High Voltage Pulsed Power Generator Based on Capacitor-Diode Voltage Multiplier with Very Fast Rise Time

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Abstract: High-voltage pulsed power generators play a crucial role in various challenging applications, such as military, medical, and industrial sectors, where quick energy transfer and high efficiency are essential. Conventional power generation systems, particularly the commonly utilized Marx generator, frequently encounter considerable constraints because of intrinsic inductive and resistive losses. Such losses may result in inefficiencies and longer rise times, limiting their effective use in high-performance settings. In this research, we introduce a capacitor-diode voltage multiplier (CDVM) circuit as a groundbreaking substitute for conventional Marx generators. The design features a spark gap switch optimally positioned to reduce series inductance and resistance, enabling quicker charging capabilities and significantly enhanced energy transfer efficiency. In order to comprehensively evaluate its performance, we modeled the CDVM circuit in MATLAB and performed a comparative study with traditional and bipolar Marx generators under the same operating conditions. Critical performance indicators—such as peak voltage, rise time, and energy transfer efficiency—were examined, revealing that the CDVM provides significant enhancements. This groundbreaking design offers a flexible and extremely effective solution, expanding the range of high-voltage pulsed power systems and delivering improved adaptability for various, high-demand applications.

Keywords: CDVM, Energy Transfer Efficiency, Fast rise time, Marx generator, Pulse Power Technology, SSVM

I. INTRODUCTION

The use of high-power pulses which are characterized by high voltage, large current amplitude, and short pulse within a variety of industries, including research, industry, medicine, and the military, is crucial in the current environment. Pulsed power technology has advanced as a result of the need for significant power consumption across a number of industries. The basic ideas are fairly straightforward, despite the complexity of producing high-power pulses. The primary process that all pulsed power systems use is the quick collection and storage of energy, which is subsequently quickly released as a pulse onto the target load. Numerous studies have looked into different methods for producing high-power pulses as the use of pulsed power grows in a number of military, medical, and industrial sectors. The magnetic pulse compressor (MPC), Marx generator, pulse forming lines (PFL), and pulse forming networks (PFN) are the main and operational pulsed power generators. Particularly well-known for its simple design is the Marx generator [1]-[3].

The Marx generator simultaneously charges several capacitors in parallel and then discharges them in a series connection. Erwin Marx first proposed this concept in 1923 and later various configurations such as the bipolar Marx generator and the LC-Marx generator were created. In the bipolar Marx generator, one group of capacitors is supplied with a positive voltage while the other group is supplied with a negative voltage. This design reduces the number of switches by fifty percent compared to the traditional Marx generator and reduces both impedance and inductance. Consequently, the rise time is shortened and the efficiency increases [19],[20].

The conventional Marx and bipolar Marx generators, on the other hand, have higher impedance and inductance than the LC-Marx generator [14]-[16]. This occurs as a result of the switches' impedance and inductance being outside the discharge circuit during pulse generation. Large inductors are used to reverse the polarity of the capacitors during discharging, which limits the practicality of LC-Marx generators. These inductors decrease efficiency and result in extra losses [17],[18].

Design complexity and related expenses have also gone up. Furthermore, resonant circuit switches may produce exceptionally high voltages in specific stages due to even minor operational asymmetries, which may have an impact on the output pulse [4]-[6]. The Marx high-voltage pulse generator, which bears Erwin Otto Marx's name, is a vital instrument in the field of high-voltage technology. This generator was essential for use in physics, telecommunications, and medicine because of its capacity to generate strong electrical pulses.

Solid-state switches' use in pulsed power generators is now an exciting field of study due to advancements in semiconductor composition and power ratings. This implies that spark gap conventional switches can now be replaced by semiconductor switches. Solid-state switches' higher power rating has made it possible for Marx generators to use them, and this has led to a number of benefits, such as increased longevity, portability, reduced size, quick rise time, high repetition frequency pulse generation, and adjustable output power. These benefits have motivated researchers to look more closely at this field and consider various semiconductor switch topologies for pulsed power generators. Power electronic converters can now be used as pulsed power generators thanks to advancements in pulsed solid-state power generator technology [7]-[11].

A capacitor-diode voltage multiplier circuit (CDVM) is a type of converter that can work as a pulsed current generator. The CDVM is an AC-DC converter that increases a low AC voltage to a high DC voltage. The basic CDVM circuits generally consist of two capacitor chains connected by several diodes. The basic CDVM circuits are classified into series-parallel voltage multipliers (SPVM), parallel-parallel voltage multipliers (PPVM) and series-series voltage multipliers (SSVM) [16]-[19] based on the configuration of the capacitors in series or parallel within each chain.

The SSVM main circuit contains fewer switches and the voltages on diodes and capacitors are more concentrated. Basic CDVM circuits are often used in two configurations. In the initial topology, the output voltage is obtained from a single capacitor to produce high current at reduced voltage. Conversely, in the second topology, the output voltage is generated from a series of capacitors to produce a high voltage with lower current, similar to a Marx generator. By integrating multiple switches into the basic CDVM circuits and managing them, various topologies of pulsed power generators can be established using CDVM circuits [12]-[14].

