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Low-Cost High-Voltage Generator For Electrostatic Charging Of Pesticide Droplets And Laboratory Uses

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Keywords: Cockcroft-Walton voltage multiplier, high-voltage generators, agricultural pesticide electrostatic spraying

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ABSTRACT

The study aimed to develop a low-cost high voltage circuit for laboratory uses and compare its performance with a commercial one in the electrostatic charging of spray droplets. Because the Cockcroft-Walton voltage multiplier is considered the simplest and cheapest, it was used to design this circuit. Two dc–ac inverters (50 Hz and 20 kHz) and capacitors with two capacities (10 and 470 nF) were used to develop three different circuits. The circuits were loaded with several electric currents to study the effect of the capacitor capacity and frequency value on the output voltage, output voltage ripple, and response time of the circuit. According to the results, loading the first circuit developed with a low-frequency inverter (50 Hz) and high-capacity capacitors (470 nF) by an electric current, even including the microampere, seriously affected the output voltage and the voltage ripple. Also, the second circuit developed using a high-frequency inverter (20 kHz) and low-capacity capacitors (10 nF) was subject to voltage drop at the lowest load currents. However, the third circuit developed using high-capacity capacitors (470 nF) with the high-frequency inverter (20 kHz) significantly improved the output and ripple voltage at different high load currents. In addition, they reduced the response time from 15 s (in circuit 1 and 2) to 40 ms. The developed high-voltage circuit (3) can provide the same efficiency in water droplet charging as a commercial circuit. Moreover, it was enhanced to provide high voltages values until 15 kV.

Pestisit Damlacıklarının Elektrostatik Yüklenmesi ve Laboratuvar Kullanımları İçin Düşük Maliyetli Yüksek Voltaj Jeneratörü

ÖZ

Çalışma, laboratuvar kullanımları için düşük maliyetli bir yüksek voltaj devresi geliştirmeyi ve sprey damlacıklarının elektrostatik yüklenmesinde performansını ticari bir devre ile karşılaştırmayı amaçlamaktadır. Cockcroft-Walton voltaj çarpanı en basit ve ucuz olarak kabul edildiğinden, bu devreyi tasarlamak için kullanılmıştır. İki dc-ac çevirici (50 Hz and 20 kHz) ve iki kapasiteli kapasitörler (10 and 470 nF) kullanılarak üç farklı devre geliştirilmiştir. Kondansatör kapasitesinin ve voltaj frekansı değerinin üç devrenin çıkış voltajı, çıkış voltajı dalgalanması ve tepki süresi üzerindeki etkisini incelemek için devreye farklı elektrik akımı değerleri yüklenmiştir. Elde edilen sonuçlara göre, düşük frekanslı invertör (50 Hz) ve yüksek kapasiteli kondansatörler (470 nF) ile geliştirilen birinci devrenin mikroamper içinde bile elektrik akımla yüklenmesi çıkış gerilimini ve gerilim dalgalanmasını ciddi şekilde etkilemiştir. Ayrıca yüksek frekanslı invertör (20 kHz) ve düşük kapasiteli kapasitörler (10 nF) kullanılarak geliştirilen ikinci devre, en düşük yük akımlarında voltaj düşüşüne maruz kalmıştır. Ancak, (20 kHz) yüksek frekanslı invertör ve (470 nF) kapasitörler kullanarak geliştirilen üçüncü devre, farklı yük akımlarında çıkış ve dalgalanma voltajını önemli ölçüde iyileştirmiştir. Ayrıca tepki süresini 15 saniye (1. ve 2. devrelerde) 40 milisaniyeye düşürmüştür. Geliştirilen yüksek gerilim devresi (3), su damlacıkları yüklemesinde ticari devre ile aynı verimi sağlayabilmektedir. Üstelik, geliştirilen devre, 15 kV'a kadar yüksek voltaj değeri sağlayacak şekilde iyileştirilmiştir.

Anahtar Kelimeler: Cockcroft-Walton voltaj çarpanı, Yüksek voltaj jeneratörleri, Tarımsal pestisit elektrostatik püskürtme

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1. Introduction

Generally, commercial high-voltage devices are employed to test different equipment such as high-voltage cables, transformers, etc. In addition, dc high-voltage generators can be used in applied physics, industrial applications, electromedical equipment, and communications electronics [1]. The high-voltage multiplier circuit developed by Cockcroft-Walton (C-W) is considered to be the simplest and cheapest circuit for high-voltage generation. This circuit was improved in 1932 by Cockcroft-Walton [2] over the circuit developed by Greinacher [3] for the generation of a high dc voltage to power their particle accelerator [4], [5]. The working principle of this voltage multiplier circuit depends on stepping up the low input ac voltage by several stages (each stage includes two diodes and capacitors) to acquire a final high output dc voltage. Figure 1 shows the working method of the Cockcroft and Walton voltage multiplier for only two stages. In these types of circuits, the first side of the ac power supply is at zero potential (grounded), while the other side varies between plus and minus voltage ±Vp. Let's assume that the input voltage Vp is equal to ±220 V (The dashed line indicates the direction of current flow). (1) At the negative peak -220 V, the capacitor C1 is charged through diode D1 with Vp=220 V. (2) In the next positive cycle, the upper side of the power supply becomes +220 V, and this voltage adds to the voltage in C1. Therefore, capacitor C2 is charged through D2 to 2Vp=440. (3) When the power supply source is at a -220 negative peak again, the Capacitor C1 is charged as in step 1. Also, capacitor C3 is charged through D3 to 440V. (4) The power supply is at a +220 positive peak, and the capacitor C4 is charged to 440 V.

