Design of a 6-MW Solid-State Pulse Modulator Using Marx Generator for the Medical Linac

Heuijin Lim, Dong Hyeok Jeong, Manwoo Lee, and Sung Chae Ro

***Abstract*—The linear accelerators (linacs) producing high energy and high power of electron-beam or X-ray beam have been used in medicine, industry, national security, etc. In the linac, the electrons are generated by the electron gun and accelerated in the accelerating column with the high-power RF fields. The high-voltage pulses from the pulse modulator are supplied to the RF power source and the electron gun. The pulse modulator is one of the big and expensive components in the linac. The commercial medical linacs commonly use the pulse modulator based on the thyratron-switched pulse-forming network. In order to improve the power efficiency, achieve the system compactness, and optimize the cost and space, the solid-state pulse modulator based on the Marx generator was proposed. The low-power solid-state pulse modulator was developed for the electron gun operation. The conceptual design and functional results were confirmed. In order to apply it to the RF power source, such as a magnetron or a klystron, the 6-MW pulse modulator with the same Marx scheme is proposed. It consists of 40 storage-switch stages and one high-voltage pulse transformer, producing the pulse of 50 kV and 120 A required by the magnetron in the medical linac. A storage-switch stage was designed for insulated gate bipolar transistors to switch high current of 280 A and 720 V and to use the capacitor of 25 μF which was chosen for the voltage droop of 10% with the pulsewidth of 5 μs. The prototype system with eight storage-switch stages was fabricated and tested with a load system. The performance results show that it can be extended to be the 6-MW solid-state pulse modulator. In this paper, we describe the design features, and discuss the results and also the future plan to optimize the solid-state pulse modulator in the medical linac.**

***Index Terms*—Electron accelerators, insulated gate bipolar transistors (IGBTs), linear accelerators (linacs), pulse power systems.**

I. Introduction

MORE than 30 000 accelerators have been built worldwide over the past 60 years for use in medicine, industry, national security, basic science research, etc. More than 14 000 particle accelerators have been produced exclusively for medical therapy with electrons, ions, neutrons, or X-rays [1], [2]. The majority of the radiation therapies are still performed with linear accelerators (linacs) producing electron and X-ray beams. The linac accelerates the charged particles using the radio frequency electric field with a harmonic time dependence provided by the RF power source. Since the RF power sources are operated by the pulse modulators, the market data of radiotherapy machines tell us how many pulse modulators are used for the cancer treatment application.

The C-band linac has been designed and constructed to generate the electron and X-ray beams with megavoltage energy in the Dongnam Institute of Radiological and Medical Sciences, Busan, South Korea. For the medical application, we proposed a radiotherapy machine including a gantry based on this 6-MeV C-band linac, a rotatable couch for treatment, and a control console [3]. In the linac, the electrons are produced by an electron gun and gained their energy up to 6 MeV in the accelerating column using 2.5-MW RF power. The electron gun and the RF power source are operated with the heating power and the high-voltage pulse from the pulse modulator. The pulse modulator is commonly constructed with the thyratron-switched pulse-forming network [4], and is the high-cost and large-size one in the linac components. With the evolution of power semiconductor devices, the solid-state pulse modulator was proposed. This kind of modulator has been developed to improve the power efficiency using the various pulsed power topologies [5]. The Marx generator invented by E. O. Marx [6] in 1924 has been applied in the pulse modulator using insulated gate bipolar transistors (IGBTs) or metal–oxide–semiconductor field-effect transistors (MOSFETs) instead of the spark gaps. The fast switching speed, high-voltage rating, and high current rating of IGBTs and MOSFETs allow this generator to produce high-power square-shaped output pulses at high repetition rate. If this modulator can be manufactured with the components including high-voltage switches, which easily can be found in the market, can produce the controllable pulse shape, and can be constructed with the compact size and the moderate cost, it would be the good candidate to be used in the commercial medical linac.