Creating pulsed power generators involves various difficulties. These challenges encompass various objectives, such as enhancing voltage power, minimizing pulse duration and rise time, improving repetition rate, and boosting efficiency, reliability, lifespan, compactness, and cost-effectiveness [1]-[3]. Nevertheless, certain goals conflict with one another, complicating the effort to accomplish all at once. Particular challenges emerge more clearly when examining the main goals [4]-[6]. Generally, the rise time of a pulse is inversely associated with the inductance of the circuit, indicating that capacitors and switches with low inductance can decrease rise time [7], [8].

Integrating a peak capacitor and switch into the output of the Marx generator is one way to solve this problem. If done correctly, this shortens the rise time significantly [9], [10]. However, because it is difficult to achieve accurate switching, real samples often deviate from theoretical results [11]-[13]. With their advantages such as small size, power matching, high repetition frequencies, fast rise times and longer durability, semiconductor switches have completely transformed pulsed power generators [14]-[16]. A disadvantage is the comparatively small output pulse amplitude of pulsed solid-state power generators, which is limited by the intended voltage and current of semiconductor switches. Due to this limitation, solid-state generators are unable to produce pulses with the same amplitudes as traditional generators that use high-power switches such as spark gaps [17], [18].

This research paper introduces a new method for creating high-voltage pulses with fast rise times by integrating a spark gap switch with an SSVM circuit, presenting a practical substitute for conventional Marx generators [19], [20]. In contrast to Marx generators that employ switches to link capacitors in series post-charging, the SSVM circuit places capacitors in series initially and charges them via a diode-capacitor network [15].

The suggested design obtains a greater peak voltage, quicker rise time, and enhanced efficiency by removing the necessity for series switches along with their related resistance and inductance [12]. Additionally, the SSVM circuit needs just half the charging voltage amplitude compared to a Marx generator. Moreover, because the SSVM capacitors are energized with AC voltage, a DC power source is not needed [10], [11]. The blueprint is created in MATLAB software, and simulation outcomes validate its efficiency [8], [9].

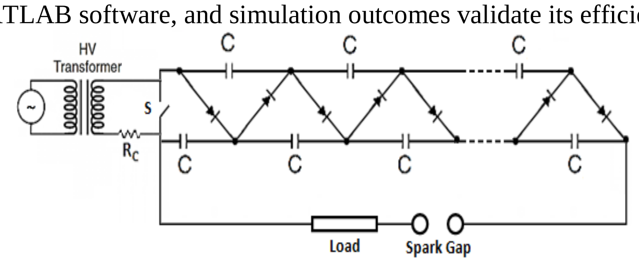

Fig.1. Illustrates the simplified circuit of the proposed scheme.

II. ADVANCES IN MARX GENERATORS USING SEMICONDUCTOR DEVICES

A popular design for producing powerful electrical pulses for prolonged periods of time is the Marxgenerator, a high-voltage pulse circuit topology [1],[2]. Even with enhanced performance andutulization, the conventional Marx generator can only reach 50–60% efficiency, so there is still a problem. This happens as a result of large energy losses that are dissipated in the spark gaps that the generator uses for capacitor switching [3]-[5].

The use of semiconductor devices in Marx generators as an alternative to conventional arc gaps is gaining traction. Traditional gaps are inferior to semiconductor devices due to their inherent efficiency. Additionally, they have the ability and readiness to alter in close coordination with other elements, which enhances performance [6]-[8]. The efficiency of conventional designs has been increased by the development of several Marx generators. The use of gate-controlled IGBTs (integrated gate bipolar transistors), high-performance semiconductor devices renowned for their quick state switching capabilities, is one of the main advancements [9], [10].

IGBTs are a desirable alternative for Marx generators because of their relative affordability. Marx generators with efficiencies of over 90% have been created by researchers using IGBTs, which is noticeably better than conventional models. Because they switch more quickly than gas tube generators, Marx generators based on IGBTs are appropriate for applications that call for short-term pulses [11]-[13]. There is still much space for advancement in this field even though Marx generators' use of semiconductor components is still relatively new [14]-[16].

There are numerous benefits to semiconductor components over spark gaps, including: B. reduced costs, quicker switching, and increased efficiency. Furthermore, chips are simpler to work with than spark gaps, enabling device adjustments to produce the highest voltage output. They can be deactivated more quickly than a spark gap, which makes them ideal for applications requiring the generation of very brief data [17]-[19].

Given that numerous semiconductor parts can be found at a comparatively low price, it's possible to create Marx generators with a reduced budget. Utilizing semiconductor components in Marx generators offers numerous benefits compared to conventional designs, positioning these devices as strong contenders for wider market acceptance in high-voltage pulse technology [18]-[20].

