

PRELIMINARY EXPERIMENT ON VOLTAGE DROOP COMPENSATION FOR HIGH POWER MARX MODULATORS*

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Abstract

Marx modulators, promising higher efficiency, longer lifetime and reduced cost compared with existing hard tube modulator options, are under intensive research. In this article, we describe the progress of work on our voltage droop compensation scheme for a Marx modulator. Experimental results on a compensation circuit at moderate voltage are presented.

INTRODUCTION

Solid-state Marx modulators have attracted many studies recently [1-8] as an alternative to conventional modulators. A Marx generator, which produces HV pulses by switching capacitors that are pre-charged with low dc voltage into a series-connected capacitor bank to output a HV pulse, is a rugged, low-impedance source of electrical energy and has been utilized in a variety of high-peak-power applications during the past few decades. In recent time, Marx has been applied to modulators with the aid of advanced semiconductor switches or solid-state switches. The current interruption capability of the solid-state switches allows a Marx modulator to produce square-shaped output pulses at a high repetition rate, and also change its output pulse width from one pulse to the next, giving Marx modulators the ability to adapt the alteration of load requirements rapidly. However, Marx modulators face significant challenges, such as voltage droop, when they are used to generate a long HV pulse. For example, voltage droop of the Marx modulator designed for the ILC may be well over tens of percentages if no compensation is added [3-5]. DULY Research has proposed a scheme of real time switching of power supply to compensate the voltage droop and obtained DOE's SBIR support. In our Phase I work, we successfully demonstrated the effectiveness of the scheme in our simulations and in low voltage experiments [9]. Higher voltage experiments have been designed and relevant tests are carried out in the ensuing Phase II work. In this paper, we will present the progress of our experiments on the active compensation of the voltage droop of the Marx modulator. Further experiments and future tests will also be discussed.

EXPERIMENTAL SETUP

The main purpose of the experiments is to demonstrate the feasibility of the compensation scheme by providing voltage pulses that have small fluctuations on flattops. To compensate the voltage droop of the main cells in a Marx modulator, we proposed to adopt modified

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vernier cells (MVC), which can store more electric energy and thus save the cost to build the modulator. We selected the second configuration (see Figure 6 in Reference 9) of the MVC for the present higher voltage experiments. By fully incorporating the high-speed solid-state switches that are used in the MVC for regulating the compensation current in the manner we proposed, we are able to smooth the flattop of the voltage pulses output by the main cells (MC) of the Marx modulator.

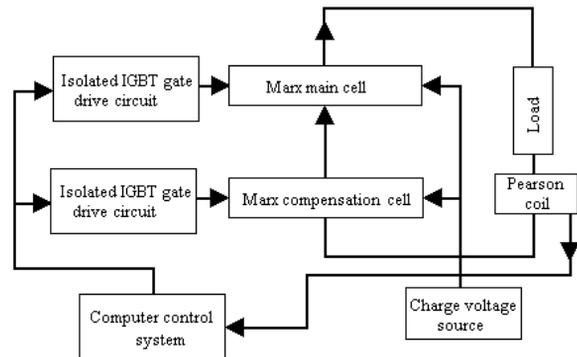


Figure 1: Diagram for the high voltage experiment



Figure 2: Experimental setup.

A diagram for the high voltage test is shown in Figure 1, and the experimental setup (not including the computer control) is shown in Figure 2. In order to facilitate change of components in the main circuit, critical components were built on an open PCB board without any enclosure. In the test, one stage Marx MC (capacitance: 2 μF) and one MVC ($C_1=30 \mu\text{F}$) were employed. The impedance of the load is 1.07 k Ω . Charge voltage source can output a voltage from 0 V to ~320 V. Optical couplers were used to isolate the IGBT drive circuits from the IGBT gates inside the MC and the MVC. The discharge processes of the MC and MVC are controlled by IGBTs through the isolated drive circuits,

which are connected with a computer control system. Voltage sampling circuit is another critical sub-system of the compensation circuit. We used Pearson coil at first for isolating the voltage detection circuit from the high voltage Marx main discharge circuit, but later we changed to a voltage divider for obtaining large signal to noise ratio. Since the voltage divider output a negative voltage signal while the computer read-in port needed a positive one, a voltage inverter was installed between the voltage divider and the computer read-in port for the voltage transformation.