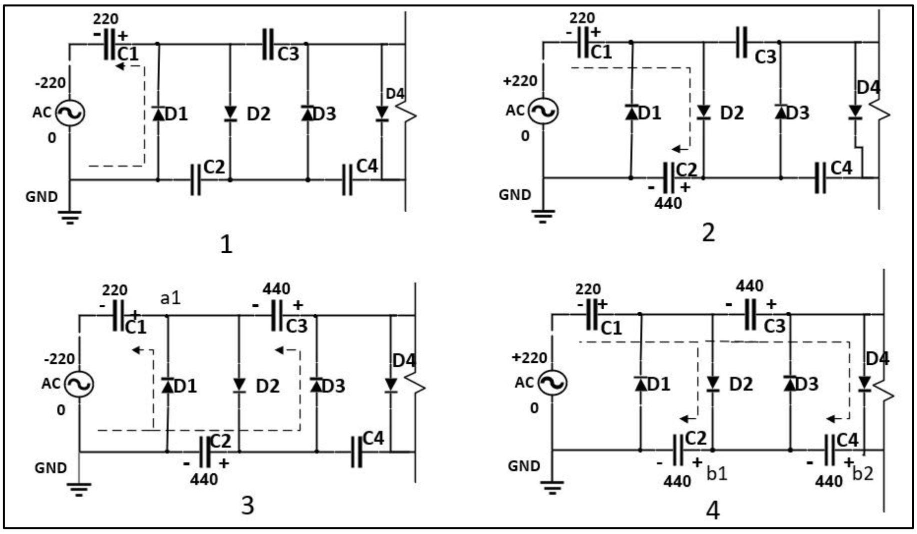


Figure 1. 2 stages Cockcroft-Walton voltage multiplier circuit

The previous explanation was for two stages of the Cockcroft-Walton circuit. Still, when this circuit has n stages as shown in Figure 2, after a certain period, the capacitors ($C'1$, $C'2$, $C'3$, …., Cn) are charged in the first half cycle by upward diodes ($D'1$, $D'2$, $D'3$, …., D'n, respectively) and in the next half-cycle, the smoothening column capacitors ($C1$, $C2$, $C3$, …., Cn) are charged by downward didoes ($D1$, $D2$, $D3$, …., Dn). Theoretically, the maximum value of the high output dc voltage of the n stage C-W voltage multiplier equals 2n times the quantity of the ac input voltage under the no-load condition [6].

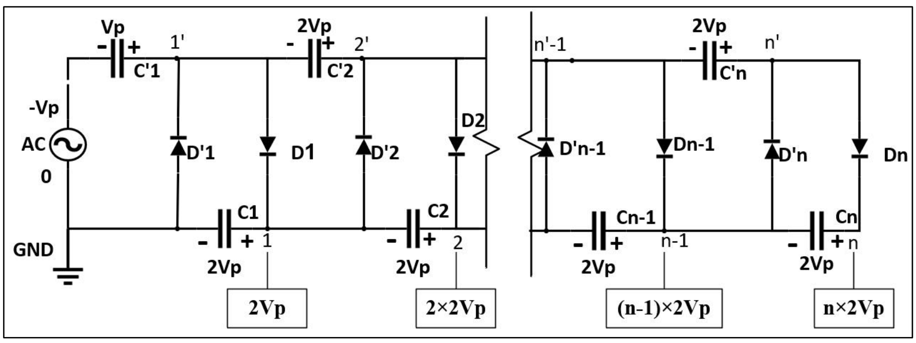


Figure 2. n stage C-W voltage multiplier circuit

Many studies have been conducted on developing and testing different voltage multipliers depending on the Cockcroft-Walton circuit. Al-Mamoori et al. (2019) simulated a voltage multiplier circuit using the PSpice software to simulate the electric field generated near the earth before starting the lightning strike [7]. An input ac voltage source that has 50 Hz and 240Vp-p was used for the simulation process. In addition, they used capacitors with 0.1 μF to construct the voltage multiplier circuit. The different values of the high voltages were obtained by connecting the loading wire after each stage sequentially. Abidin et al. (2018) used the Cockcroft-Walton voltage multiplier as a converter circuit to optimize the output voltage value of the energy harvesting technique from the raindrops [8]. The circular piezoelectric (KSPG-10) that has a resonant frequency (1200 kHz) in the boundary of the frequency of raindrops and a maximum input voltage of 30 V peak to peak was used as input ac source for the voltage multiplier circuit. The study investigated the effect of a wide range of input ac voltage frequency on the circuit's performance since the frequency of rain ranges from less than 500 Hz to 30 kHz. Proteus software was used to simulate and investigate the optimum output voltage and current. Study results showed that the output voltage and current increased by increasing the input frequency. Dwivedi and Daigvane (2010) designed a C-W voltage multiplier circuit using 0.22 μF capacitors to test high-voltage cables [5]. They used a high-voltage transformer with a 50 Hz frequency and single-phase sinusoidal waveform to feed the circuit by the ac input voltage of 5 kV and current of 50 mA. The circuit could provide a 60 kV output voltage. Spencer et al. (2001) developed a small high-voltage board that depends on the Cockcroft-Walton circuit with nine stages [9]. This board was used to power two photomultipliers[1]. The board was fed with 5–6 V DC converted to a 120 V ac sine-wave and 780kHz frequency to feed the voltage multiplier circuit. Malviya and Bhardwaj (2016) conducted a simulation study on the effect of high and low frequencies of the ac input voltage on the H.V multiplier circuit behavior, especially on the multiplier response time, using PSpice simulations [10]. The study investigated the response time for several voltage multiplier circuits that have two, three, four, or five stages. The simulation results showed that the output voltage becomes stable and reaches its final value more quickly by using a high-frequency input voltage. In addition, increasing the number of the circuit stages increase the response time for both used low and high frequencies. Unfortunately, the loading current of the C-W voltage multiplier circuit seriously affects the output voltage and voltage ripple. The ripple voltage is determined as the unwanted residual magnitude of the fluctuation in the dc output voltage at a specific output current [6]. Voltage ripples can have various negative effects on electric devices, such as heating and damaging electronic components and noise in audio circuits and television displays [8].

In all previous works, it was noted that no studies have practically investigated the effect of the load current on the output voltage of high-voltage multiplier circuits. Therefore, the study aimed to: (1) able the researchers' non-specialists in electronic engineering to develop a simple low-cost high-voltage circuit by using only some electronic elements, (2) investigate several parameters to reduce the voltage drop and ripple under the effect of different loading currents, and (3) compare the developed circuit with commercial one to determine it performance in electrostatic charging of water droplets. The article will be helpful for many postgraduate students to develop low-cost high voltage devices for different simple laboratory uses.

