Development of Rectangle-Pulse Marx Generator Based on PFN
Hongtao Li, Hong-Je Ryoo, Jong-Soo Kim, Geun-Hie Rim, Young-Bae Kim, and Jianjun Deng

Abstract—In this paper, two designs of the rectangle-pulse Marx generator based on pulse-forming network (PFN) for pulse-power application are reported. The PFN is composed of inductors and capacitors. Proposed schemes consist of several identical PFNs that are connected according to Marx generator scheme. PFN Marx generators can output rectangle pulse several hundreds of nanoseconds in duration and several tens of nanoseconds in rising time. The effect of component parameter to the waveform is studied. Prototypes made of four PFNs have been tested. One of the prototypes is designed according to classical Marx mode, while another is designed as an $L - C$ Marx generator in which only one command switch and one isolating switch is needed. In a 500-ns duration, 65-ns rising-time rectangle pulse has been achieved on the matching load.

Index Terms—Classical mode, $L - C$ mode, Marx generator, pulse-forming network (PFN), rectangle pulse.

I. INTRODUCTION

HIGH-POWER rectangle pulse has wide application in science research and industry fields. It is very favorable in high-power microwave, X-ray, and laser research because of improvement to the quality of the electron beam. However, it is difficult to generate several hundreds of kilovolts or more high-power rectangle pulse with several hundreds of nanoseconds in duration using the existent Marx generator or solid state pulser because of the limitation of the mechanism or the property of the switches [1]–[3]. For example, the typical Marx generator can output damped sine pulse. For those Marx generators based on semiconductor switches, the shortest duration is determined by the turn-on and turn-off time of the switch, which is always more than 1 μs.

Pulse-forming networks (PFNs) have two merits: 1) They can store the exact amount of energy required for a pulse; and 2) they have the ability to discharge the energy into the load in the form of a pulse with a rectangle waveform [1]–[7]. In this paper, two modes of Marx generators based on PFNs composed of identical inductors and capacitors connected in ladder fashion are proposed. The effect of the component parameters on the waveform of output pulse is researched.

II. ANALYSIS AND CHARACTERIZATION OF PFN

To generate high-power rectangle pulses, PFNs consisting of identical inductors and capacitors connected in cascades by ladder style are generally used. The most widespread mode is voltage-fed PFNs with capacitive energy storage (CES) [1]. The PSpice circuit model and simulation results for the PFN pulse generator are shown in Fig. 1(a) and (b), respectively.

As shown in Fig. 1(b), the PFN can generate low front rising-time pulse with several hundreds of nanoseconds. In order to understand the tolerance of waveform to the deviation of the components’ parameters, the effect of the components’ parameters to the overshoot, rising time, and effective width of the output pulse is studied.

As shown in Fig. 2, the normal voltage of the output pulse ($U_0$) for the matched load is 5 kV as the charging voltage is 10 kV, but approximately 10% overshoot will be present if the inductance of the first inductor ($L_{1st}$) is set as normal inductance ($L_0 = 1 \ \mu H$). Therefore, $L_{1st}$ needs to be increased in order to decrease the overshoot. As $L_{1st}$ is set as 1.8 $\mu H$, the overshoot is eliminated. However, because of the existence of the connection line, $L_{1st}$ is always more than $L_0$. The 10%–90% frontal rising time of the pulse ($t_r$) increases to about...
Fig. 2. Maximum output voltage versus inductance of first inductor.

Fig. 3. Rising time versus inductance of first inductor.

Fig. 4. Ratio of reversed voltage over $U_0$ versus capacitance of the load.

Fig. 5. Effect of switching time to the rising time of output.

1.5 $t_{r0}$ ($t_{r0}$—rising time when $L_{1st} = 1 \mu$H) as $L_{1st}$ increases 60% from 1 to 1.6 $\mu$H (Fig. 3).

The capacitance of a load has great effect on the output pulse. The reverse voltage increases from 0.10 $U_0$ to 0.30 $U_0$ as the capacitance increases from 0 to 3 nF (Fig. 4). Simultaneously, the waveform of output pulse is distorted depending on the increase of the width of reverse pulse.

The resistance of the load ($R_{load}$) affects the voltage of output pulse and the reverse pulse. The reverse pulse fades away as the resistance approaches 1.25 $Z_0$ ($Z_0$ is match load). It is also found that the switching time of the switch ($t_s$) (the time interval for the impedance of the switch decrease to 0.1 m$\Omega$ from 1 M$\Omega$) affects $t_r$ slightly. In case the impedance transition of the switch is linear, $t_r$ increases from 42 to 54 ns, as $t_s$ increases from 10 to 150 ns (Fig. 5).