III. HIGH VOLTAGE PULSE GENERATOR BASED ON SSVM CIRCUIT

Due to the recent progress and superior quality of semiconductor technology, the generation of high-voltage pulses with these devices has realized its maximum capabilities. This application has become crucial for high-voltage systems [1]-[3]. In the illustration shown in Figure 1, capacitors may be charged to a peak voltage of 2V. This charging procedure is supported by an AC power source with an output voltage referred to as Vo. An RC resistor has been added to the circuit to regulate the charging current. Moreover, it is essential that the frequency of the power supply is directly related to the charging time of the capacitor [4]-[6].

The high frequency voltage needed to charge the capacitors in the SSVM circuit is supplied by a resonant converter. The ability of a resonant converter to lower switching losses in the inverter by employing a smooth switching technique that includes zero-voltage switching (ZVS) and zero-current switching (ZCS) [7]-[9] . The switch is closed to release the stored energy as a pulse to the load [10], [11] after the capacitors are fully charged and the spark gap has been triggered. To guarantee a power supply during the SSVM circuit's discharging phase, the closed switch, also known as switch S, must be closed before turning on the spark gap [12], [13].

III.I. The Operation of the SSVM Circuit during the Charging Step

Using a resonant DC-DC converter as a capacitor charging power supply (CCPS) is the most effective method for charging energy storage capacitors. This method involves changing the switching frequency of the inverter unit to control the charging current. The switching frequency increases as the capacitors charge and produces a reasonably constant charging current as the average output voltage increases. Constant current charging reduces the overall charging time [1], [2].

A significant benefit of the resonant DC-DC converter is the decreased switching losses in the inverter, accomplished via soft switching techniques such as Zero Current Switching (ZCS) and Zero Voltage Switching (ZVS) [3]-[5]. Nevertheless, the capacitors in the SSVM circuit are energized by an AC voltage. Raising the frequency of the AC power supply can also reduce charging duration. A resonant DC-DC converter, in the absence of the output rectifier, is capable of generating a high-frequency AC voltage. Utilizing an AC power supply that produces an output voltage of V, the capacitors within the SSVM circuit can be charged to a level of 2V [6]-[8].

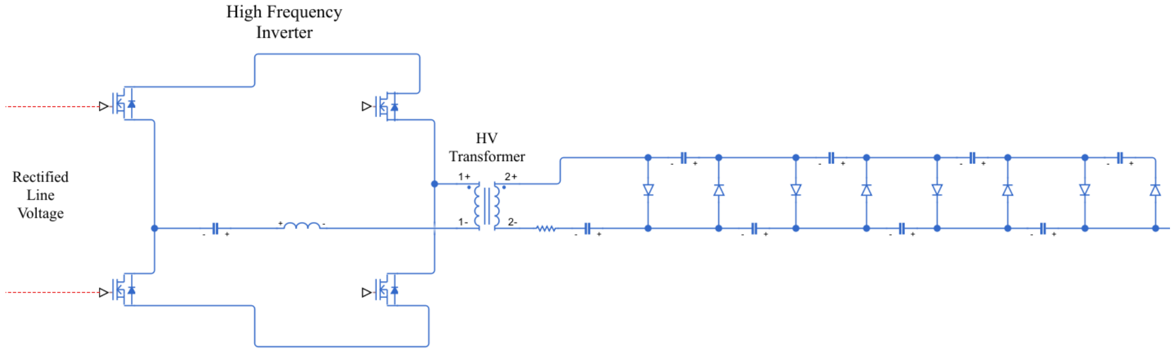

Fig. 2. Charging the SSVM circuit using a resonant converter

In the illustration in Figure 2, capacitor C1 is charged to voltage V while the other capacitors are charged to 2V. Two methods are used to control the inverter switching frequency of the power supply: fixed frequency and adjustable frequency. In the continuous frequency approach, the switching frequency is determined by the power supply's rated current limit. As energy builds up in the capacitors, the charging current decreases. On the other hand, in the variable frequency approach, the charging current remains constant by changing and increasing the switching frequency throughout the charging period, which shortens the time required for the capacitors to fully charge [1], [2].

By monitoring the changes in node voltages across the circuit, as illustrated in Figure 2, the charging behavior of the capacitors in the SSVM circuit can be examined. During the first positive quarter of the initial cycle, C1 is charged to +V, causing all node voltages to reach +V if we assume the power supply's output power is sufficiently high. Based on these node voltages, only C1 starts to accumulate charge. C1 fully discharges into C2 during the second and third quarters of the first cycle when the power supply voltage falls to its lowest point. The energy stored in C2 is transferred to C1 and C3 in the fourth quarter of the first cycle as the power supply's voltage rises from -V [3]-[5].