We developed the solid-state pulse modulator based on the Marx generator to provide the pulsed power to a medical linac electron gun. This modulator was designed and constructed to generate high-voltage pulse up to 25 kV by 35 storage-switch stages. Each stage has a storage capacitor of 500 nF and two IGBTs to control charging and discharging of the capacitor. The results verified the conceptual design and the functional operation with the medical linac electron gun [7]. With this Marx generator scheme, we designed the high-power solid-state pulse modulator for 50 kV and 120 A magnetron

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H. Lim, D. H. Jeong, and M. Lee are with the Dongnam Institute of Radiological & Medical Sciences, Busan 46033, South Korea (e-mail: heuijin.lim@gmail.com; physics@dirams.re.kr; mwlee@dirams.re.kr).

S. C. Ro is with Dong-A HiTECH Company Ltd, Busan 46935, South Korea (e-mail: dongel@chol.com).

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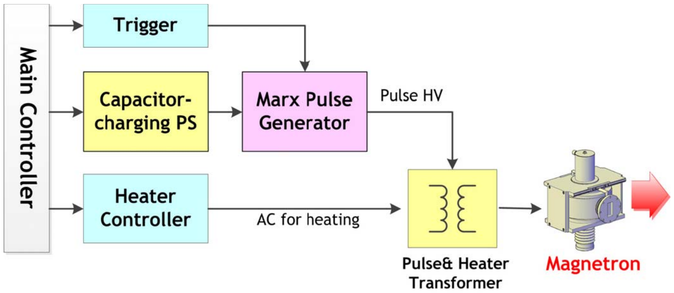

Fig. 1. Schematic illustration of the solid-state pulse modulator for a medical linac magnetron.

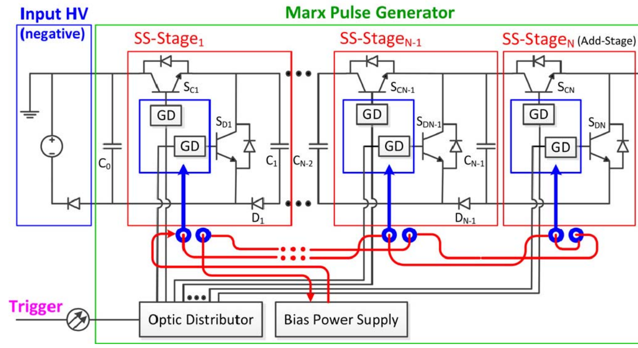

Fig. 2. Circuit diagram for producing the negative high-voltage pulse with series semiconductor switches in the Marx pulse generator with the input source. Each stage contains a storage capacitor C_i, two semiconductor switches (S_{Ci} and S_{Di}) controlled by each gate driver (*GD*), a diode D_i, and so on. However, the last stage (called *Add-Stage*) has no storage capacitor. The bias power per stage is delivered by the isolated transformer (blue ring) from the bias power supply board.

operation, consisting of 40 storage-switch stages. For the prototype system, eight storage-switch stages, a bias power board, and a trigger optic distributor were constructed and tested with a resistive load system. This paper focuses on the design of the solid-state pulse modulator in the medical linac magnetron and the design validation with high-speed IGBTs allowing high current switching, with the large storage capacitor and with components that are stably working under high voltage and current condition. And the test results and future plan were discussed.

II. Design

In the linac, the electron gun and the RF power source, such as magnetron or klystron, require the pulsed power. The high-power solid-state pulse modulator for the 50-kV and 120-A magnetron was designed. As shown in Fig. 1, the solid-state pulse modulator for a magnetron contains a capacitor-charging power supply, a Marx pulse generator, a pulse and heater transformer, a heater controller, a trigger, and a main controller.

