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Design of solid-state Marx modulator with high duty factor for the proton beam extraction

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1. Introduction

Various techniques have been utilized to generate high voltage (HV) pulses for the proton beam extraction. Direct switching from a large capacitor bank has the risk of a high voltage failure since the switch must withstand full voltage and it is difficult to configure the circuit to protect the switch. On the other hand, transformer-based pulse modulators are not suitable for the case where the overshoot on the leading edge or fluctuation in the flat-top is not allowed because the waveform is distorted during the pulse induction process [1]. To overcome these limitations, various solid-state Marx modulators have been proposed in recent years [2-7]. The solid-state Marx modulator is a concept that substitutes HV diode and solid-state switch (metal oxide semiconductor field effect transistor; MOSFET or insulated-gate bipolar transistor; IGBT) for charging resistor, grounding resistor and spark gap switch in conventional Marx configuration. The pulse width can be adjusted flexibly and the repetition rate can be increased by using only a small portion of the energy stored in the Marx capacitors.

The structure proposed by Dale *et al.* [8] eliminated the need for a charging inductor by adding a switch in parallel to the diode of the grounding path in the previously proposed diode-directed structure [2] and enables a long pulse operation of several ms. This structure has the same working principle as proposed by Pepitone *et al.* [9], but there are detailed differences in the driving circuit due to operation purpose and required specifications. In addition to the advantages of diode-directed structures such as flexible shaping of output pulse and self-snubbing for switch protection, high recharging efficiency [2] and crowbar function of the grounding switch are suitable for high duty operation [9] in this study. In this paper, we propose a solid-state Marx modulator design optimized for required performance based on these merits and describe its operating principle.

2. Solid-state Marx modulator

The simplified circuit and the operating principle of the proposed Marx modulator are shown in Fig. 1. Each stage consists of one capacitor bank and two MOSFETs connected by HV diodes. In the figure, the MOSFETs connecting the capacitor in the series direction are the discharging switches (symbol- D) and the MOSFETs connected in parallel with the bypass diodes of the ground path are the charging switches (symbol- C).

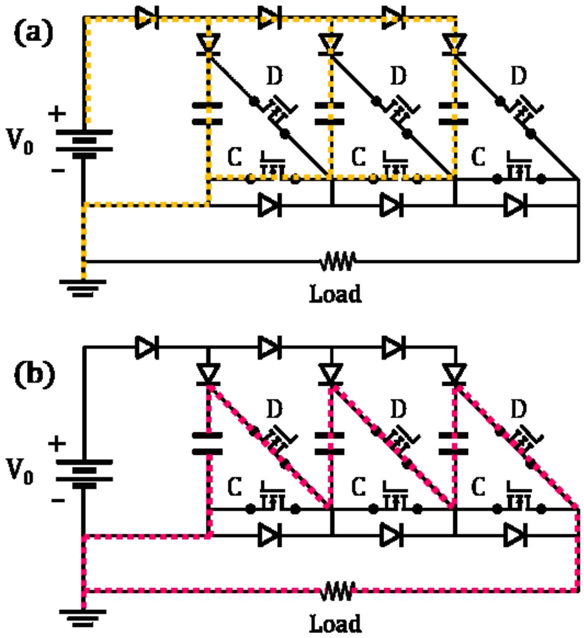

Fig. 1. Working principle of the solid-state Marx modulator: (a) charging mode and (b) discharging mode.

2.1 Charging mode

In the charging mode, as the current loop is completed by turning off the discharging switches and turning on the charging switches, the HV dc-power supply begins charging Marx capacitors up to V_0. The duty factor of the modulator is the limiting factor on the recharging speed during the repetitive mode operation, except for the initial start-up in which a fully discharged capacitor is to be charged. If the charging current of the dc-power supply is large enough, the ballast resistor can be positioned considering the RC time constant by the total capacitance ($N \times C_0$) in the charging mode. Charging diodes are forward biased, so the voltage charged on the capacitor is slightly lower than the voltage of the charging power supply. Since all the charging switches are located on the ground path, the first stage (from the left in the figure) is always charging regardless of whether the charging switches are turned on or not.

