A Mini-Marx Generator Powered by a Cockcroft–Walton Voltage Multiplier

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***Abstract*— A Marx generator generates a high-voltage (HV) pulse by charging two or more capacitors in parallel and then suddenly connecting them in series. In principles, a comparatively lower voltage dc power supply has to be used for the charging to achieve the desired HV. However, a moderate dc HV power supply is still quite expensive and bulky but not in full-time usage. In this work, a mini-Marx generator powered by a Cockcroft–Walton (CW) voltage multiplier has been proposed to form a more efficient, compact, but affordable configuration of pulsed HV power sources. For generating an HV in a range of 20–150 kV with the mini-Marx generator consisting of eight stages, a CW multiplier operating up to 3–20 kV is required. Numerical simulations using PSpice have been performed for validating the concept. For demonstration, a prototype of the 22-stage CW-powered four-stage mini-Marx has been built and tested with an ac voltage of 110 V at 60 Hz. In the experiment, the CW generator can reach 3.6 kV to power the mini-Marx, delivering an HV of 12.7 kV, consistent with the PSpice modeling. With an ac household voltage of 220 V at 60 Hz, a dc voltage of 5.2 kV can be obtained from the CW to charge an eight-stage mini-Marx generator, achieving an output voltage of 33 kV to drive a field emission-based X-ray source. The proposed CW powered mini-Marx generator is general and can be used as a compact pulsed voltage supply for some portable devices.**

***Index Terms*— Cockcroft–Walton (CW) voltage multiplier, mini-Marx generator, portable X-ray, PSpice.**

I. Introduction

THE design of high-voltage (HV) generators for powerful electric sources with high-output voltage has been in use for many decades in industrial, military, and scientific applications. Some critical applications include the production of electrical arcs, generation of particle beams, flash X-ray devices, ignition, photomultiplier tubes, cathode ray tubes, micro-plasma applications, electric field sensors, field-emission diodes, and high-power vacuum tube amplifiers and oscillators [1]–[17]. The X-ray unit powered by an alternating current (ac) power supply results in "peaks and troughs," thus limiting an X-ray tube to produce X-rays only half of the cycle. To create an uninterrupted voltage by overcoming this "voltage ripple," three-phase HV generators and constant potential generators were introduced. The X-ray production in a portable X-ray tube requires an HV of from 20 to 150 kV. The design of HV generators is usually bulky, preventing the creation of portability of X-ray devices. Developing a compact, low-cost flash X-ray source may require a compact HV power supply that is not bulky yet produces a very short HV pulse to drive an X-ray tube. In 1924, Erwin Otto Marx described an HV generator namely, Marx generator, capable of producing an HV pulse from a low-voltage direct current (dc) power supply just by charging two or more capacitors in parallel and then suddenly connecting them in series. Literature survey shows that a mini-Marx generator can multichannel field distortion gaps or fire a number of gaps with little gap-to-gap isolation and with short rise time [1]. Marx generators can be a good alternative for designing compact flash X-ray sources because the current pulse begins to rise almost simultaneously with the tube voltage while not delayed as is the case with cable-driven and high-inductance transformer generators [2]. Marx generators are used in applications mentioned in HV generators and also in radio-frequency (RF) production and RF energy harvesting [3]. In developing a compact Marx generator, another problem is encountered where the dc power supply used for charging the Marx generator is bulky [4] and needs an alternative. The classical Marx generators did not use semiconductor switches until recent years, but with spark gaps. Recent studies show that semiconductor switches are used in Marx generators. It can be classified into two categories. The first type is low-cost and readily available components such as insulated-gate bipolar transistors (IGBTs) and metal-oxide-semiconductor field-effect transistors (MOSFETs). These switches are limited in power capability with a certain power range; hence research is ongoing to improve the performance of the switches and their gate driving circuits. The second type is specially designed switches such as semiconductor opening switch, drift step recovery diodes, reverse switching dynistor, fast ionization dynistor, and so on

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[5]. With specially designed and optimized architecture, these devices give high performance, but on the downside, being too expensive and rare. Whether these switches can be an excellent alternative to spark gap switches to make a portable X-ray source needs an in-depth analysis.