The capacitor-charging power supply was used for providing the input power and was designed with a series resonant high-frequency converter technology [7], [8]. The operating frequency is 50 kHz in LC resonant circuit. It provides the output voltage of 100–1000 V and the peak charging rate of 15 kJ/sec. The Marx pulse generator produces the high-voltage pulse by multistacked stages with the input voltage from the capacitor-charging power supply. In order to reduce the number of storage-switch stages and to use the intermediate input voltage for protecting the internal circuits from the high-voltage arcing, the input voltage in the Marx pulse generator was chosen as 720 V and will be amplified up to 25 kV with 40 storage-switch stages. And the pulse transformer is added for boosting two times of the pulse voltage from the Marx pulse generator to be satisfied with the magnetron requirement. Due to the magnetizing current of the pulse transformer, the large backswing can appear at the end of pulse. The tail clipper of series combination with resistors and diodes is proposed to be installed in parallel with the primary winding of the pulse transformer to reduce the backswing. When the 6 MeV C-band linac was constructed, our first modulator based on the thyratron-switched pulse-forming network included this kind of tail clipper installed after the thyatron switch for the above reason [9]. The heater controller and transformer were designed for 6.3 VAC and 22 A, which are normally used for the magnetron heater. The pulse tank will contain the pulse transformer, the heater isolated transformer, and will be filled with the insulation oil. The main controller with the trigger determines the pulse amplitude of 4–28.8 kV, the pulsewidth of 1–10 μs, and the repetition rate of 10–300 Hz. It monitors the input power, the voltage and current of output pulse, and the environmental parameters of heater states, temperature, etc. The interlock is also implemented in the main controller. Since the capacitor-charging power supply and the Marx pulse generator were designed for 25 kV and 240 A, the required pulse voltage for the load system can be adjusted with the pulse transformer. Therefore, this solid-state pulse modulator can be easily used to other applications required up to 6 MW by a matched pulse transformer.

The detailed description of our designed Marx pulse generator including the input source and the load system can be seen in Fig. 2. The negative high-voltage pulse is generated with the multistacked stages. A storage-switch stage consists of an energy storage capacitor C_i, two semiconductor switches for charging S_{Ci} and for discharging S_{Di}, a diode D_i, a gate controller including two gate drivers, bias supply circuits for powering the gate drivers, and some auxiliary protection circuits. If the load system contains the capacitance component, the pulse shape is distorted by the remaining charge of load system. The last stage (also called *Add-Stage* in Fig. 2) only contains two switches S_{CN} and S_{DN} and has no storage capacitor. It is used to discharge the charge of the load system to the ground, resulting in improving the voltage droop. Since the capacitor-charging power supply is based on the open circuit, the C_0 capacitor is introduced to protect the storage-switch stage for the discharging mode. By the help of this C_0 capacitor, the total number of storage capacitors amounts to N and finally the input voltage is amplified with N capacitors.

Since two switches can be controlled independently, they allow to generate the pulse with various shapes in discrete step and to have the fast rise and fall times which are determined by the IGBTs specification. The gate driver is controlled via the fiber optic from the trigger optic distributor and powered from the bias power supply board through

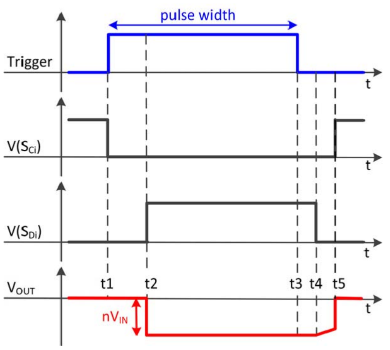

Fig. 3. Timing sequence of trigger, charging switch (S_{Ci}), discharging switch (S_{Di}), and the output voltage [7].

the isolated transformer [7]. The previous version of a gate driver [7] was designed to control two switches simultaneously with a single fiber per stage. Because the charging switch requires the opposite logic of the discharging switch (see Fig. 3), this logic function was implemented by the active logic devices installed in the gate controller. However, the high-power version controls two switches independently using two fibers from the trigger optic distributor, though the scheme makes the system bulky. The simple photoconversion logic is only set to each stage in order to reduce the malfunction of active devices caused by the high current fast switching.

The timing sequence of the Marx pulse generator is shown in Fig. 3. The trigger signal contains the pulse start timing, the pulsewidth, and the pulse repetition rate. After $t_2 - t_1$, the output voltage is generated. As the timing $t_5 - t_4$ becomes shorter, the pulse fall time becomes shorter. This $t_5 - t_4$ is limited by the charging/discharging semiconductors switching timing in order to protect the stage with the short circuit caused by the switches transient state. While it was set to longer than 1 μs in [7], it is set to 200 ns with the fast switching IGBTs to minimize the influence to the voltage droop and pulsewidth.