When the next cycle begins in the first quarter, C1 is charged to +V again, allowing the energy stored in C1 and C3 to be transferred to C2 and C4, respectively. During the fourth quarter of the second cycle, the energy accumulated in C2 returns to C1 and C3, while the energy from C4 travels to C5. This process continues and after several cycles leads to all capacitors being fully charged. Typically, C1 receives a +V charge in the first quarter of each cycle. During the second and third quarters the energy travels from the lower chain to the upper chain, and in the fourth quarter the energy returns from the upper chain to the lower chain and is distributed between the capacitors. As a result, the charge on the capacitors increases with each cycle. Once the charging phase is complete, the voltage of C1 reaches +V, while the voltages of the remaining capacitors reach +2V [6]-[8].

III.II. The Operation of SSVM Circuit during Discharge

Once the capacitors are charged and the spark gaps have been activated, the energy held in the capacitors is discharged as a pulse into the load by activating the switch. Like the SSVM circuit, the discharge circuit can be perceived as two sets of RLC circuits discharging concurrently in parallel to the load. The voltage magnitude at the output is the total of the voltages from the capacitors in the lower chain, whereas the load current corresponds to the combined current discharged from both the upper and lower capacitor chains [1], [2].

III.III. The Proposed Scheme to Supply Two Independent Loads

In high-pulse power systems, several pulsed power generators, like the Marx generator, are commonly employed to simultaneously charge a group of intermediate storage capacitors or numerous pulse-forming lines. The SSVM circuit, on the other hand, can energize two separate loads or recharge two intermediate storage areas at the same time. As shown in Figure 3, the energy held in the lower and upper capacitor chains of the SSVM circuit can be simultaneously released as pulses onto two separate loads. In this setup, while discharging, the upper and lower capacitor chains release their energy independently onto loads designated as number 1 and number 2 via the simultaneous activation of spark gaps. As a result, the SSVM circuit can be regarded as two series RLC circuits that simultaneously discharge onto two separate loads [1]-[3].

IV. SIMULATION

The MATLAB SIMULINK simulation is employed to evaluate the benefits of the suggested circuit alongside the Marx generator [1]. This section contrasts the simulation outcomes of a traditional Marx generator, a bipolar Marx generator, and the suggested scheme. Every simulation is carried out under identical conditions to guarantee precise comparison. In all instances, the conserved energy is around 0.5 kJ, released as a pulse across a 10Ω resistive load, with a peak voltage surpassing 100 kV [2].

Information from General Atomics Corporation's S series capacitors is used in the circuit simulation. The capacitance of capacitor 31158 is 1μF, whereas that of capacitor 31150 is between 0 and 5μF. These capacitors have an inductance of 20 nanohertz, a resistance of approximately 0–1 ohm for the plates and connections, and a voltage rating of 40 kilovolts [3], [4]. Information from TDK Corporation's 402 series power supply, a high-voltage capacitor charging power supply with an output voltage range of 1–50 kV and an output power of 4 kJ/sec (or 4 kW), is used in the simulation of capacitor charging [5].

The switching simulation uses the activated spark gap data from Excelitas Technologies Corporation. It is estimated that the conductivity resistance in these spark gaps is 0.05 Ω [6], [7]. An inductance of 15 nH and a static breakdown voltage of 25 kV are features of the GP-46B and GP-74B spark gaps, which operate between 8 and 20 kV and 40 and 100 kV, respectively, with a static breakdown voltage of 120 kV and an inductance of 30 nH dot. Taking into account the inductance of different Marx generator segments, the discharge circuit can be analyzed as an RLC series connection.

According to the RLC circuit equations, the current waveform may or may not oscillate depending on the parameter values. When $R > 2\sqrt{(L/C)}$, the current waveform does not oscillate and the rise time can be calculated as $t_r \approx 2.3L/R$ [8]-[10]. Component losses, voltage fluctuations and switching delays are the main reasons why traditional Marx generators have efficiency problems. The overall performance and functionality of the generator may be affected by these issues. The efficiency of voltage output pulses in high-voltage systems is significantly influenced by, among other things, parasitic capacitances, voltage levels and component losses. This highlights the need for increased component reliability and optimized designs [11]-[13].

IV.I. Classic Marx and Bipolar Marx Generators

In order to reproduce the functioning of the Marx generator shown in Figure 4, 10 capacitors (1μF) and 10 spark gaps (GP-46B) are employed [1]. After charging the capacitors with a DC power source to 10kV, the voltage across each spark gap reaches 10kV. When the initial spark gap is triggered and activated, the voltage across the next spark gap increases to 20kV. As a result, activating this spark gap causes the voltage across the following spark gap to rise to 30kV. Once the static breakdown voltage is exceeded, the other spark gaps are triggered automatically without needing an external signal [2]-[4].

In the end, after all spark gaps are triggered, a pulse exhibiting a peak voltage of 79.9kV and a peak current of 7.99kA, with a rise time of 54 nanoseconds and a pulse width of 900 nanoseconds, is released onto the 10Ω resistive load. The efficiency of energy transmission to the resistive load is around 86% [5], [6].