On the other hand, the Cockcroft–Walton (CW) generator or voltage multiplier is an electric circuit that generates a high dc voltage from a low-voltage ac or pulsing dc input [18]. It was developed at the University of Cambridge in the early 1930s by John Cockcroft and Ernest Walton to accomplish the first artificial splitting of the atom, hence becoming an essential part of particle accelerators where a high-energy pulse is needed [19]. It comprises a voltage multiplier ladder network of capacitors and diodes to generate HVs with multiplying, rectifying, and filtering the alternating voltage supplied by a power source such as a household outlet. Under ideal conditions, the output voltage of a CW generator is nearly equal to twice or thrice the product of the number of stages and the peak voltage. The main advantage of CW generators is requiring relatively low cost components, light in weight, easy to insulate, and the output can be tapped from any stages similar to a multitapped transformer.

In this work, we propose the integrated design of a Marx generator powered by a CW voltage multiplier as a compact HV power supply to drive a portable X-ray source [15], [20]. We present the detailed simulation and experimental setup in Section II, and the results and discussion in Section III. Finally, the conclusion is given in Section IV.

II. Experimental Setup and Simulation Models

A. CW Voltage Multiplier

A CW voltage multiplier is a generator that uses a network of capacitors and diodes to generate an HV dc output from a low-voltage ac or pulsing dc power supply. The biggest advantage of a CW generator is that the voltage across each stage of the cascade is equal to only twice the peak input voltage in a half-wave rectifier while it is three times that in a full-wave rectifier. Therefore, it has the advantage of requiring relatively low-cost components and being easy to insulate. In addition, one can tap the output from any stage, like in a multitapped transformer. CW voltage multipliers are widely used in a variety of applications such as X-ray machines, electron microscopes, magnetrons in microwave ovens, accelerators, and so on. The design of the CW voltage multiplier begins with determining the required output dc voltage and knowing the available input ac voltage. The simple, cost-effective, yet lightweight design makes CW generators very attractive for a compact dc power supply. To understand the operation, we consider a simple two-stage CW multiplier, as shown in Fig. 1, with a switch S_{cw}, four diodes, and capacitors powered by an ac input voltage V_i with a peak value V_p.

In the CW voltage multiplier, all the capacitors are connected in series with the load while being charged in parallel. The capacitors are uncharged initially, and when the input voltage is turned on and reaches its negative peak value $-V_p$, the diode D_1 is switched on as forward-biased to charge the capacitor C_1 to the peak value V_p. The input voltage polarity is reversed in the next half-cycle and reaches a positive peak V_p. This adds to the capacitor's voltage to produce a voltage of $2V_p$ on C_1's right-hand plate. Here, the diode D_1 becomes off as reverse-biased, and diode D_2 is forward biased; hence the current flows from C_1 through D_2, charging the capacitor C_2 to a voltage of $2V_p$. The current flows up the ladder of capacitors through the diodes with each change in input polarity and charges all capacitors to twice the input peak voltage except for the initial capacitor C_1, which is charged to V_p. Note that capacitors C_2 and C_4 are in series between the ground and the output; hence the voltages are summed up to produce four times the input peak voltage ($4V_p$) under no-load conditions. The output voltage from a CW generator is twice the product of the input peak voltage V_p and the number of stages N and is defined as

$$V_{out} = 2^* V_p{}^* N. \tag{1}$$

In a CW generator, the output voltage can be achieved for the given input voltage by controlling the number of stages. However, with many stages, the stray shunt capacitances allow ac to flow in the series capacitances. These currents have the effects of lowering the output voltage and of increasing the ripple even under no load [18]. From our PSpice simulation of the CW generator, as shown in Fig. 2, it is found that the output voltage gets saturated as one increases the number

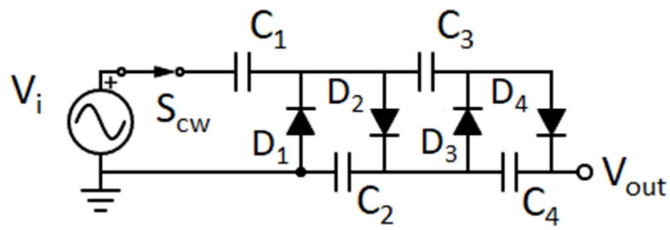

Fig. 1. Schematic of a circuit model for a two-stage CW voltage multiplier.