2.2 Discharging mode

In discharging mode, discharging switches are turned on and charging switches are off, so the connection of capacitors is changed from parallel to series. The MOSFET(C) and the charging diode isolate the charged voltage between each stage, and finally the voltage of

NxV_0 is output to the load. The effective capacitance in discharging mode is reduced to C_0/N as the connections between the capacitors change in series. The pulse output is terminated with the MOSFET(D) turned off, and after a certain delay, the crowbar function exhibits as the grounding switches are turned on, so that the load voltage quickly falls to zero. It is noted that the cross conduction which occurs when both gate signals of the MOSFET(D) and the MOSFET(C) are high must be prevented. For this purpose, it is necessary to appropriately set a period in which both gates are low based on the signal propagation characteristics of the gate control system.

Table I: Marx modulator specifications

Parameter	Value
Max. output voltage (V_{out})	55 kV
Max. output current (I_{out})	30 mA
Peak power (P_{pk})	1.65 kW
Pulse width (t_{on})	$\leq$ 2 ms
Repetition rate	$\leq$ 120 pps
Voltage droop	$\leq$ 2%
Duty factor	$\leq$ 24%
Charging current	$\geq$ 20 mA
Voltage per stage (V_0)	1.83 kV
Effective capacitance (C)	66.7 nF
Number of stages	30
Capacitance per stage (C_0)	2 μF

3. Design features

The specifications of the pulse modulator required for the extraction of the proton beam are as shown in Table I. Output pulses of 55 kV, 30 mA should last for a maximum of 2 ms and the voltage droop needs to be managed within 2%. In the erected state in which output pulses are fired, the released charge is 60 μC, so the effective capacitance (C_0/N) should be larger than 55 nF. Effective capacitance increases as the number of stages (N) constituting the modulator increases. The total number of stages (N) and the charging voltage (V_0) were determined considering the maximum voltage and capacitance specifications of commercial power capacitors. Selected capacitors (2 kV, 2 μF) are charged up to 1.83 kV when operating the modulator. Currently, repetition rate required by the accelerator system is 60 pps, but there is plan to increase it to 120 pps later. Thus, maximum repetition rate of the Marx modulator is set to 120 pps. At 120 pps repetitive mode operation, the duty factor is up to 24%, and the energy consumed by the pulse output should be fully recovered during off-period of about 6 ms. Hence, an average recharge current of 10 mA is required, and given the RC time characteristic, the current of HV dc-power supply can be marginally determined to be greater than 20 mA.

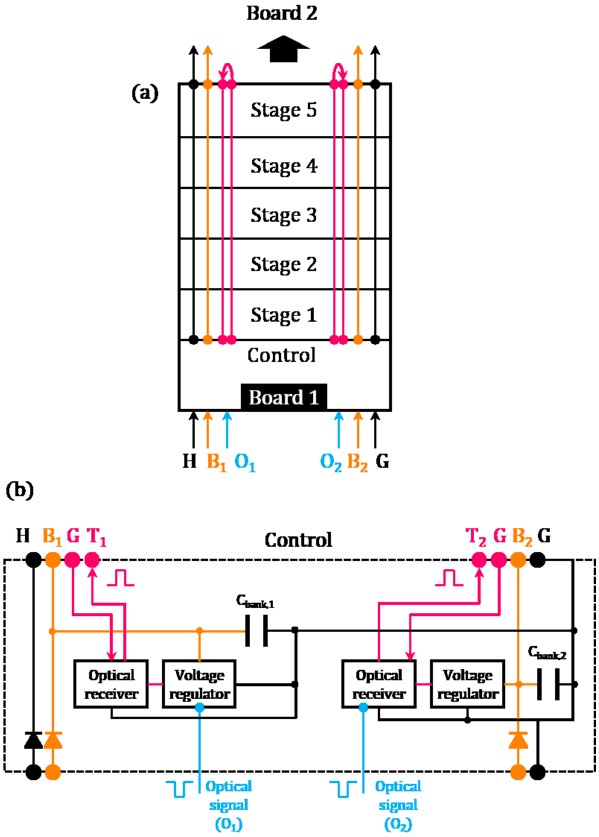

Fig. 2. Schematic diagram of the Marx modulator layout: (a) single board (5 stages) and (b) board control unit.

