Design and Scaled Test of Solid-State Marx Modulator for Proton Beam Extraction

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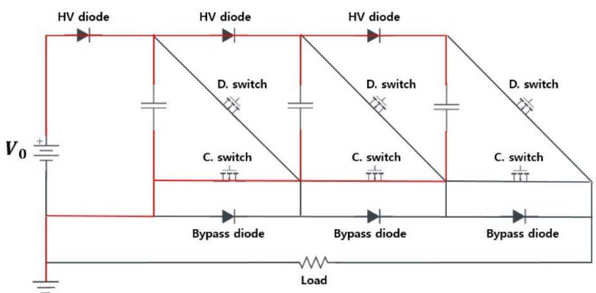
1. Introduction

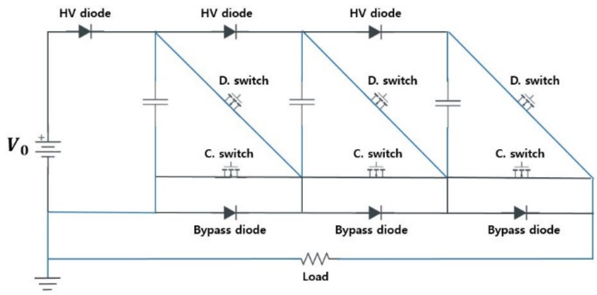
Pulsed extraction of a proton beam from an ion source and its acceleration to a few hundred keV requires a high-voltage pulse modulator. In recent years, all solid-state Marx modulator has been considered as a power modulator accelerating the ion beam in many high energy ion beam accelerator facilities due to its compactness and reliability. In solid-state Marx modulators, solid-state switches are used to erect the capacitor voltage instead of conventional spark-gap switches. In some cases, isolating resistors were replaced by high-voltage (HV) diodes and adapted to reduce the capacitor charging time, thus increasing the repetition-rate [1]. This enables one to obtain a long pulse up to several hundred milliseconds because the isolation inductor limiting the long pulse operation could be removed [2]. In addition, arbitrary waveforms might be easily obtained with the solid-state Marx modulator, owing to its ability of independent switching for each stage [3]. This paper describes the design of a solid-state Marx modulator for the extraction of a proton beam with energy of 150 keV and pulse width of 1 ms. Initial test results with a unit module is discussed as well.

2. Operating principle

A topology of the modulator adapted in this paper is the same as the solid-state modulator previously proposed by Lee *et al*. [4], as shown schematically in Figs. 1(a) and 1(b) for charging mode and discharging mode respectively. It consists of a charging power supply, capacitors, HV diodes, MOSFET switches for charging (C. switch) and discharging (D. switch), and bypass diodes connected in parallel with the charging switches.



(a)



(b)

Fig. 1. Schematic diagram of the Marx modulator for charging mode (a) and discharging mode (b).

When the charging switches are closed simultaneously while the discharging switches open, capacitors are charged from the power supply through the path depicted in Fig. 1(a). Note that the voltage on the capacitors always lower than the power supply voltage V_0, because a HV diode has an intrinsic forward bias voltage drop. The charging time is determined by

$$\Delta t = \frac{\Delta V}{I} \times C_{eff} \tag{1}$$

where, Δt is the charging time, ΔV is the voltage droop, I is the charging current, and C_{eff} is the effective capacitance when all stages are connected in parallel.

In the discharging mode, the capacitors are connected in series by closing the discharging switches just after the opening of the charging switches. The maximum output voltage comes to NV_0 when all discharging switches are closed. If some discharging switches are open, output current flows through the bypass diode connected in parallel with the switches. This feature can be used to shaping of output waveform. Note that the effective capacitance is reduced to C_0/N because of the series connection of the stages.

3. Design features

The required design parameters of the Marx modulator for high energy proton beam extraction is described in Table 1. The maximum output voltage and current are 150 kV and 120 mA, respectively. The required voltage droop during 1 ms discharge is limited to 5%. In order to keep the modulator size compact, unit voltage per stage is selected as 4 kV. By considering the forward voltage drop across diodes, the number of stages of the modulator is determined to be 40.

Table 1. Design parameters of the Marx modulator

Parameter	Design value
Output voltage	150 kV
Output current	120 mA
Pulse width	1 ms
Voltage droop	< 5%
Charging current	< 6 mA
Duty factor	< 4.8%
Voltage per stage	4 kV
Capacitance per stage	0.66 µF
Number of stages	40

The capacitance value of each stage is determined by the required voltage droop during the discharge. From Eq. (1), the effective capacitance is calculated as 16 nF. Hence, the capacitance value of 0.66 µF per stage is determined. For 1 ms discharge, the electric charge of 120 µC is released. To compensate the consumed charge, at least 20 ms charging time is required when the charging power supply with maximum current of 6 mA is used. In this situation, a duty factor is about 4.8% and repetition rate is 47 pps.

A unit module of the Marx modulator is composed of two parts. One is the main power circuit including capacitors and switches, and the other is a board control unit that controls the switches of each stage, as shown in Fig. 2. The board control unit converts external optical trigger signal into electric TTL signal using an optical receiver. Trigger signals for charging and discharging operate independently. Besides, it supplies the operating power from the battery to all of the components which make up one-unit module.