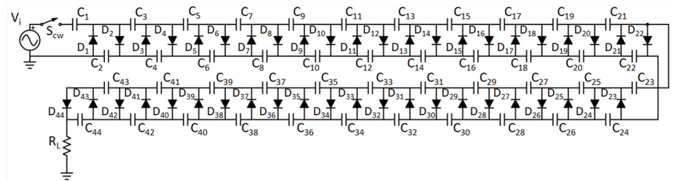

Fig. 2. PSpice simulation model of the 22-stage CW voltage multiplier.

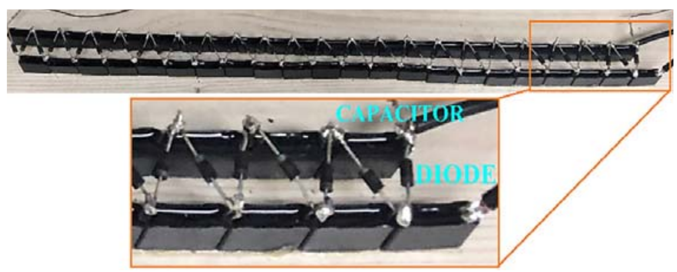

Fig. 3. Experimental setup of the 22-stage CW voltage multiplier used as a dc power supply.

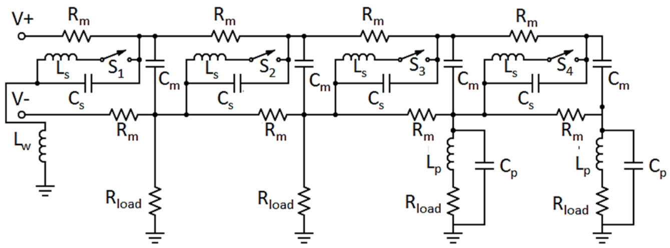

Fig. 4. Circuit diagram of a four-stage mini-Marx generator used in the PSpice modeling.

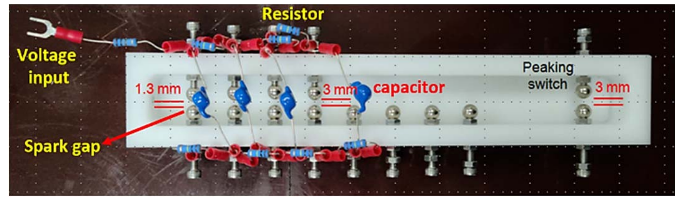

Fig. 5. Experimental setup of the four-stage mini-Marx generator.

of stages, and therefore, a 22-stage CW voltage multiplier giving a relatively high output voltage at an efficiency of 89% is chosen in this work, as shown in Fig. 3. There are two 100-nF capacitors and two 1-kV rating diodes (1N4007) in each stage, and a resistive load (R_L) of 10 GOhms is used for the CW generator performance test. The total cost of the components used in the 22-stage CW generator is about 10 U.S. dollars while that of a dc/dc converter for generating a similar dc output voltage is estimated as ~200 U.S. dollars. In addition, the circuitry of a CW generator is much simpler than that of a dc/dc converter. Using only capacitors and diodes, these voltage multipliers can step up relatively low voltages to extremely high values, while being far lighter, simpler in design and analysis, and cheaper than those HV generators based on transformers.