From the analysis of the PFN, it can be found that small stray capacitance or inductance and some degree load mismatch are acceptable for the application of the PFN.

III. DESIGN AND ANALYSIS OF MARX GENERATOR BASED ON PFNS

A. Brief Description

In order to achieve high-voltage high-power pulse, Marx generator is a favorable scheme for voltage multiplication. If the capacitors are replaced by the PFN, the new Marx generator will output rectangle pulse. In this scheme, the PFN will confine the waveform while Marx generator scheme will multiply the voltage amplitude. Two mode PFN Marx generators have been designed. In mode A, the circuit is arranged according to the classical Marx generator scheme. Mode B is designed as an $L-C$ Marx generator in which the voltage multiplication is based on the polarity reversal of half of the capacitors.

For both schemes of the PFN Marx generators, the dependence of the parameters of output pulse on the parameters of the PFNs can be expressed by (1)–(4). Pulse duration:

$$\tau = 2k\sqrt{LC}. \quad (1)$$

Characteristic impedance of PFN Marx:

$$Z_M = n\sqrt{\frac{L}{C}}. \quad (2)$$

Voltage across the match load:

$$U_L = \frac{nU_0}{2}. \quad (3)$$

Pulsed power on the match load:

$$P_L = \frac{nU_0^2}{4\sqrt{L/C}}. \quad (4)$$
where $U_0$ is the charging voltage of capacitors, $C$ is capacitance of the individual capacitor in the PFN section, $L$ is inductance of the individual inductor in the PFN section, $n$ is the number of the PFNs, and $k$ is the number of sections in one PFN.

### B. Simulation of Mode A

The circuit of the mode-A PFN Marx generator is shown in Fig. 6(a). Pspice calculation indicates that the voltage waveform of output pulse is determined by the parameters of the PFN components, and it is totally different from the damped sine wave output of the ordinary Marx generator [Fig. 6(b)]. This generator is also unlike those pulsers in which the waveform is controlled by the opening of the switch at high-power state.

### C. Simulation of Mode B

Mode-B PFN Marx generator is an $L-C$ Marx, which is based on the low-leak-inductance transformer [Fig. 7(a)]. In this scheme, only two switches are needed: one is the command switch; and another is a self-fired switch, which isolates the load from the generator during erection. As the command switch closes, the capacitors in the second and fourth rows are connected to the leak inductance of the transformer. As any flux is generated, the current flowing in the primary winding will be cancelled by the flux produced by the same current flowing in the second winding. The capacitors fixed in the second and fourth rows that are connected with the transformer reverse their polarity. This leads to voltage multiplication. After the $L-C$ Marx generator is erected, the voltage at the output end is high enough to breakdown the self-fired switch. The erection time of the generator is determined by the ring frequency of the capacitors in one row with the leak inductance of the transformer and the pulse-forming inductor. The calculation shows that the voltage of PFNs is multiplied as the command switch is closed [Fig. 7(b)]. The waveform of the output pulse revealed in Fig. 7(b) is determined by the parameters of the components of the PFNs. The charging voltage of the capacitors in both modes A and B is set as 10 kV in the simulation.

### IV. Experimental Results

Prototypes of the PFN Marx generator composed of four PFNs have been tested. Each PFN (one stage of the Marx generator) is composed of seven inductors and seven capacitors. One inductor and one capacitor compose one section. The capacitance of each capacitor is 2 nF. The inductance of the first inductor is $1.8 \, \mu H$ (in which the inductance of the connection line is included), and others are $1 \, \mu H$. The capacitors are fixed on an aluminum disk. The inductors are fixed between capacitors.

As shown in Fig. 8(a), the air gaps are utilized as switches in mode A. Only one gap is the command switch which is designed as a trigatron triggered by a 10-kV pulse. The remaining gaps are self-fired gaps. Fig. 8(b) shows the waveforms of the voltage pulse gained on the matching resistive load. The charging voltage of capacitors is about 10 kV. The amplitude of the output pulse is about 22 kV. It can be found that the pulse duration is approximately 650 ns with the rising
time less than 65 ns. The erection coefficient (the ratio of measured amplitude of output pulse to the calculation) is about 0.9. The tail voltage is lower than calculation results and only persists for less than 2 μs.