As the input voltage becomes higher and the discharging current becomes lower for the fixed storage capacitance at each stage, the voltage droop ratio becomes lower and better. However, our proposed low input voltage and high discharging current can give us the big droop ratio. In order to solve the voltage droop issue, the capacitor of 25 μF was chosen for the voltage droop of 10% with the pulsewidth of 5 μs. While the stage was designed for switching the current of 1 A and 720 V with the storage capacitor of 500 nF in the low-power modulator [7], this stage was redesigned and the operation parameters also were reoptimized for switching the high current of 280 A and 720 V with 25 μF.

III. Prototype System and Results

For the prototype system, eight storage-switch stages, a bias power board, and an optic distributor were constructed. It was shown in Fig. 4. In the storage-switch stage, we chose the IXYS model, IXYN120N120C3 (S_{Di}) for the discharging switch, and the Fairchild model, FGA30S120P (S_{Ci}) for the charging switch. These IGBTs have the voltage rate up to 1200 V and the fast falling time to allow the high-speed switching. Also the freewheeling diodes were additionally attached to these IGBTs. A fast recovery diode of IXYS DSEI30-12A (D_i) with the fast reverse recovery time of 40 ns was chosen to pass the current in the charging mode and immediately to block it in the discharging mode. The film capacitor of UL3_L256K (C_i) manufactured by Electronic Concepts was used for the storage capacitor. The board size of each stage was designed to be 150×260 mm^2. These stages were stacked with the space gap of 100 mm. From this test, we learned that the board size can be reduced by 15% and the space gap can be also reduced by 10%–15%, achieving the compact size for the fully integrated system.

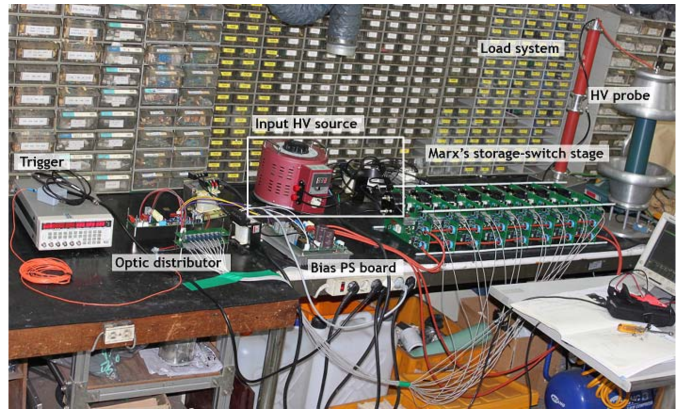

Fig. 4. Constructed prototype solid-state pulse modulator. It was tested with the resistive load system.

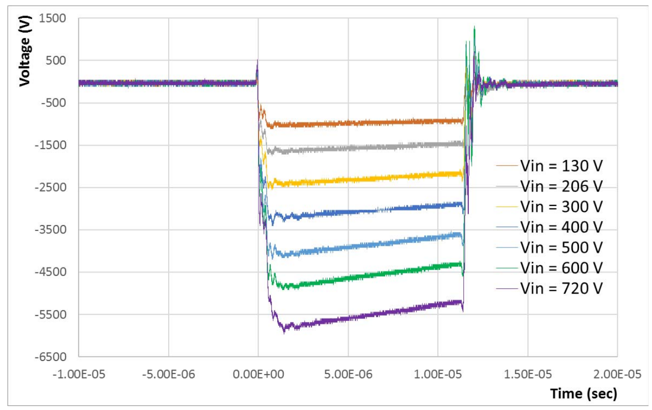

Fig. 5. Test with the resistive load of 24.36 Ω. Different amplitudes of pulse voltage were taken from the input voltages of 130–720 V. The pulsewidth is 12 μs.