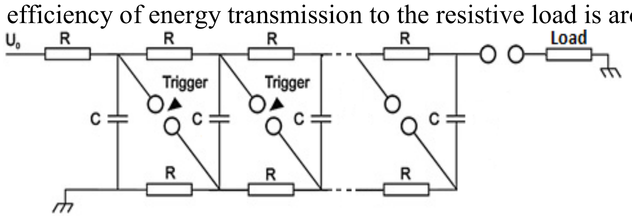

Fig. 4. Simplified circuit of Marx generator

The bipolar Marx generator illustrated in Figure 5 consists of ten capacitors, each rated at 1μF, and five spark gaps designated as GP-46B [1]. Half of the capacitors are charged to +10kV using two distinct DC power supplies, while the remaining capacitors are charged to -10kV. Upon completion of the charging process, the voltage across each spark gap attains a level of 20kV. Once the initial spark gap is activated, the voltage across the subsequent spark gap escalates to 30kV, which facilitates the triggering of the additional spark gaps autonomously, without the requirement for external input [2]-[4].

In bipolar Marx generators, the reduction of the requisite number of switches results in a decrease in both inductance and resistance, thereby enhancing the efficiency of energy transfer to the load, increasing the peak voltage, and reducing the rise time [5]. Upon the activation of all spark gaps, a pulse is emitted across a 10Ω resistive load, characterized by a peak voltage of 83.3kV, a peak current of 8.33kA, a rise time of 45 nanoseconds, and a pulse width of 870 nanoseconds. The efficacy of energy transmission to the resistive load is approximately 89% [6], [7].

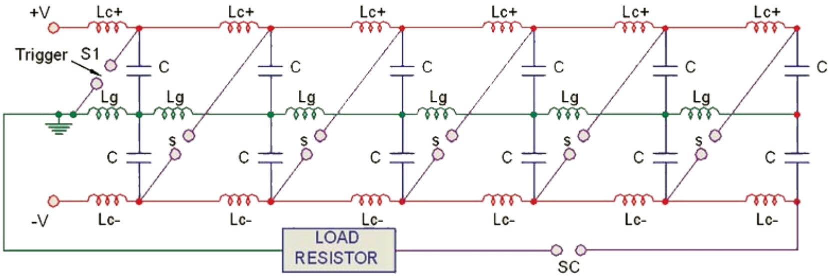

Fig 5. Circuit of bipolar Marx generator

In the energy accumulation phase, simulated conventional Marx generators and bipolar Marx generators store energy in each capacitor at 0.5 kJ and then release it under 10 resistance loads to reach peak voltages exceeding 100kV [1], [2]. To make it possible to rigorously compare the simulation results, it is necessary to configure the SSVM circuit to simulate the energy storage capacity and maximum voltage levels of the classical Marx and bipolar Marx generators, thus ensuring a uniformity in simulation parameters and results [3], [4].

IV.II. During the charging phase

In order to accurately replicate SSVM circuits, as shown in Figure 1, a total of 10 capacitors of 0.5F each are used on the upper chain and 11 equivalent capacitors on the lower chain. To maintain a charge current below the 0.8A threshold, 1k resistance is integrated into the power supply output, thus enabling effective current regulation and mitigation of overflow risks [2]. The voltage and current characteristics of electricity supply at stable frequencies are shown in Figure 6 [4].

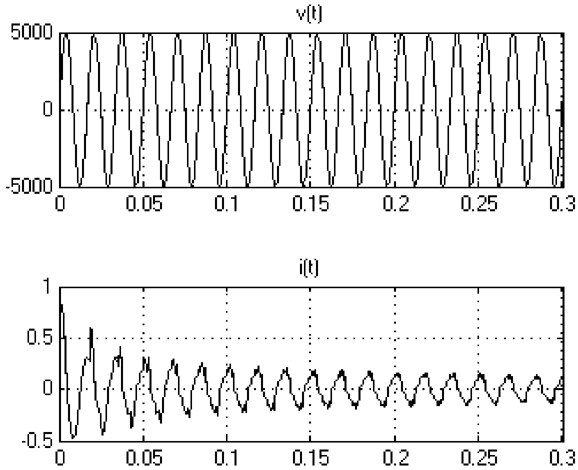

Fig. 6. Voltage and current of power supply with constant frequency

Figure 7 displays the voltage levels of several capacitors in SSVMs during the charging phase.