EXPERIMENTS ON THE MVC CIRCUIT

There are several factors that impact the compensation effectiveness of the MVC (see Figure 6 in Reference 9). They are: a. main electric energy storage capacitor C1; b. IGBT switching speed; c. current limiting inductor L1; d. charge voltage V; e. fluctuation smoothing capacitor C2. Among these, L1 is the most sensitive factor for smoothing the flattop of the voltage pulses, although the other factors also have significant impacts on the compensation function. In prior low voltage experiments, we have observed or analysed the compensation variations under the first four factors [9]. In this higher voltage test, we have conducted experiments when L1, V, and C2 are changed in sequence with the aim of searching for proper component parameters of stabilizing the voltage flattop.

In prior simulations, we found that the minimum inductance should be around 4-6 mH for our computer to control the IGBTs effectively. For the present experiments, the inductance value of the inductor in the MVC was changed while C2 was kept at 1 μ F. The fluctuations of the flattop of the voltage pulses (duration: 1.7 ms) output by the MC under different compensation circumstances were observed and the results were shown in Figure 3. Figures 3a, b, c, and d show the pulses when the MC discharges but the MVC is turned off; L was set at 5 mH, 8 mH, and 15.3 mH respectively. Both charge voltages for the MC and MVC are 320 V.

Table 1: The percentage of the fluctuation amplitude to the charge voltage for various values of inductance.

Inductance	Fluctuation amplitude (division)	Percentage to charge voltage
5 mH	1.7	32.7
8.1 mH	1.25	24.0
15.3 mH	0.45	8.7

It is seen from Figure 3a that a voltage droop is more than 50% of the original pulse height at the end of the pulse if no any compensation is made. When the MVC was turned on, the droop was removed with varying degree of variations of the pulse flattop. The variations were dependent on the value of the inductor inside the

MVC. The percentage of the variations to the charge voltage (5.2 divisions) is summarized in Table 1.

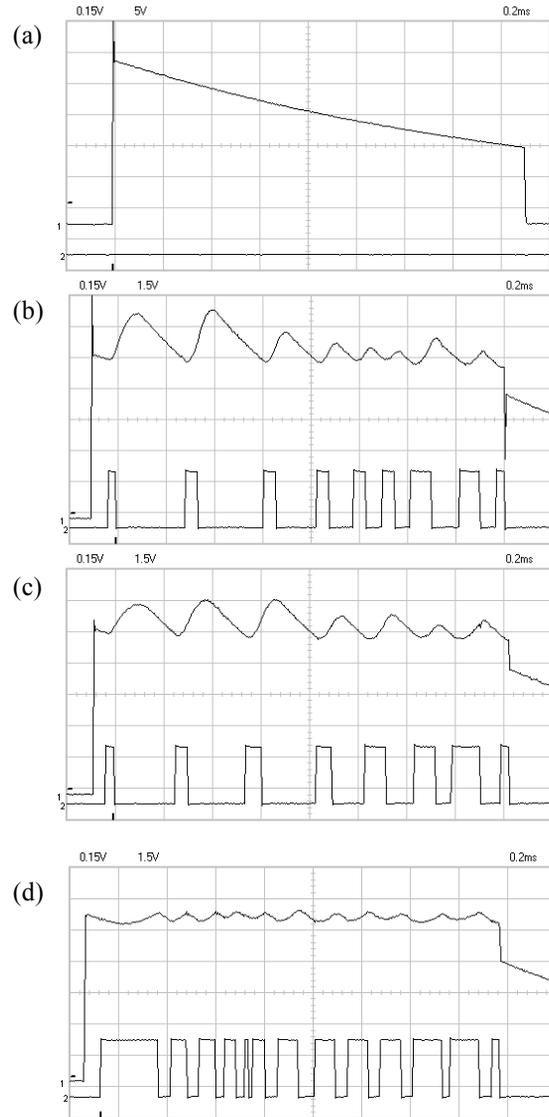


Figure 3: Voltage pulses output by the MC: a. no MVC function; b. L=5 mH in MVC; c. L=8 mH in MVC; and d. L=15.3 mH in MVC. Trace 1 is the voltage pulse and Trace 2 is the computer trigger signal curve to turn on (use high voltage level) the MVC.