As shown in Fig. 9(a), the key components in mode B are the low-leak-inductance transformer and the isolation switch. If the coupling coefficient of the transformer is not high enough, the voltage of the capacitors fixed in the first and third rows will fall down when the other capacitors reverse their polarity. The coupling coefficient of the transformer with a metal–glass core can be as high as 0.99. In the prototype, a multigap surface flashover self-fired switch is utilized as the isolation switch. Fig. 9(b) shows the waveforms of the mode-B PFN Marx generator. The charging voltage of capacitors is limited to 3 kV because of the poor insulation of the transformers. The core of the transformer is too small to fill in enough insulators. Mode B is suitable for frequency operation. Because there is not a resistive component in the generator, the thermal diffusion is not a limitation to the operation frequency. The waveform is controlled by the circuit structure, and the current flowing through the command switch is fairly low (about several percent of the main current), so the switch could be a semiconductor switch.

V. CONCLUSION

The PFN Marx generator, which combines the merits of PFN and the Marx generator, output the pulse that has several hundred nanoseconds in duration and fast rising time. It is also suitable for the repeated or high-voltage operation. The scheme of the PFN determines the waveform of the pulse. The scheme of the Marx generator achieves the multiplication of voltage and power. Prototypes of two modes have been designed and tested. The experimental results agree with the simulation well and show the feasibility of such design. The PFN Marx generator has been proved to have the following merits.

1) The PFN Marx generator can generate high-power high-voltage rectangle pulse with several hundred nanoseconds in duration and several tens nanoseconds in frontal rising time.
2) It is easy to modularize and to adjust pulse parameters. The sections in the generator are identical. The duration of the output pulse can be easily adjusted by changing the number of sections.

REFERENCES


Hongtao Li was born in 1968. He received the B.Sc. degree from the Radio-technology Department, Hefei Polytechnic University, Hefei, China, in 1990, the M.Sc. degree from the Faculty of Communication Science, China Science and Technology University, Hefei, in 1998, and the Ph.D. degree from the Faculty of Accelerator Physics, Graduate School, China Academy of Engineering Physics (CAEP), Mianyang, China, in 2003. Since 2007, he has been a Professor of pulsed power with the Institute of Fluid Physics, CAEP. His main interests include experimental and theoretical plasma physics and applications.

Hong-Je Ryoo received the B.S., M.S., and Ph.D. degrees in electrical engineering from Sungkyunkwan University, Seoul, Korea, in 1991, 1995, and 2001, respectively. From 2004 to 2005, he was with WEMPEC, University of Wisconsin-Madison, Madison, as a Visiting Scholar for his postdoctoral study. Since 1996, he has been with Korea Electrotechnology Research Institute, Changwon, Korea, where he is currently a Principal Research Engineer in the Industry Application Research Laboratory. His research interests include pulse-power application and static-power conversion. Dr. Ryoo is a member of IAS, IES, and PES of IEEE.

Hongtao Li

Jong-Soo Kim received the B.S. degree from Seoul National University, Seoul, Korea, in 1982 and the M.S. and Ph.D. degrees in electrical engineering from Kyungnam University, Masan, Korea, in 1991 and 1999, respectively. Since 1982, he has been with Korea Electrotechnology Research Institute, Changwon, Korea, where he is currently a Principal Researcher. His specialized research area includes microprocessor application for industrial apparatus and power converters based on power electronics.

Geun-Hie Rim received the B.S. degree from Seoul National University, Seoul, Korea, in 1978 and the M.S. and Ph.D. degrees in electrical engineering from Virginia Polytechnic Institute and State University, Blacksburg, in 1988 and 1992, respectively. Since 1978, he has been with Korea Electrotechnology Research Institute, Changwon, Korea, where he is currently a Principal Researcher. His specialized research areas include power electronics, high-power energy conversions, power quality, and high-voltage pulsed-power generation for plasma applications. He has published numerous technical papers and is the holder of 25 Korean and international patents on these subjects. Dr. Rim is a member of various professional organizations including KIEE and KITE. He is also a member of Phi Kappa Phi.

Jong-Soo Kim

Young-Bae Kim received the B.S. degree in electrical engineering from Kyungnam University, Masan, Korea, in 2006. Since 1982, he has been with Korea Electrotechnology Research Institute, Changwon, Korea, where he is currently a Senior Researcher.

Jianjun Deng was born in 1964. He received the Ph.D. degree from Qinghua University, Beijing, China, in 2001. Since 1998, he has been a Professor of accelerator physics with the Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang, China, where he is also the President of the Institute of Fluid Physics. His main research interests include experimental and theoretical plasma physics and applications.

Young-Bae Kim

Jianjun Deng