2. Material and Methods

2.1 Selection of C.W. circuit elements

The Cockcroft-Walton voltage multiplier circuit consists of several diodes and capacitors. These electronic elements must be chosen carefully to avoid damage since they are stressed with twice the input voltage (except for the first capacitor).

2.1.1 DC Power supply

It supplies the required dc voltage to the dc-ac inverter. The dc power supply used in the experiments can provide 0~30 V dc and 0~5 amp.

2.1.2 DC-AC inverter selection

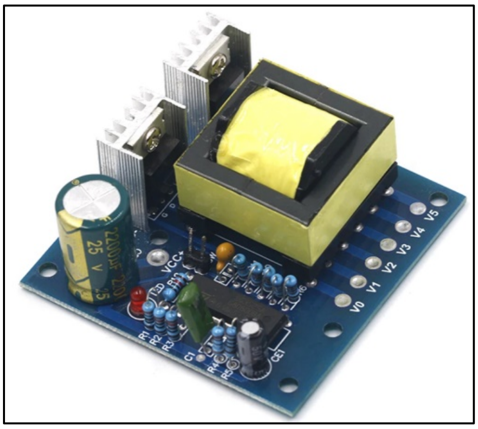
It plays two main roles: converting the direct current drawn from the previous dc power supply to the

[1] photomultiplier tubes (PMTs) are used extensively in the nuclear industry as a method of radiation detection.

alternating current required to operate the Cockcroft-Walton circuit. Raising the ac input voltage (feed ac voltage of the multiplier circuit) to a higher value to reduce stages' numbers of the voltage-multiplier circuit. In this study, two inverters, as shown in Figure 3, were used to feed the circuit separately to investigate the effect of the input ac voltage frequency on circuit efficiency.

- 12 V dc input and 220 V ac output voltage inverter with 50 Hz low-frequency and sine wave.
- 12 V dc input and 250 V ac output voltage inverter with 20 kHz high-frequency and square wave.

50 Hz dc-ac inverter with a sine wave.



20 kHz dc-ac inverter with a square wave.

Figure 3: The DC-AC inverters used in the study

2.1.3 Capacitor and diode selection

The voltage applied to each capacitor (except C'1) and the diode in this circuit was approximately 615 V. Therefore, high-voltage polyester capacitors with specifications of 630 V, and 470 nF, and diodes with specifications of 1N4007 and 1000 V were chosen to build the high voltage multiplier.

2.2 The effect of load currents on the output voltage and voltage ripple

The effect of the load current on the output voltage value and peak-to-peak ripple 2δV were discussed in many studies [1], [4], [11], [12]. The output voltage without applying any load current to the circuit is given by Equation (1).

$$V_T = 2nVp \quad (1)$$

n: number of stages.
Vp: the peak value of input voltage.

The value of the voltage ripple 2δV in the C.W voltage multiplier circuit is given by Equation 2:

$$2\delta V = \frac{I}{fC}\frac{n(n+1)}{2} \quad (2)$$

f: frequency of ac input voltage.
I: load current.
C: capacitor capacity.

The voltage drop ΔVo determines the difference between the theoretical no-loaded output voltage and the loaded output voltage Vo. The mathematical value of the voltage drop was symbolized by ΔVmo and can be calculated using Equations 3. Thus, the mathematical loaded output voltage symbolized by Vmo can be calculated using Equation 4.

$$\Delta V_{mo} = \frac{I}{f.C}\left(\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}\right) \quad (3)$$

$$V_{mo} = 2nVp - \frac{I}{f.C}\left(\frac{2n^3}{3} + \frac{n^2}{2} - \frac{n}{6}\right) \quad (4)$$

Three circuits were developed to study the impact of the capacitor capacity and frequency level of the DC – AC inverters on circuit performance.

Circuit 1: 50 Hz dc-ac inverter and 470 nF capacitors.
Circuit 2: 20 kHz dc-ac inverter and 10 nF capacitors.
Circuit 3: 20 kHz dc-ac inverter and 470 nF capacitors.

As shown in Figure 4, many resistors connected in series were used to load the circuit with five different load currents and investigate the effect of these currents on the output voltage of the circuit. The load current value gradually was increased by decreasing the number of resistors connected to the circuit voltage output.

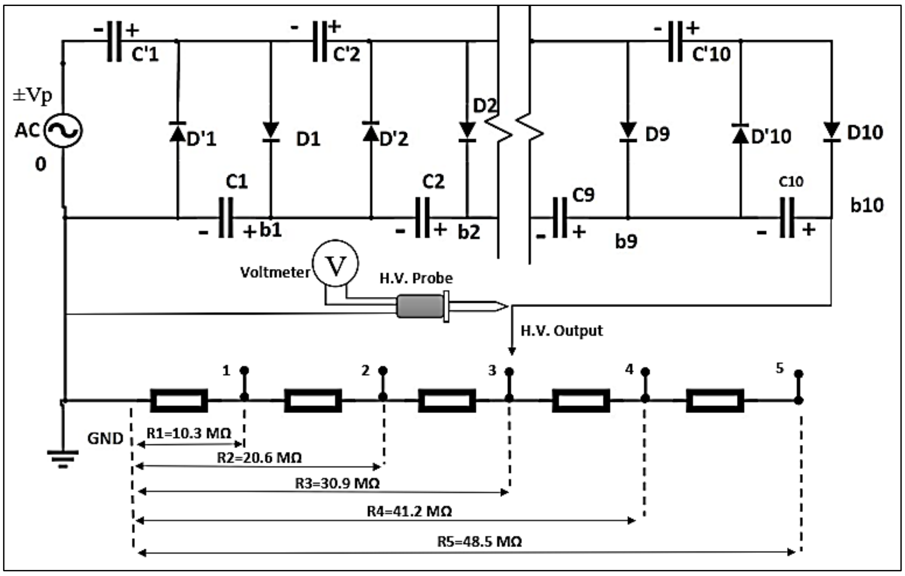


Figure 4. Diagram showing how to load the circuit with different load currents.

2.2.1 Mathematical output voltage Vmo

It was calculated mathematically using Equation (4). It is the maximum output voltage (without load current) minus the voltage drop.