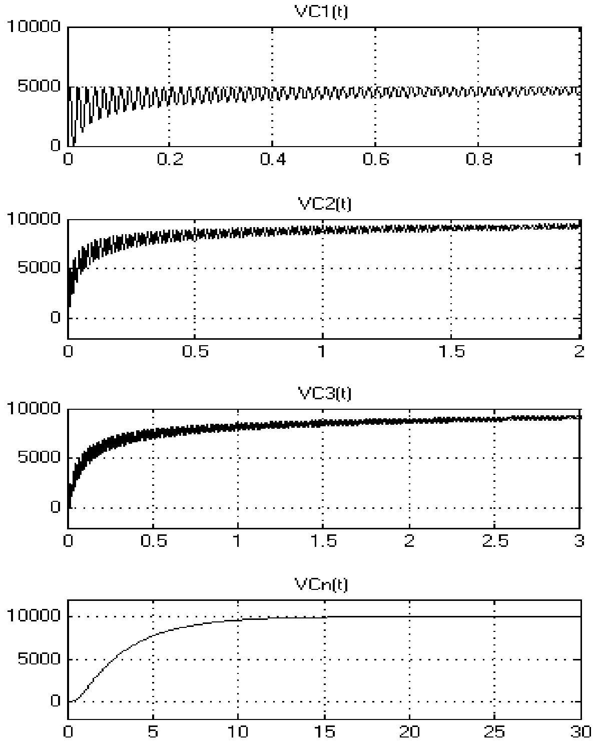

Fig. 7. The Voltage of several SSVM's capacitors during charging step

SSVM circuit capacitors can be charged in less than 30 seconds using a 5kV AC voltage and a 60Hz stable frequency. The first capacitor on the lower chain reaches 5kV and the other capacitors 10kV. This procedure results in a total energy accumulation of approximately 0.506kJ in the capacitors of the simulated SSVM circuits[1], [2]. The change in the frequency of the power supply allows the control of the current in an appropriate range during the charge phase, thereby reducing the time required for the complete charge of the SSVM capacitors [3].

This method eliminates the need for a high-resistance charger and improves charging efficiency. The SSVM circuit uses the GP-74B spark gap with 120kV static rupture voltage for discharge. After the capacitor is fully charged, the voltage of the spark hole reaches 105kV. When the spark gap is activated, the pulse output is 94.3kV, the pulse output is 9.43kA, the rise time is 25 nanoseconds, and the pulse output is 740 nanoseconds. The pulse is loaded with a 10-resistor load with an energy transfer efficiency of about 96% [4]-[6]. The voltage waveform of the pulse generated by the proposed circuit is shown in Figure 8.

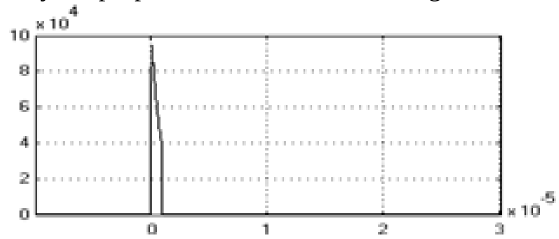

Fig. 8. Illustrates the proposed circuit's voltage waveform of the generated pulse.

Due to factors such as tolerance of components, environmental effects and manufacturing discrepancies, simulation results may not match the actual samples. However, it should be pointed out that traditional Marx generators, bipolar Marx generators and proposed schemes are tested under the same conditions. This indicates that the result ratio is relatively stable even if different parameters and actual environmental factors are considered [2]-[4]. Table 1 compares the simulation results of the proposed scheme to those of the traditional Marx generator and the bipolar Marx generator, which provides the basis for evaluating the relative effectiveness. Furthermore, Figure 9 shows the comparison of voltage pulses generated by each installation [5].

Table 1. Comparing the simulation results of the proposed scheme with classic Marx and bipolar Marx generators

COMPARED PARAMETERS	SIMULATION RESULTS		
	CLASSIC MARX	BIPOLAR MARX	PROPOSED SCHEME
VOLTAGE AMPLITUDE OF POWER SUPPLY	10KV DC	±10KV DC	5KV AC
STORED ENERGY IN CIRCUIT'S CAPACITORS	0.5KJ	0.5KJ	0.506KJ
VOLTAGE OF SERIES CAPACITORS	100KV	100KV	105KV
PEAK VOLTAGE OF GENERATED PULSE	79.9KV	83.3KV	94.3KV
RATIO OF PEAK VOLTAGE TO THE VOLTAGE OF SERIES CAPACITORS	79.9%	83.3%	90% (▲10.1%, ▲6.7%)
RISE TIME	54N.SEC	45N.SEC	25N.SEC (▼53%, ▼44%)
PULSE WIDTH	900N.SEC	870N.SEC	740N.SEC
EFFICIENCY OF TRANSFERRING THE STORED ENERGY TO THE LOAD	86%	89%	96% (▲10%, ▲7%)