The fluctuation tends to be small if a large inductance is used. But we couldn't test more inductance values at this time because non-saturation inductors with higher values of inductance were unavailable temporarily. More tests are scheduled in the near future. From Table 1, we observed that variation at 15.3 mH for a single MC was 8%. Compared with the ILC requirement of $\pm 0.5\%$ variation, at first this would seem that the ILC requirement was not met. However, we need to consider the fact that a Marx modulator used for high-energy accelerators is generally made of tens of MCs. For the interim test, our experiments used only one MC. The droop of the output voltage is due to the MC capacitive

discharge. The fluctuations during compensation were caused by the MVC during the time when it was triggered by the computer to output its electric energy gradually. So the fluctuations mainly depended on the properties of the MVC and its control system, not those of the MC. Increasing the number of discharge MCs should not vary the fluctuations' amplitudes, but only change the overall voltage pulse amplitude, resulting in an even lower percentage of the fluctuations in that voltage pulse. For a Marx modulator having tens of MCs, the fluctuation percentage could be reduced in proportion to tens of times smaller. Thus, it is expected that a 10% fluctuation tested with a single MC ought to diminish to 1% or smaller when more than 10 MCs are employed in a Marx. It should be noted that the data shown in Table 1 were not yet optimized. There is much room to improve the fluctuation range. By contrast, if a MVC compensates to a MC with an identical capacitor and if no any regulation measure is applied to the MVC, the fluctuation will be 100% of the charge voltage, which can be simply calculated by RC discharge equation. The comparison shows the great advantage of our MVC scheme. The projected results in this case with many more MCs will be confirmed experimentally with tests on a real Marx modulator used in accelerator application. These experiments are being planned and will be performed in the final stage of this project.

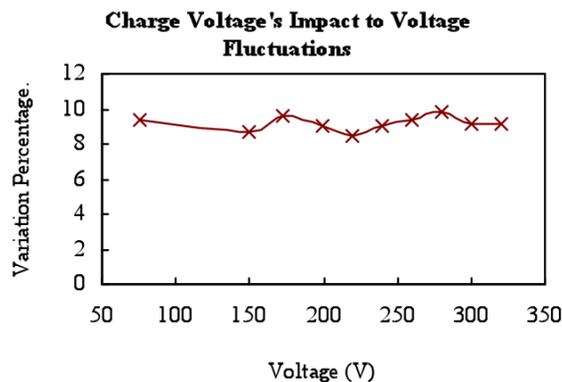


Figure 4: Relation between the charge voltage of MVC and the fluctuation of pulse flattop.

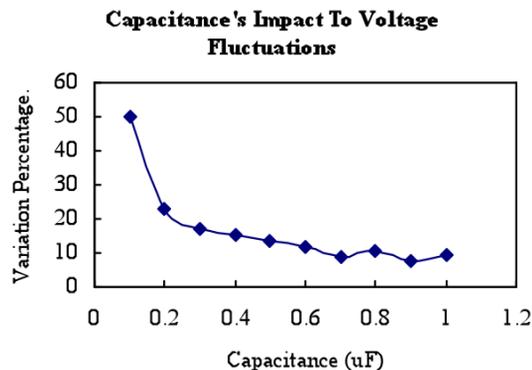


Figure 5: The dependence of the voltage fluctuations on the capacitance of C2 when L1 is at 15.3 mH.

The relation between the MVC charge voltage and the flattop variation has been experimented when the inductance was kept at 15.3 mH, and the results are plotted in Figure 4. Charge voltages were raised from 75 V to 320 V, the limit of our present voltage source. It is observed that voltage fluctuations ranged 8% to 10%, indicating the charge voltage at these values may not significantly impact the voltage fluctuations, which is a good omen for our later higher voltage experiments.

In addition to L1, there is another crucial circuit component, i.e. capacitor C2, that can be adjusted for further smoothing the fluctuations. The circuit topology is slightly different to the one we used in Phase I work. Tests regarding the impact of the values of the capacitor to the fluctuations have been performed (see Figure 5). For this set of measurements, we maintained the value of the inductance and varied the values of the capacitor. The voltage fluctuation dropped rapidly when the capacitance was less than 0.3 μF , but its decrease slowed (to around 9%) for higher value, indicating a non-sensitive region in which to select the capacitor's values. The diminish of the fluctuations may be due to the increment of the LC oscillation periods, which gives the switching devices (IGBT) adequate time to regulate the compensation voltage. To fully test the function of this capacitor, we will schedule more tests with different inductances.

These experiments showed that our simple scheme for compensating the voltage droop is feasible up to the current charge voltage level of 320V. Experiments for charge voltage level of the MC and MVC around 1 kV will be conducted in the following time.

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