2.2.2 Simulation output voltage Vso

Multisim 14.2 software was used to draw and simulate the circuit shown in Figure 4. All laboratory experiments were simulated using this software before any practical experiments to predict any damage that may occur in the used parts (Figure 5). In addition, the simulated output voltage was determined for comparison with the mathematical and actual values.

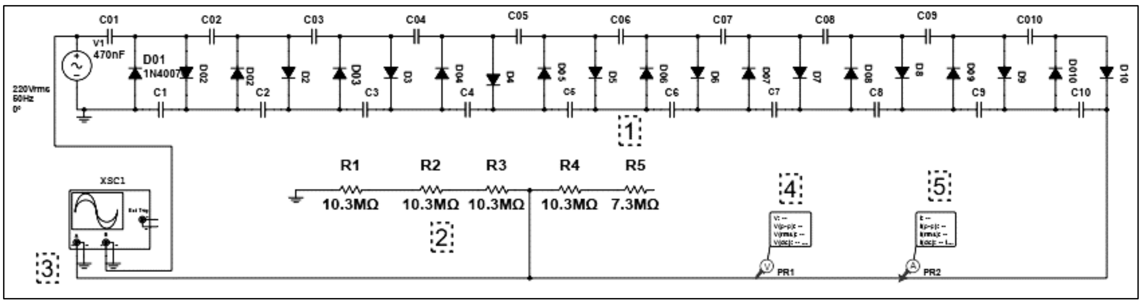


Figure 5. Scheme of the investigation of the circuit using the Multisim 14.2 software. 1-C-W circuit; 2- resistors; 3- oscilloscope; 4, 5- voltage and ampere probe.

2.2.3 Actual output voltage Vo

It was obtained from laboratory experiments according to the diagram in Figure 4 using the devices and tools shown in Figure 6. The Figure shows a voltage-multiplier circuit and several resistors connected in series. As mentioned previously, the circuit load current was gradually increased by decreasing the number of resistors connected to the circuit voltage output. At each value of load current, the actual output voltage is taken from the high-voltage probe.

2.3 The effect of capacitor value on the circuit efficiency

Capacitor selection depends on the frequency value of the ac input voltage. For 50-60 Hz applications, 1.0 to 250 μF capacitors are usually used. However, for higher-frequency applications, capacitors of 20 to 60 nF are used [5]–[7]. In this study, two capacitor capacities were used to study the effect of the capacitor values on the circuit efficiency. The first value was 470 nF and the second was approximately 10 nF.

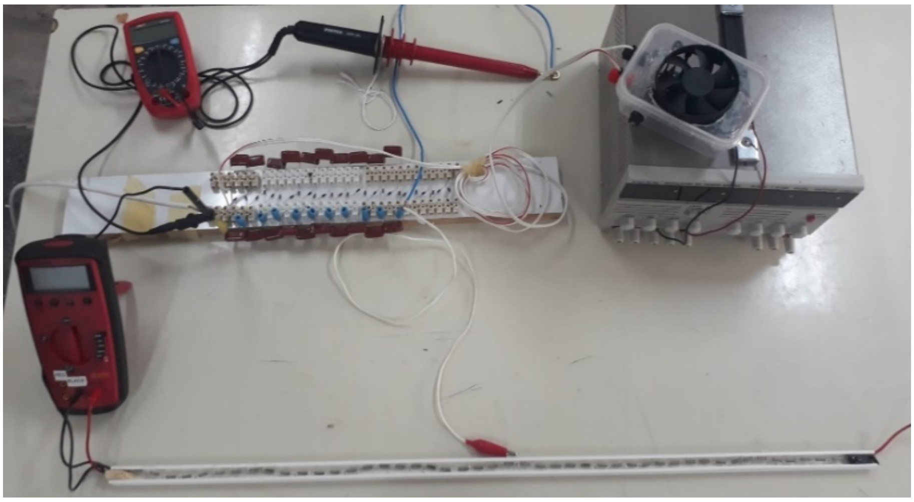


Figure 6. C-W voltage-multiplier circuit with a 20 kHz inverter and the tools used in testing its performance.

2.4 The effect of the input ac voltage frequency on the circuit performance

As shown in Figure (3), dc-ac inverter with 20 kHz and squire wave was used to study the effect of the frequency on the output voltage drop and on response time (the time required for the output voltage to reach the final high value).

2.5 The ability of the developed high-voltage circuit to charge spray droplets electrostatically.

The high-voltage circuit developed in this study using 50 Hz ac input voltage and 470 nF capacitors was used to electrostatically charge spray droplets for comparing its performance with a commercial device (VSM2016, Udescon Company, Turkey). All tools and equipment used to charge spray droplets and evaluate the charging efficiency (charge-to-mass ratio) were presented in a previous study conducted by Amaya and Bayat 2023 [13].

3. Results and Discussion

3.1 The effect of loading currents on the output voltage and voltage ripple

3.1.1. Circuit 1: 50 Hz input ac voltage and 470 nF capacitors

The actual Vo, simulated Vso, and mathematical Vmo values of the output voltage were compared with the theoretical output voltage. Figure 7 shows that using a low-frequency dc-ac inverter to operate the circuit can cause a critical drop in the output voltage. The values of the voltage drop in Vo, Vso, and Vmo were similar at all load currents. Increasing the loading current from 0 μA to only 0.150 mA was sufficient to decrease the output voltage Vo from its theoretical value of 6.15 kV to 1.61 kV. In addition, the mathematical value of the voltage ripple 2δv calculated by Equation (2) increased with increasing load current of the voltage multiplier circuit. It reached 366 V at a load current of 0.156 mA. This enormous voltage ripple can be observed in the simulation results in Figure 10-a.