B. Marx Generator

A Marx generator is an electrical circuit whose purpose is to generate an HV pulse from a low-voltage dc supply. Its operation is similar to that of a CW voltage multiplier, where the capacitors stacked in stages are charged in parallel and connected in series during a discharge. It consists of a capacitor, a resistor, and a spark gap in each stage powered by a dc voltage source. When the spark gaps are not activated, they act as open circuits, and the capacitors in all stages are charged in parallel. Once the spark gaps are activated, forming short circuits during the discharge, the capacitors are connected in series to deliver an HV pulse to the load. Theoretically, the output voltage obtained is the product of the charging voltage and the number of Marx stages. Fig. 4 shows the circuit diagram for a four-stage mini-Marx generator consisting of 100-kOhms resistors (R_m), 220-pF capacitors (C_m), and spark gaps with an inductance (L_s) of ~1 nH and a capacitance (C_s) of ~0.3 pF. The number of stages can be increased to achieve a higher output voltage if needed. Later on, we extend the design to an eight-stage mini-Marx generator after validating the PSpice modeling. The experimental setup shown in Fig. 5 consists of a spark gap with a gap distance of 1.3 mm in the first stage and three ones of 3 mm for the other stages. The inductance and capacitance for a spark gap of 3 mm were determined to be 1 nH and 0.3 pF, respectively, using the finite-element analysis. A proper design of a compact Marx generator can give faster rise time, higher peak voltage, and increased load voltage efficiency [7], [8]. One crucial advantage of employing a Marx generator for X-ray production is that most of the energy stored in the capacitors is used to accelerate electrons across the anode–cathode gap of the X-ray tube with only a small fraction of the stored energy dissipated by the spark gap switches. In addition, the resulting X-ray pulse is produced with minimum heat load on the anode when operated in optimal conditions [2]. An HV probe with a 3-pF input capacitance (C_p) and a 0.5 μH probe wiring inductance (L_p) is used to measure the output at each stage with a resistance (R_{load}) of 100 MOhms.

C. Mini-Marx Generator Powered by a CW Voltage Multiplier

A moderate dc HV power supply which is still quite expensive and bulky but not in full-time charging can be replaced by a CW voltage multiplier. Ideally, a 22-stage CW multiplier with an ac supply voltage of 220 V at 60 Hz driven by household electricity can generate a dc voltage of >13 kV that can charge the mini-Marx generator to produce a pulsed voltage high enough to power an X-ray source or other devices. In this work, we propose the hybrid configuration of CW-powered Marx generator, taking advantages of both designs to achieve a compact HV pulsed power source. A prototype of the four-stage mini-Marx powered by the 22-stage CW voltage multiplier has been built and tested with an ac voltage of 110 V at 60 Hz to demonstrate the idea and validating the PSpice modeling, as shown in Fig. 6.

III. Results and Discussion

In the experiments, the 22-stage CW voltage multiplier is charged with a household outlet of 110 V at 60 Hz for 100 s. Theoretically, under ideal conditions for 110 V 22-stage CW, an output voltage of 6.84 kV should be obtained but as mentioned earlier the saturation of output voltage occurs with the increased number of stages, thus reducing the efficiency. During the charging time, the switch connecting the CW voltage multiplier and the mini-Marx generator is open to ensure a complete charging of all the capacitors in the CW circuit; this provides a stable dc voltage of 6.08 kV at an 89% efficiency in the experiment, as shown in Fig. 7(a). The output voltage in the PSpice simulation is 6.09 kV, as given in Fig. 7(b), demonstrating a good agreement with the experiment and a solid validation of the CW model. A further investigation of the diodes used in the CW generator in the PSpice modeling indicates that the efficiency loss of 2% should be attributed to the diode "1N4007" which is not an ideal diode but with a small turned-on voltage and non-negligible resistance as the capacitors used are ideal ones without any stray capacitance