The test was performed with the resistive load of 24.36 Ω. As shown in Fig. 5, the results of pulse voltage were achieved from −1 to −5.76 kV for the different input voltages. They were fit to the form $V_{\mathrm{OUT}} = n \cdot V_{\mathrm{IN}} + V_{\mathrm{CONST}}$, where V_{OUT} is the pulse voltage, n is the number of stages in the Marx pulse generator, V_{IN} is the input voltage, and V_{CONST} is an additional offset voltage. The fit yields $n = 8$ and $V_{\mathrm{CONST}} = -167$ V with $\chi^2/N_{\mathrm{data}} = 0.99$ and describes that the number of stages is eight. The current was measured from 46 to 288 A for the different input voltages (see Fig. 6), resulting that the net impedance of the final load was estimated to be 21.15 0.45 Ω. It confirms that each stage drives the current rate up to 288 A with the input voltage of 720 V and the pulse voltage is amplified with the number of stages.

With an over-current protection circuit, the safe operation was also tested. In the over-current case, the short circuit immediately discharges the storage capacitors to the ground.

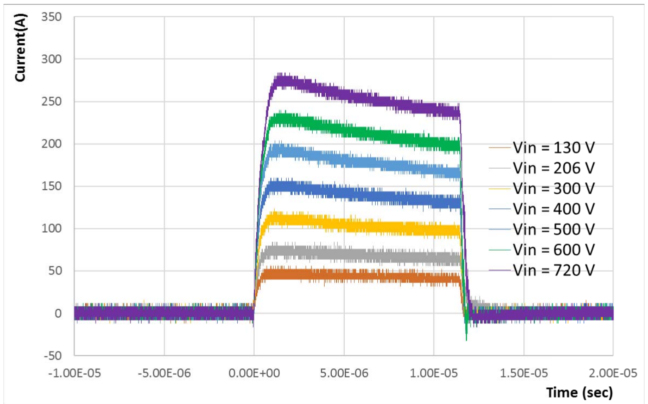

Fig. 6. Test with the resistive load of 24.36 Ω. Different amplitudes of pulse current were taken from the input voltages of 130–720 V. The pulsewidth is 12 μs.

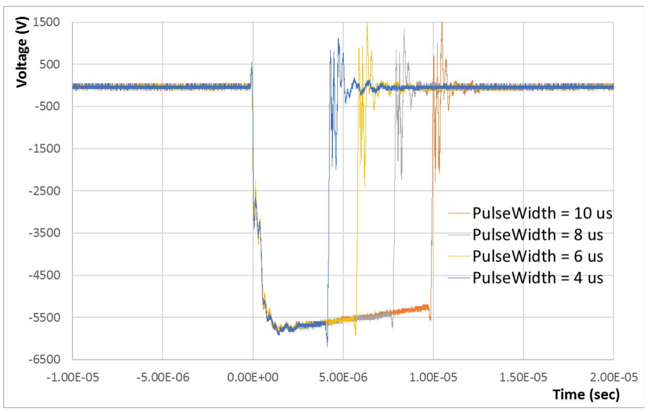

Fig. 7. Test with the resistive load of 24.36 Ω. Generated pulse voltages for the input voltage of 720 V with variable width from 4 to 10 μs.

The output pulses were taken with the width of 12 μs in Figs. 5 and 6. As shown in Fig. 7, the pulse shapes were studied with various pulse widths from 4 to 10 μs. For the voltage droop, it was measured to be 6% at 4 μs and 12% at 12 μs. It is satisfied with the required voltage droop of our magnetron. Therefore, our system will be optimized without any active circuit of the voltage droop correction. The IGBTs of IXYN120N120C3 and FGA30S120P have the half switching time ($<$100 ns at 25°) comparing with the IGBTs used in [7]. In addition, by help of the shorter timing of $t_5 - t_4$ and the switches of *Add-Stage*, we achieved the pulse fall time of 400 ns, resulting in reducing the distortion in the pulsewidth and shape.

IV. Conclusion

The 6-MW solid-state pulse modulator with the multi-stacked storage-switch stages based on the Marx generator for the medical linac was proposed and designed according to the same scheme which was already developed for the low-power solid-state modulator for the electron gun. Especially, the stage was designed with two active switches to control charging and discharging of the storage capacitor of 25 μF for switching the voltage of 720 V and the current of 288 A with the pulsewidth of 5 μs. The prototype eight storage-switch stages were constructed and tested with the resistive load of 24.36 Ω.

