arduino Nano, which is energized by an ATMega328P microcontroller. The DC high voltage generating system was evaluated by conducting tests at an input voltage of 12 V. The system employed a Cockcroft-Walton circuit that was divided into two sections: a positive Cockcroft-Walton circuit and a negative Cockcroft-Walton circuit. Each section consisted of 20 levels. The hardware experiment yielded conclusive results, demonstrating the successful generation of an output voltage of 14.12 kilovolts. The results demonstrate the system's potential for reliable and economical high-voltage DC generation, highlighting its applicability across various industrial and scientific fields. The use of readily available components and a straightforward control mechanism ensures cost-effectiveness and ease of replication, with future work aimed at optimizing efficiency and exploring broader applications.

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