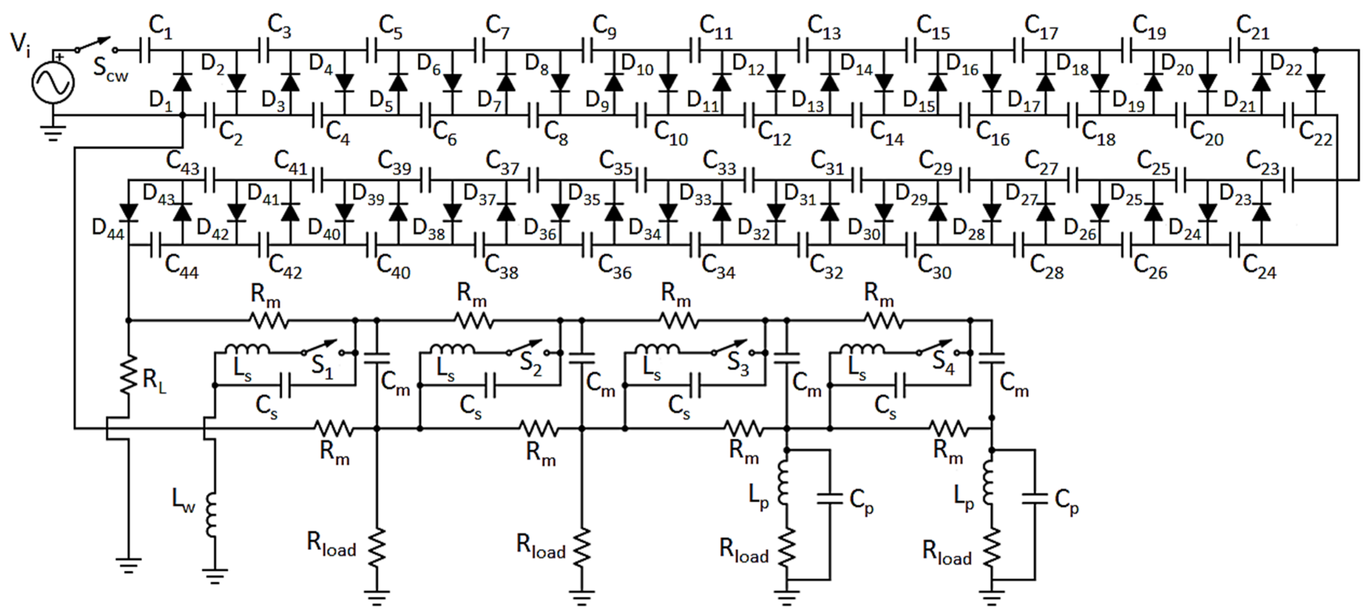

Fig. 6. PSpice model of the four-stage mini-Marx generator powered by the 22-stage CW voltage multiplier.

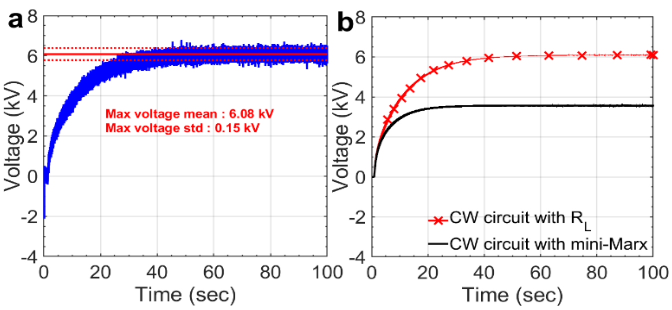

Fig. 7. Comparison of the output voltage measured from the CW circuit in (a) experiments and (b) PSpice simulations with a resistive load R_L (red lines with symbols x) and mini-Marx (black solid lines).