A single stage module consists of a capacitor bank and two switches for charging and discharging. In Fig. 2(a), the left side of the main capacitor is discharging switch and its driving circuit, and the right side is for charging. The switch driving circuit has an optocoupler for isolation of trigger signal, gate driver, and capacitors for bootstrap bias current. When a discharging TTL signal is injected to each stage, all stages are connected in series. As a result, not only the capacitor but also driving components are in the high voltage state. The optocoupler provides high voltage isolation between board control unit and each stage. Since the isolation voltage value increases as the number of stages increases, the maximum number of stages for a unit module is limited by the capability of components against HV isolation. The optocoupler used in this study has a capability of 20 kV isolation performance. It means that the maximum number of stage per unit module is limited to 5 stages. Under these condition, 8 modules which have 5 stages each are needed to be stacked vertically to obtain 40 stages.

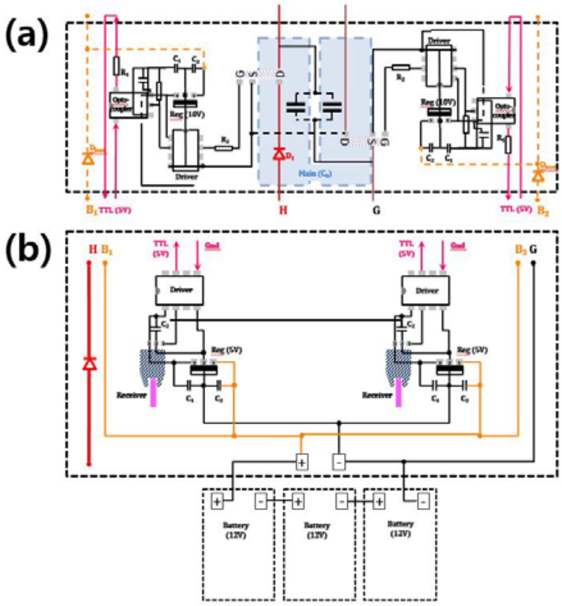


Fig. 2. Schematic diagram of a unit module: (a) single stage and a board control unit.

4. Unit module test

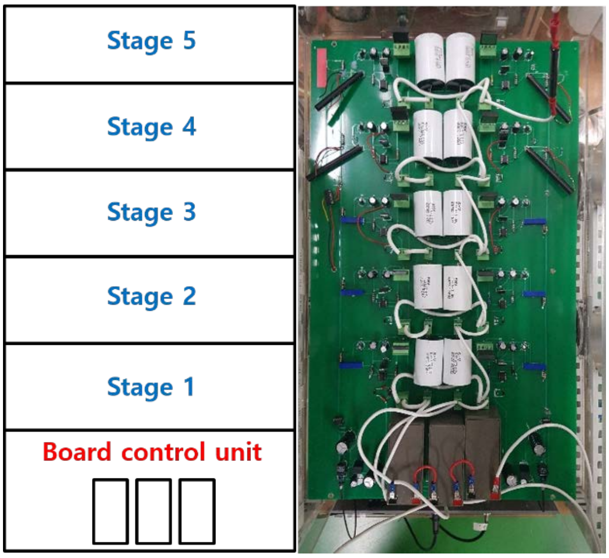


Fig. 3. A unit module consisting of 5-stage Marx and a board control unit.

Figure 3 shows the unit module developed to test high voltage insulation and operation performance. The high voltage insulation and voltage multiplication test results performed for various charging voltages are shown in Fig. 4. The output voltage is fired into a 100 kΩ resistive load for the duration of 1 ms. As shown in Fig. 4, the output voltage is limited to 18 kV for the charging voltage of 4 kV because of the voltage drop across diodes. In this case, the output current is ~180 mA which is slightly larger than the design value. Although the output current is higher than the design value, voltage droop is lower than 5%, satisfying the design requirement. The voltage rise time and the time delay between the trigger signal and the initiation of output voltage were measured to be 0.2 μs and 0.4 μs, respectively.

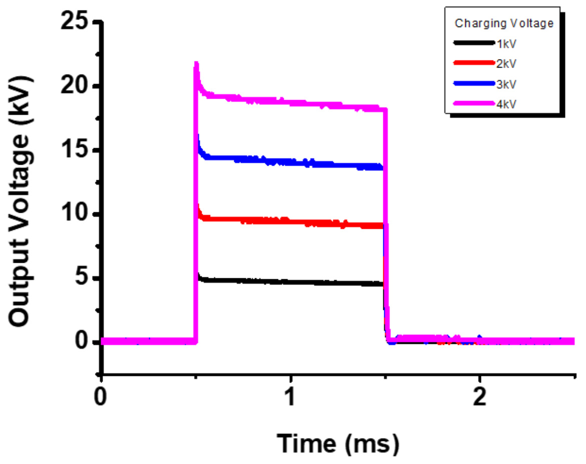


Fig. 4. Output voltage in different charging voltages

5. Summary

An all-solid-state Marx modulator using switch-directed structure has been designed for high voltage of 150 kV proton beam extraction. Using 40-stage Marx modules, it can provide the maximum output voltage of 150 kV and current of 120 mA with 5% voltage droop for 1 ms. A unit module of the Marx modulator has been constructed and tested. The maximum output voltage of 18 kV were achieved for the charging voltage of 4 kV without failure. The voltage rise time and the time delay between the trigger signal and the initiation of output voltage were measured to be 0.2 μs and 0.4 μs, respectively. These results have shown that this design can meet the requirements. Based on the test results, the 150 kV output Marx modulator using 8 modules will be constructed and tested for proton beam extraction at Seoul National University.

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