Fig. 8. Constructed storage-switch stage boards with component assembly.

The performance results showed that the voltage droop ratio with the pulsewidth of 5 μs is less than 10%, and the storage capacitor of 25 μF and IGBTs was chosen properly. They also verified to amplify the input voltage with the number of stages.

This design is applied for the solid-state pulse modulator with 40 storage-switch stages and optimized with the pulse and heater transformer for the 2.5-MW magnetron operation. As shown in Fig. 8, we are producing these stage boards with components assembly. After passing the board-level quality test, these stages will be integrated and stacked.

As the turns ratio of pulse transformer increases, the number of stages can be reduced. It also leads that the discharging current increases and the voltage droop in the given storage capacitance becomes worse. The current design was optimized with 40 storage-switch stages and two-time boost transformer. However, there is a cost issue to use the expensive pulse transformer of 1:2. We will perform the pulse droop test as increasing the discharging current of IGBTs at each stage, and also check the protection limitation as increasing the input voltage of stacked stages with the constructed system. From these studies, we expect to readjust the turns ratio of the pulse transformer with the reduced number of stages, achieving the system compactness and minimizing the cost.

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Heuijin Lim was born in Daegu, South Korea, in 1974. She received the B.S., M.S., and Ph.D. degrees in physics from Kyungpook National University, Daegu, in 1997, 1999, and 2003.

From 2003 to 2005, she was a Post-Doctoral DESY Fellow with the DESY Laboratory, Hamburg, Germany. From 2005 to 2009, she was a Post-Doctoral Research Associate with the Argonne National Laboratory, Lemont, IL, USA. She was involved in experimental particle physics based on HERA collider and LHC collider. From 2009 to 2013, she was a Research Professor with Ewha Womans University, Seoul, South Korea, and Sungkyunkwan University, Seoul. She developed the space telescope which measures the Gamma-ray burst events as a satellite experiment. Since 2013, she has been a Senior Researcher with the Dongnam Institute of Radiological and Medical Sciences, Busan, South Korea. Her current research interests include the pulse modulator, the control system, and the beam diagnostics system for the radiotherapy machine.

Dong Hyeok Jeong was born in Gimje, South Korea, in 1970. He received the B.S. and M.S. degrees in physics from Chonbuk National University, Jeonju, South Korea, in 1995 and 1999, and the Ph.D. degree from Kunsan National University, Gunsan, South Korea, in 2006.

He was a Medical Physicist with the Department of Radiation Oncology, Wonkwang University Hospital, Iksan, South Korea, from 1995 to 2011. Since 2011, he has been a Chief Researcher with the Research Center, Dongnam Institute of Radiological and Medical Sciences, Busan, South Korea, where he was involved in the development of medical linac and radiation dosimetry. His current research interests include the high-power pulse modulator and the treatment system for the radiotherapy machine.

Manwoo Lee was born in Pohang, South Korea, in 1971. He received the B.S., M.S., and Ph.D. degrees in physics from Kyungpook National University, Daegu, South Korea, in 1998, 2000, and 2006.

From 2006 to 2012, he was a Research Professor with the Physics Department, Kyungpook National University. He was involved in the scintillation detector development, the space-based radiation detector development, and the nuclear data analysis. Since 2012, he has been a Senior Researcher with the Dongnam Institute of Radiological and Medical Sciences, Busan, South Korea. His current research interests include the C-band linac, the RF system, and the pulse modulator for the radiotherapy machine.

Sung Chae Ro was born in Busan, South Korea, in 1960. He received the B.S. and M.S. degrees in electrical engineering from Dong-a University, Busan, in 1988 and 1990, respectively.

From 1990 to 1992, he was with SAMWON FA Ltd., Busan, where he was involved in the research and development of the motor drive systems. From 1992 to 1999, he was the President of DONGA System Company Ltd., Siheung, South Korea, and was leading for the development of high-voltage power supply. Since 1999, he has been the President of Dong-A HiTECH Co., Ltd., Busan. His current research interests include high-power pulse systems for the medical and industrial applications.