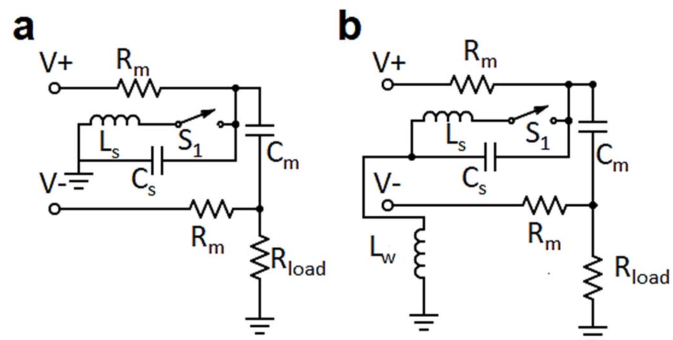

Fig. 8. Circuit of stage 1 in the four-stage mini-Marx generator without (a) and with (b) wiring inductance connected between stage 1 and the ground.

or internal resistance. Additional 9% loss is due to the loading effect of the HV probe with a resistive load (R_L) of 10 GOhms.

When the four-stage mini-Marx generator is connected with the CW voltage multiplier, the output voltage from the CW generator drops to 3.55 kV [black solid line in Fig. 7(b)] due to the loading effect. The first spark gap in the mini-Marx generator plays an essential role in the operation. In the PSpice model, we use time-controlled switches (S_1–S_4) to activate the spark gaps at 100 s while with a transition time of 12 ns between each stage so that the capacitors in all stages of the mini-Marx are fully charged [6]. A resistive load of 100 MOhms is used for each stage and the circuit of the first stage is shown in Fig. 8(a). In the experiments, we use two probes to measure the voltage at each stage; the first probe was fixed at the fourth stage, and the second probe changed from stages 1 to 3. Hence, the PSpice simulations are arranged in three independent runs. During the first run, the probe circuit is kept at stages 1 and 4, next at 2 and 4, and finally at 3 and 4, as shown in Fig. 6.

In the experiments, the gap distances of the spark gaps for stage 1 and stages 2–4 are set as 1.3 and 3 mm, respectively. The corresponding spark gap parameters set in the PSpice simulation for each stage are listed in Table I. The PSpice

TABLE I

PSpice Simulation Settings and Comparison of Mini-Marx Output Voltages in the Experiments and PSpice Modeling

Stage	R_{open} (GOhms)	R_{close} (Ohms)	Output voltage (kV)		
			PSpice	*Experiment*	*Ideal condition*
1	5	20	3.14 kV	3.60 kV	6.09 kV
2	6	50	6.30 kV	6.70 kV	12.18 kV
3	6	50	9.40 kV	9.60 kV	18.27 kV
4	6	50	12.66 kV	12.70 kV	24.36 kV

simulation parameters for the switch, R_{open} and R_{close}, are obtained after the fine tuning to fit the experimental results.

In comparing the experiments with the PSpice simulations for case A using the circuit in Fig. 8(a), there is no oscillation in the PSpice results; instead, a pulse with a steady state is obtained, as in black solid lines with dots shown in Fig. 9. While in the experiments, oscillations are observed as in blue solid lines shown in Fig. 9, indicating there seems to be some additional inductance in the circuit. Therefore, in the PSpice simulation, a wiring inductance (L_w) of 4 μH, corresponding to the case B in Fig. 8(b) is added to the first stage, as shown in Fig. 6, to recover the oscillating frequency in our PSpice modeling and the output voltages at each stage are shown in Fig. 9 with red dotted lines. This is consistent in the wiring