Figure 2 shows the layout of the overall Marx modulator. Each board consists of five Marx stages and a board control unit. Since a total of 30 stages are required, the modulator system can be constructed by assembling 6 boards. The output side of each board is connected to the input side of the next board, and solid-state switches are controlled independently from the optical signals (O_1, O_2) provided by the external optical transmitters. Thus, only a total of 12 optical transceiver pairs are required in the entire system and the O_1 and O_2 signals (6 pairs each) are separately controlled in synchronization. The utility power for the five stages on each board is maintained by the capacitor banks ($C_{bank1,2}$) on the board control unit. The concept of a bootstrap bias supply can be used to efficiently manage the charged voltage of these capacitor banks. Since the capacitor banks are referenced to the ground node of each board, they are recharged only during the Marx's charging mode. This is practically the same as the process of recharging the Marx main capacitors. However, since the capacitor banks of the control unit has only a few tens of charged voltage, the bootstrap diode should be selected so that the forward bias drop is as low as possible. If necessary, the capacitor banks can be replaced by batteries.

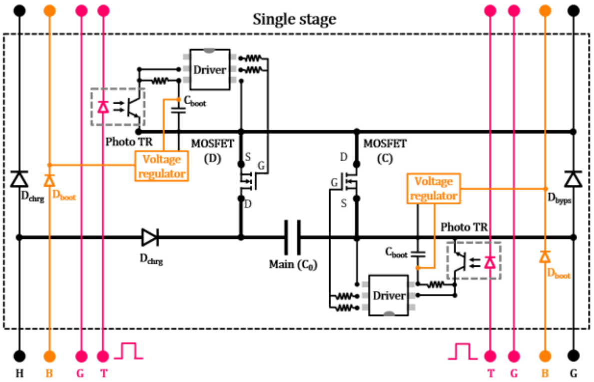

Fig. 3. Circuit diagram of a single Marx stage.

Circuit diagram of a single Marx stage is shown in Fig. 3. HV diodes positioned on the left arm are the charging diode and the one positioned on the right arm is bypass diode. MOSFET(C) shown in Fig. 3 defines the ground potential of next stage. Considering the crowbar function, both MOSFET(D) and MOSFET(C) require high-side drive and two design factors are employed. One is the bootstrap bias supply for the utility power and the other is isolation of control signals using optocoupler (photo-transistor). Aiming at a current output of 30 mA, a MOSFET that can handle both turn-on and turn-off with a unipolar drive is suitable. On the other hand, the pulse width on the ms scale alleviates the requirement for pulse rise time or fall time. Therefore, using the optocoupler, which has a slower response than the usual optical transceiver, can greatly simplify the gate control circuit, which can reduce the power consumption by the MOSFET drive. Therefore, it is expected that the utility power for the gate driver can be effectively sustained even with the bootstrap bias supply scheme. The inverter circuit for supplying isolated power to each stage is no longer necessary, in this configuration. The bootstrap capacitors (C_{boot}) can be charged during the Marx's charging mode, as the source potentials of both MOSFETs are pulled down to ground. The bootstrap diodes are reversely biased in the discharging mode and the stored energy in the bootstrap capacitors (C_{boot}) sustain the gate-drive. Optical signals are transformed to the electrical pulses by the optical receivers placed in the board control unit. Since the electrical trigger signals ($T_{1,2}$) shares the reference potential with that of board control unit, the optocoupler must withstand more than 10 kV(max) on the last stage of each board. The propagation delay (~2 μs) which occurs in the optocoupler slows down the response of the actual pulse output compared to the control signals. Therefore, the end user must consider the characteristics of the delayed pulse output to fully synchronize the modulator to the accelerator system.

4. Conclusion

A solid-state Marx modulator with high duty factor is proposed for the extraction of proton beam. The designed modulator has a total of 30 stages and it fires output pulses of 55 kV, 30 mA at 120 pps. The switch located in the grounding path enhances recharging efficiency and implements the crowbar function. This enables high duty operation up to 24%. We designed the overall circuit layout and the driving circuit optimized for the required performance. Each board consists of five Marx stages and a board control unit which sustains the utility power required at each stage. The control signals delivered to each stage are isolated using an optocoupler, and the gate power is supplied through the bootstrap bias supply. The structure of the driving circuit is simplified, and further variation and optimization are expected in various research fields. The Marx modulator proposed in this paper will be constructed and tested at Seoul National University.

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