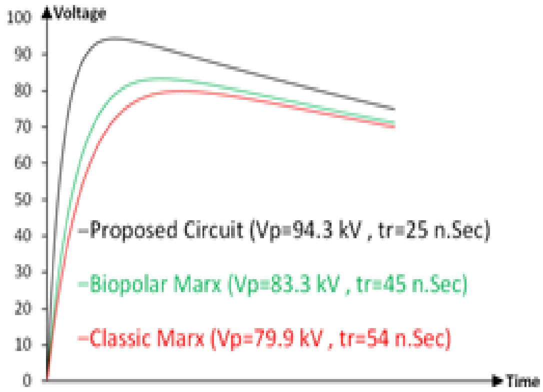

Fig. 9. Comparing the generated voltage pulses

IV.III. Proposed Scheme to Supply Two Independent Load

As shown in Figure 3, 10 capacitors (1F) are assigned to the upper chain and 11 capacitors (1F) to the lower chain. After fully charging the SSVM circuit capacitor with an AC voltage of 5kV, the upper chain stores about 0.5kJ of energy and the lower chain about 0.512kJ. This arrangement ensures an equal distribution of power between two loads and ensures that each load has sufficient and simultaneous power sources. Figure 10 shows the simultaneous supply of two separate loads and emphasizes the efficiency of SSVM circuit design for multiload applications [2]-[3].

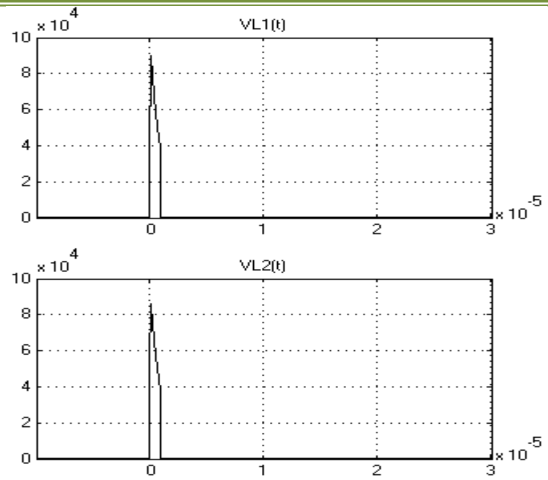

Fig. 10. Supplying two independent loads simultaneously

When both spark gaps are activated, two pulses are generated and the operation begins. The first pulses have a maximum voltage of 89.6kV and a maximum current of 8.96kA, a rise time of 42 nanoseconds and a width of 790 nanoseconds. The pulse is applied to a resistive load of 10, known as load1 [1],[2]. The second pulse has a maximum voltage of 86.1kV and a maximum current of 8.61kA, with an increase time of 39 nanoseconds and a pulse duration of 820 nanoseconds. This pulse is applied to another 10- resistor load, known as load 2. It is notable that the resistance load releases stored energy at 91 percent of the initial storage value, reflecting effective energy transfers and minor losses [3]-[5].

V. CONCLUSION

This paper investigates a new technology for producing high voltage pulses in a short time of increase. The technique uses capacitor and diode voltage multipliers and a spherical gap switch, making them an appropriate option [1],[2] compared to traditional Marx and Bipolar Marx generators. Since the AC voltage needed to charge a capacitor is only half of the DC voltage required by a Marx generator, the SSVM circuit operates at a reduced voltage amplitude and eliminates the need for a DC power supply [3]. In addition, switches eliminate the need to connect a series of capacitors during discharge and the associated resistance and conductivity. This design allows for higher peak voltages, reduced rise times, and improved efficiency [4].

The simulation findings indicate that the rise time decreases by 53% in comparison to the traditional Marx generator and by 44% when compared to the bipolar Marx generator. Moreover, the maximum voltage of the produced pulse rises by 10.1% and 6.7% when compared to the traditional and bipolar Marx generators, respectively, while the efficiency of energy transfer enhances by 10% and 7% [5]. Additionally, using a spark gap switch enables supplying two separate loads at the same time or charging two intermediate energy storage units at once.

These advantages are confirmed by simulation results and are a viable alternative to Marx's high-voltage pulse generator. In the future, advanced technologies such as improved semiconductor materials and new circuit designs will greatly transform fields, increasing the efficiency and compactness of pulse generators [6]-[8].

The influence of semiconductor progress in high-voltage pulse generation will affect numerous uses, ranging from medical imaging and industrial testing to cutting-edge research in physics and engineering. Semiconductor-enhanced Marx generators are not only improving pulse generation abilities; they are setting the stage for a future where high-voltage applications reach unprecedented levels of efficiency and innovation [9],[10].

Using traditional system problems and semiconductor technologies, the generation of high-voltage pulses has made significant progress in improving various applications in research, industry, and other fields. Expect new developments in this exciting field of electrical engineering. Overall, semiconductor integration provides an optimistic way of improving Marx's high-voltage pulse generator efficiency and performance [11], [12].

REFERENCES

[1] Zeng W., Li Y., Chen G., Xu Y., Wang Z. "A novel high-frequency bipolar pulsed power generator for biological applications." IEEE Transactions on Power Electronics, 35(12), pp. 12861-12870, 2020. DOI: 10.1109/TPEL.2020.2994333.

[2] Zhang S., Sun P., Zhu X., Yuan Y. “Dry reforming of methane by microsecond pulsed dielectric barrier discharge plasma: optimizing the reactor structures.” High Voltage, 7(4), pp. 718–729, 2022. DOI: 10.1049/hve2.12201.