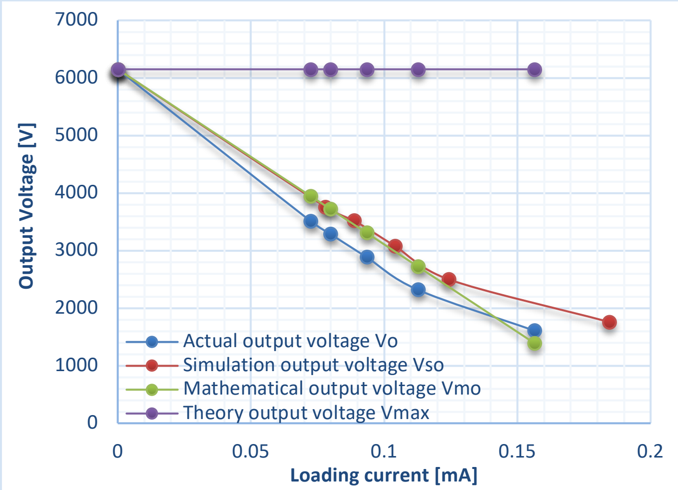


Figure 7. The effect of the loading current on the output voltage in circuit 1.

3.1.2. Circuit 2: 20 kHz input ac voltage and 10 nF capacitors

Here, the capacitors and low-frequency dc-ac inverter used in circuit 1 (470 nF and 50 Hz) were replaced by capacitors with capacities of 10 nF and a high-frequency inverter of 20 kHz to reduce output voltage dropping and residual electric-charge amount in capacitors after turning the circuit off. Figure 8 shows that when the circuit is loaded with increasing electric currents, the output voltage drop occurs only for the actual and simulation values. The voltage drop in the actual value Vo was larger than that in the simulation value Vso. It starts from Vo= 5.26 kV at zero load current until 2.67 kV at 0.27 mA load current. It is worth noting that this circuit has a voltage drop of ΔVo=0.9 kV, even without any load current. However, the actual voltage drop and ripple in this circuit were less than those in the previous circuit. Although the loading current of 0.15 mA caused a drop in the output voltage to approximately reach Vo=1.7 kV in the circuit (1), it reduced the output voltage to only Vo=3.45 kV in this circuit. The mathematical value of the voltage ripple 2δv calculated by Equation (2) reached 121 V at a load current of 0.442 mA. It can be observed in the simulation results in Figure 10-b. Although the high-frequency dc-ac inverter improved the output voltage value and reduce the ripple, the results indicate that using so low values of the capacitor capacities with this inverter causes primary voltage drop without any loading current. Thus they are inappropriate for developing the Cockcroft Walton voltage multiplier [5]–[7]. So, circuit (3) was developed and tested.

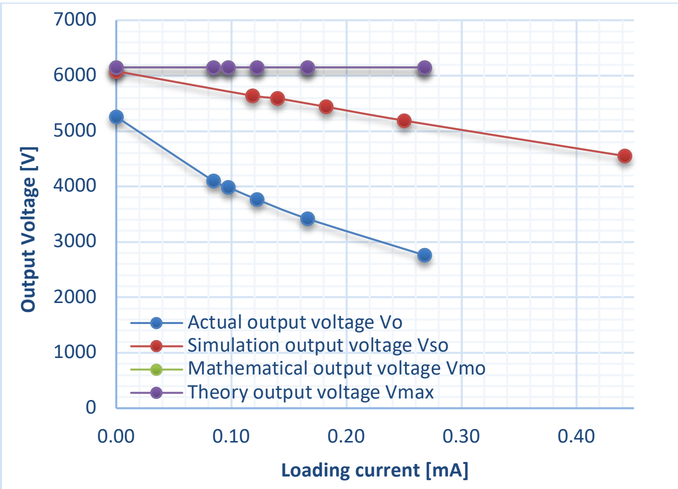


Figure 8. The effect of the loading current on the output voltage in circuit 2.

3.1.3. Circuit 3: 20 kHz input ac voltage and 470 nF capacitors

The capacitors with a capacity of 10 nF in the second circuit were replaced by 470 nF ones to improve the output voltage and voltage ripple at different load currents. It was noted in Figure 9 that all the output voltage values improved and are equal to the theoretical value Vmax except the actual value obtained in the laboratory experiments. It decreased from Vo=6.15 to 5.32 kV at a load current of 0.594 mA. Also, it is noted that at the first value of load current (0.126 mA), the output voltage Vo suddenly reduces by 10.9 %. Then, increasing the load current from 0.126 to 0.594 mA, decreases the output voltage Vo only by 2.9 %. Loading this circuit with an electric current of 0.150 mA could reduce the output voltage to only Vo=5.46 kV, while this loading current value reduced the output voltage to 1.7 and 3.45 kV in both the previous first and second circuits, respectively. It was noted that the mathematical value of the ripple 2δv calculated by the formula (2) was completely reduced by using 0.47 μF capacitors with the high-frequency dc-ac inverter to build the circuit. This low value of the voltage ripple can be seen in the simulation results in Figure 10-b-c.

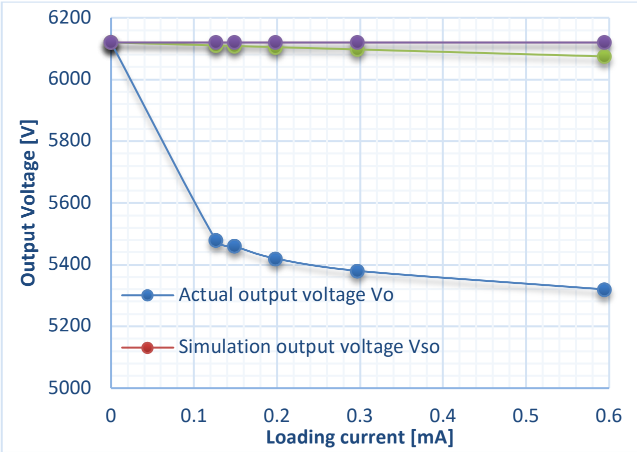
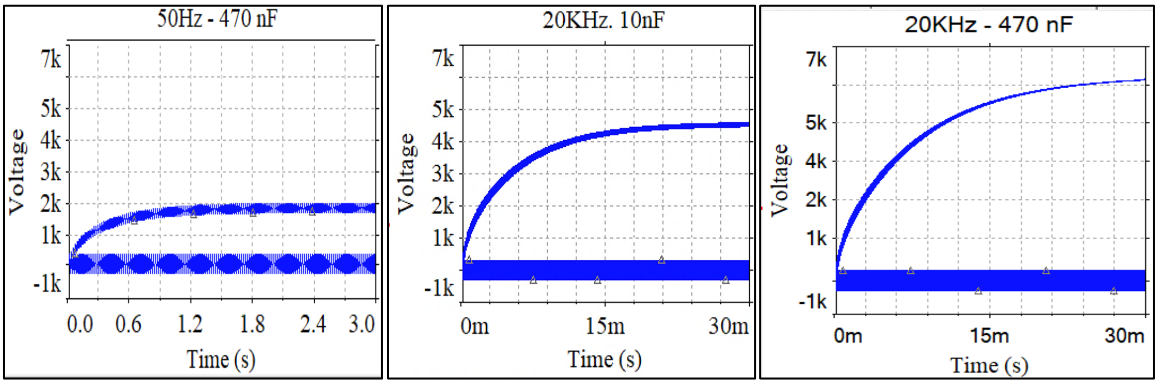