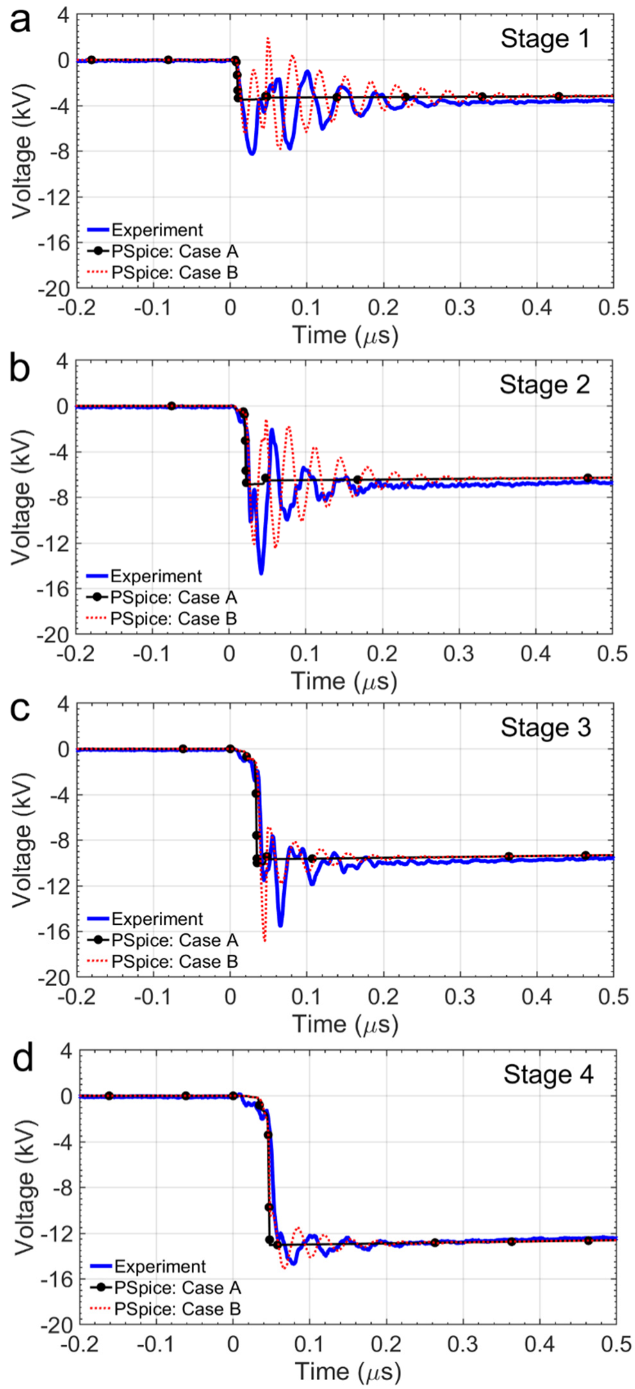

Fig. 9. Comparison of the output voltages at (a) stage 1, (b) stage 2, (c) stage 3, and (d) stage 4 of the CW powered mini-Marx generator measured in the experiments (blue solid lines) and obtained in the PSpice modeling with (red dotted lines) and without (black solid lines with dots) considering the wiring inductance.

TABLE II

PSPICE SIMULATION RESULTS FOR MINI-MARX GENERATOR POWERED BY A 22-STAGE CW VOLTAGE MULTIPLIER WITH DIFFERENT HOUSEHOLD VOLTAGES AND NUMBER OF STAGES

Number of Marx stages	Input power supply	CW multiplier output	Marx generator output
4	110 V	3.55 kV	12.66 kV
4	220 V	7.20 kV	25.20 kV
8	220 V	5.20 kV	33.58 kV

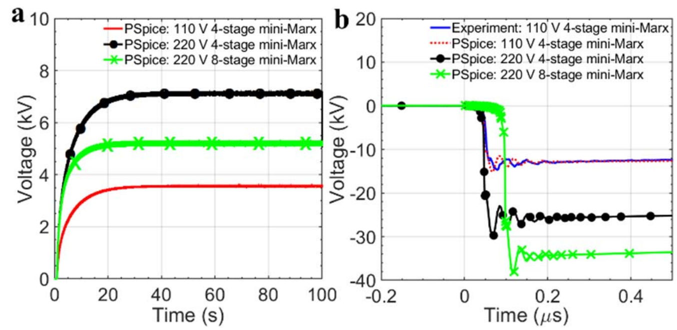

Fig. 10. Comparison of the output voltages of (a) CW voltage multiplier and (b) mini-Marx generators for different household outlets and the number of Marx stages used in the PSpice modeling. The blue solid line represents the experimental result of the four-stage mini-Marx generator powered by the 22-stage CW multiplier with a 110-V household outlet. The validated PSpice simulation results are shown in red. The case of a 220-V household outlet is shown in black lines with dots. The case of the eight-stage mini-Marx with a 220-V input for the CW generator is shown in green lines with symbols x.

in the experiments although the inductance of the wire is not measured. Hence, the R_{open} (R_{close}) values in the PSpice simulation are set as 5 GOhms (20 Ω) and 6 GOhms (50 Ω), respectively, in stage 1 and for the other stages, as listed in Table I, to get the steady-state values of the output voltages close to the experimental results (blue solid lines), as shown in Fig. 9.