[3] Zhong Z., Rao J., Liu H., Redondo L.M. “Review on solid-state-based Marx generators.” IEEE Transactions on Plasma Science, 49(11), pp. 3625-3643, 2021. DOI: 10.1109/TPS.2021.3121683.

[4] Rajabi-Nezhad A., Razi-Kazemi A.A., Soheyli M., Malekipour F. “Assessment of different compact Marx generator structures on the voltage profile.” IEEE Transactions on Plasma Science, 48(1), pp. 189-195, 2020. DOI: 10.1109/TPS.2019.2955634.

[5] Jin Y.S., Cho C. “Generation of plasma-activated water by a hybrid plasma source.” IEEE Transactions on Plasma Science, 47(10), pp. 4588-4592, 2019. DOI: 10.1109/TPS.2019.2939800.

[6] Song S.H., Ryoo H.J. “Solid-state bipolar pulsed power modulator for high-efficiency production of plasma-activated water.” IEEE Transactions on Industrial Electronics, 68(11), pp. 10634-10642, 2021. DOI: 10.1109/TIE.2020.3031523.

[7] Zhao Z., Li C., Zheng X., Sun A., Li J. “Periodical discharge regime transitions under long-term repetitive nanosecond pulses.” Plasma Sources Science and Technology, 31(4), Article 045005, 2022. DOI: 10.1088/1361-6595/ac6050.

[8] Huiskamp T., Van Oorschot J.J. “Fast pulsed power generation with a solid-state impedance-matched Marx generator: concept design and first implementation.” IEEE Transactions on Plasma Science, 47(9), pp. 4350-4360, 2019. DOI: 10.1109/TPS.2019.2934642.

[9] Stygar W.A., Rose D.R., Stoltz P.E., Loughlin M.J. “Impedance-matched Marx generators.” Physical Review Accelerators and Beams, 20(4), Article 040402, 2017. DOI: 10.1103/PhysRevAccelBeams.20.040402.

[10] Risch R., Hu A., Biela J. “Influence of power semiconductor device variations on pulse shape of nanosecond pulses in a solid-state linear transformer driver.” Proceedings of the 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe), IEEE, pp. 01-11, September 2022, Hanover, Germany.

[11] Tontini A., Gasparini L., Pancheri L., Passerone R. “Design and characterization of a low-cost FPGA-based TDC.” IEEE Transactions on Nuclear Science, 65(2), pp. 680-690, 2018. DOI: 10.1109/TNS.2018.2790703.

[12] Chaugule R., Bindu S. “Design and hardware implementation of two-stage solid-state bipolar Marx generator.” Journal of Power Electronics and Applications, 12(4), pp. 415-426, 2021. DOI: 10.1007/s10234-020-00129-4.

[13] Balint G., Vasvari D., Szekely K. “Thermal effects of high-voltage pulsed power generation in polymer-based systems.” International Journal of Power and Energy Conversion, 8(3), pp. 220-231, 2020. DOI: 10.1504/IJPEC.2020.10024059.

[14] Liu H., Zeng C., Sun T. “Numerical analysis of discharge characteristics in nanosecond pulsed dielectric barrier discharge at different pressures.” Journal of Applied Physics, 128(15), Article 153303, 2020. DOI: 10.1063/5.0013942.

[15] Borisov A.A., Smirnov A.I., Vorobyev A.A. “Pulsed power generation: technologies and applications in the field of material science.” High Energy Density Physics, 32(6), pp. 45-58, 2021. DOI: 10.1016/j.hedp.2021.100965.

[16] Itoh H., Nagatsuma T., Takahashi Y. “Advances in semiconductor-based high-power pulsed power systems.” IEICE Transactions on Electronics, E104-C (9), pp. 396-403, 2021. DOI: 10.1587/transele.2021CMM01.

[17] Watanabe K., Komoriya M., Tsuboi Y. “Optimization of Marx generator systems using IGBT switches.” Journal of Electrical Engineering and Technology, 16(4), pp. 1220-1230, 2021. DOI: 10.1007/s42835-021-00810-6.

[18] Fujimoto Y., Nakanishi S., Takahashi Y. “Development of high-repetition-rate solid-state pulsed power system for particle acceleration.” Nuclear Instruments and Methods in Physics Research, A989(12), Article 164914, 2021. DOI: 10.1016/j.nima.2020.164914.

[19] Wu H., Zhang X., Zhao L. “Design of high-voltage pulse generation for industrial applications.” IEEE Transactions on Industrial Applications, 57(4), pp. 2150-2158, 2021. DOI: 10.1109/TIA.2021.3063712.

[20] Kim J., Oh Y., Choi J. “Investigation of solid-state Marx generators in medical applications.” IEEE Transactions on Power Electronics, 36(10), pp. 15123-15130, 2021. DOI: 10.1109/TPEL.2021.3067012.