Figure 9. The effect of the loading current on the output voltage in circuit 3.



a: I= 0.184 mA b: I= 0.442 mA c: I= 0.5944 mA

Figure 10. The effect of the loading current on the output voltage and ripple using Multisim 14.2 software

3.2 Response time

Since the voltage multiplier circuit consists of more than one stage, the time required to reach the final maximum value Vmax of the output voltage increases with the number of circuit stages. To reduce this time, charging process of the first stage must be accelerated by replacing the low-frequency dc-ac inverter by a high-frequency one. The effect of replacing the low-frequency dc-ac inverter with another high-frequency one on the response time was simulated for the previous three circuits using Multisim software. According to the results shown in Figure 11, when the low-frequency inverter was used to feed the circuit, the response time required for the output voltage to reach the theoretical value equals 15 seconds. However, the high-frequency inverter has greatly decreased this response time to only 40 milliseconds. The decreasing of the response time was noted in both the second and third circuits with the same value. That indicated that capacitor capacity does not have any effect on response time.

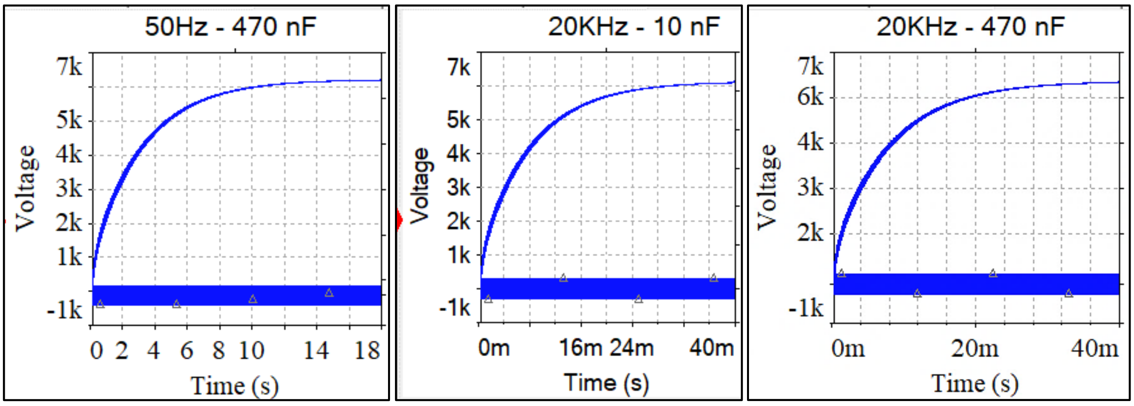


Figure 11. The effect of the low and high-frequency inverters on the response time using Multisim 14.2 software, I=0.

3.3 Comparing the developed voltage multiplier with the circuits in the previous literature studies

Table 1 compares the performance of the voltage multiplier circuits developed in this work with the high voltage devices working with the same principle presented in the previous literature studies.

Table 1. the comparison of the developed circuits in this study with that in the above Literature studies.

		Vmax	Vow I=0	Vo	%ΔVo	2δV I=0.5 mA	%2δ V	Response time
Amaya (2023)	Circuit (1) n=10, f=50 Hz, C=0.47 μF	6.15 kV	6.15 kV	1.76 kV at I=0.16 mA	71% (I=0.16 mA)	365	5.93 %	14 s
	Circuit (2) n=10, f=20 kHz, C=0.01 μF	6.15 kV	5.62 kV	2.76 kV at I=0.27 mA	8.62% (I=0 mA)	0.1	0.00 %	35 ms
	Circuit (3) n=10, f=20 kHz, C=0.47 μF	6.15 kV	6.15 kV	5.36 kV at I=0.5 mA	12.84% (I=0.5 mA)	2.9 V	0.06 %	40 ms
Mamoori et al. (2019) n=8, f=50 Hz, C=0.1 μF		4.92 kV	3.6 kV	⊗	26.53% (I=0)	⊗	⊗	⊗
Abidin et al. (2018) n=2, f=10-2000 Hz, C=47 μF		⊗	⊗	⊗	⊗	⊗	⊗	⊗
Dwivedi and Daigvane (2010) n=6, f=50 Hz, C=0.22 μF		60 kV	59.7	45.36 kV I=0.5 mA	24.4% (I=0.5)	1.91 kV	3.18 %	4.5 s
Spencer et al. (2001) n=9, f=780 kHz, C=0.22 μF		1000	950	⊗	⊗	⊗	⊗	⊗
Malviya and Bhardwaj (2016) n=5, f=25 kHz, C=0.1 μF		5 kV	5 kV	⊗	⊗	⊗	⊗	80 ms

Vmax: the theoretical output voltage value, Vow: output voltage value without loading, Vo: output voltage value with certain loading current, %ΔVo: the percentage of voltage drop, 2δV: voltage ripple, %2δV: the percentage of voltage ripple, n: circuit stages, f: frequency, C: capacitors' capacity, ⊗: no value in the study.