Assuming ideal conditions where the CW output voltage is about 6.09 kV, we should obtain an output voltage of 6.09, 12.18, 18.27, and 24.36 kV at each stage from 1 to 4, correspondingly. However, the loading effect of the mini-Marx decreases the output voltage of the CW voltage multiplier to 3.55 kV. The corresponding output voltages at each stage for the four-stage mini-Marx generator in the PSpice simulations are 3.14, 6.30, 9.40, and 12.66 kV, respectively. The output voltages measured at each stage for the four-stage mini-Marx generator powered by the 22-stage CW voltage multiplier with a household outlet of 110 V are 3.60, 6.70, 9.60, and 12.70 kV, respectively, in good agreement with the PSpice simulation results, as listed in Table I. Therefore, the PSpice model of the CW-powered mini-Marx generator is well validated by the experiments. The validated model is further used to examine different operation conditions and extend the designs. The household voltage to the CW voltage multiplier is increased from 110 to 220 V in the PSpice simulation, and a dc charging voltage of 7.2 kV is obtained, as shown in Fig. 10 (black lines with dots).

This is then fed to the four-stage mini-Marx and an output voltage of 25.20 kV can be achieved which is in the voltage range to drive a portable X-ray source. Furthermore, by increasing the number of stages in the mini-Marx generator from four to eight stages, the output voltages of the CW multiplier and the eight-stage mini-Marx generator are also shown in Fig. 10 (green lines with symbols x) for comparison and the corresponding values are listed in Table II. An output voltage of 33.58 kV can be obtained from an eight-stage mini-Marx powered by the 22-stage CW with a 220 V household outlet or an inverter powered by batteries. This hybrid configuration combining a CW voltage multiplier with a Marx generator can serve as a compact HV power supply to drive a field-emission-based X-ray source under development as well as other devices. The validated PSpice modeling is general and can be used for exploring and optimizing a configuration for desired applications. As an example, for the eight-stage mini-Marx operating up to 150 kV, it is predicted that a 77-stage CW generator will be needed which can provide an output voltage of 20 kV with a matching load. Using cost-effective components, taking advantages of both designs, one can obtain a compact power source at a high efficiency. Some further investigation and PSpice modeling are continued to explore and optimize the configuration to improve the efficiency and mitigate the loading effect in the CW-powered mini-Marx generator.

IV. Conclusion

A mini-Marx generator powered by a CW voltage multiplier used as a compact HV power supply is proposed and investigated both experimentally and with PSpice simulations. For demonstration, in the experiment, a prototype of the four-stage mini-Marx powered by the 22-stage CW voltage multiplier has been built and tested by using a household outlet of 110 V to realize the concept. The measured output voltages of the CW voltage multiplier and the mini-Marx generator are also used for the improvement and validation of the PSpice modeling in order to explore the hybrid design and optimize the configuration, taking advantages of both classical designs. By extending this design to an eight-stage mini-Marx generator powered by the 22-stage CW generator being charged with a 220 V household outlet, an output voltage of up to 33 kV can be obtained. By manipulating the number of stages in the CW voltage multiplier and Marx generator, the desired output voltage can be achieved at an optimal efficiency. This integrated system configuration is general and can serve as a more efficient, compact, while affordable HV power supply to power a portable X-ray source as well as other devices using a household outlet or an inverter powered by a battery.

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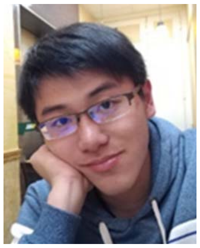

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