As mentioned previously, it was noted that the circuit (3) in this study can provide the best performance compared to the other circuits. The circuit in the study conducted by Mamoori et al. (2019) was developed to provide a theoretical output voltage of 4.92 kV. However, this circuit provided an input voltage of only 3.6 kV even without any load current. In other words, the actual output voltage was 26.5% less than the theoretical output voltage (4.92 kV) which is supposed to be provided by the circuit. Probably that happened because of the so low values of the selected capacities of the used capacitors, especially, circuit (2) developed in this study using low values of the capacitors' capacity had the same behavior. The output high voltage in the circuit (2) also dropped from the designed value of 6.15 kV to 5.62 kV without applying any loading current. But increasing the capacities by the replacement of the 0.01 μF capacitors in the circuit (2) with 0.47 μF capacitors (circuit 3) removed the problem of the voltage dropping without loading current. Thus, it was not any voltage drop in the circuit (3) without applying a loading current. The study by Abidin et al. (2018) did not apply any loading current on the developed circuit to investigate the voltage drop and ripple. Only it noted that the high values of the input ac voltage frequency improve the output voltage and current. Also, when the circuit developed by Dwivedi and Daigvane (2010) was compared with circuit (3) in this study, it was noted that the voltage drop in their device reaches about two times (24.4%) those in the circuit (3) (12.84%) at the same applied loading current (0.5 mA). Additionally, the voltage ripple in the study by Dwivedi and Daigvane (2010) was 3.18% of the theoretical output voltage, however, it was only 0.06% by the circuit (3) in this study. The response time in their study was so high (4.5 s) but it was only (40 ms) using circuit (3) in this work. The study by Spencer et al. (2001) developed a small Cockcroft-Walton circuit to power two photomultipliers. Nevertheless, it did not apply any loading current on the circuit, thus, it could not be compared its performance with the circuit present in this study. Malviya and Bhardwaj (2016) conducted a simulation study that investigated the effect of the input ac voltage frequency on the output voltage and the response time. The circuit provided better performance by using a high-frequency input ac voltage of 25 kHz. However, the study did not investigate the effect of the loading current. The response time in the circuit with 5 stages was 80 ms, whereas it was only 40 ms in the circuit (3) in this work that has 10 stages.

3.3 Droplet Charging efficiency by the developed C-W high voltage multiplier

After the third circuit was developed and tested, it was used to charge spray droplets of tap water electrostatically using the induction charging method. The aim was to investigate the performance of the developed circuit in some lab uses, such as droplet charging. In the induction charging method, when the high voltage electrode is placed close to an earthed conductive liquid jet leaving a hydraulic nozzle, opposite electric charges are induced from the earth to the surface of this liquid jet (Figure 12). The droplets breaking up from the charged coherent liquid carries a part of these charges, and thus become charged oppositely to the electrode [14]. The charge efficiency is usually evaluated by the Faraday cage, which measures the charge amount by milli Coulomb (mC) for the mass unit (kg) of spray droplets as ($mC.kg^{-1}$) [13].

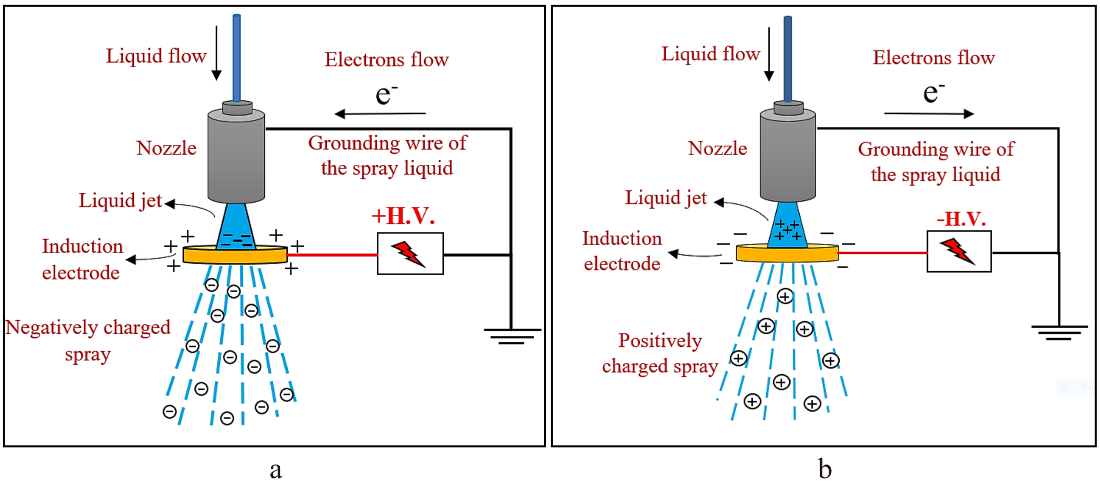


Figure 12. The working principle of the induction charging method with a positive high voltage (a) and a negative high voltage (b) applied to the induction electrode [15].

Figure 13 shows that the developed high voltage multiplier can provide the same charging efficiency required by the commercial device at all electrode voltage levels. The droplet charging efficiency increases from 0.01 $mC.kg^{-1}$ at 1 kV to about 0.5 $mC.kg^{-1}$ at 8 kV. This experiment indicates that the low-cost developed high voltage can be efficiently used for some lab uses that do not require high values of the load.

3.5 Design of a high voltage circuit with potentials of more than 10 kV for various laboratory uses

Some laboratory experiments require high voltage values that may exceed 10 kV. So previous high-voltage circuit was developed to provide an output voltage higher than 10kV. To do that, an additional number of capacitors and diodes was added to this circuit to increase stages number to 23 stages, as shown in Figure 14. Each stage was charged with a voltage value of 484 kV measured by a voltameter. The output voltage measured by a high voltage probe without any loading current was 11.19 kV. However, this value decreased to 9.6 kV when the circuit was loaded with a current of 0.93 mA as shown in Figure 15. Increasing the input dc voltage taken from the power supply to 16.2 dc V increased the output voltage of the developed circuits from 11.19 kV to 15 kV. This value decreased to 13 kV for a loading current of 1.2 mA.

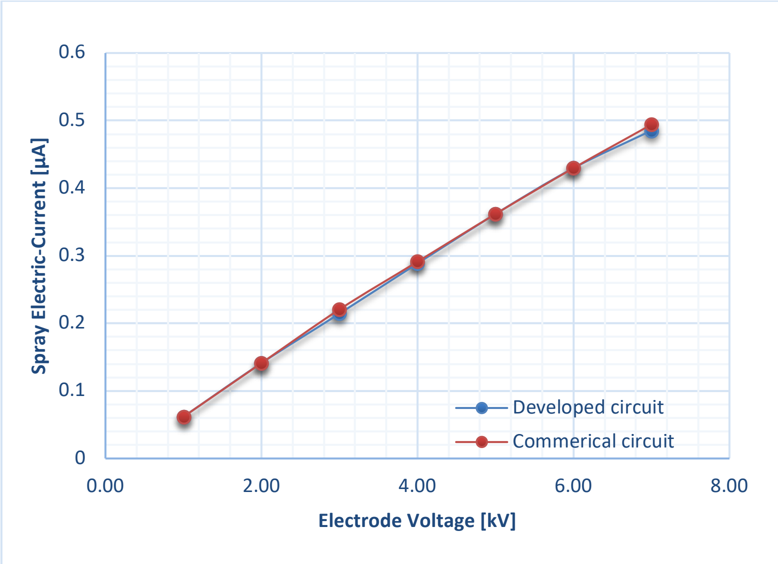


Figure 13. The charge-to-mass ratio of the spray droplets at different electrode voltage levels applied by both the developed C-W voltage multiplier and commercial circuits.

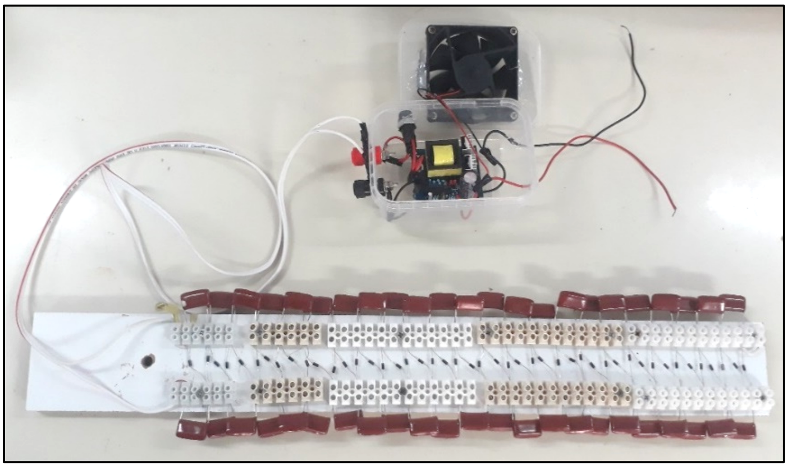


Figure 14. C-W voltage multiplier of 23 stages

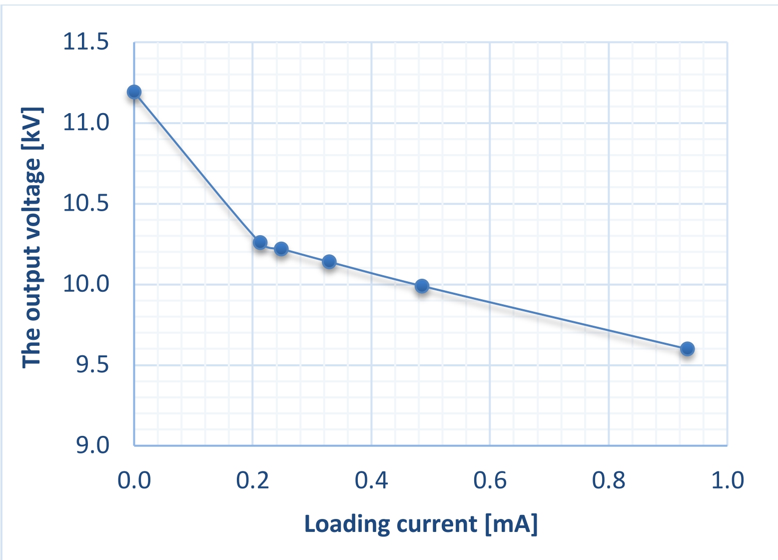


Figure 15. the effect of loading current on the C-W voltage multiplier of 23 stages

4. Conclusion

This study aimed to develop a low-cost high voltage circuit for laboratory uses and compare it with a commercial one in electrostatic charging of tap water droplets. Three circuits were developed to study the impact of the capacitor capacity and frequency level of the dc-ac inverters on circuit performance. The first, second, and third circuits use inverters and capacitors of 50 Hz – 470 nF, 20 kHz – 10 nF, and 20kHz and 470 nF, respectively. The experimental results showed that the values of inverter frequency and the capacitor capacity seriously affect the circuit performance (voltage drop, voltage ripple, and response time). Voltage dropping at the first circuit reached about 74% at a loading current of 0.150 mA current inverter. While it was only 44% in the second circuit and 11 % in the third circuit at the same loading current. That indicates that large-capacity capacitors and high-frequency inverters significantly improve the output voltage and voltage ripple. The response time did not exceed 40 mSec in the second and third circuits, while it reached 15 sec in the first circuit. Thus, response time is improved with the high-frequency inverter while not affected by capacitor capacity. Based on the previous, it is found that the best performance was for the third circuit using inverters and capacitors of 20kHz and 470 nF. When this circuit was compared with a commercial one to electrostatically charge water droplets, it provided the same charging efficiency. Also, the circuit (3) was enhanced by increasing the stage numbers to provide a voltage value of 15 kV. However, the third circuit with large capacities of 470 nF capacitors can store a large quantity of the electric potential with a relatively high current that can cause a risk to humans. Therefore, this charge must be discharged after each experiment to remove any danger that threatens human life. The large size of these capacitors will not have a negative effect in light of laboratory uses. On the other hand, the high-frequency dc-ac inverter has a square alternating output voltage. Still, the formulas (2), (4) that are used to calculate the ripple and the voltage drop are inferred concerning the sine wave [1]; this may affect the mathematical results of output voltage and ripple somewhat in the second and third circuits. The study helps postgraduate students to develop low-cost high voltage devices for different laboratory uses. Moreover, the electronic elements used to build the Cockcroft-Walton voltage multiplier are exposed to a small stress of the output voltage, thus, it can work for a long time without being damaged.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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