VOLTAGE DROOP COMPENSATION FOR MARX MODULATORS*

P. Chen#, M. Lundquist, D. Yu, DULY Research Inc., Rancho Palos Verdes, CA, USA

Abstract

Marx modulators operated by solid-state switches (e.g. MOSFET, IGBT) offer an alternative to traditional high voltage (HV) modulators for rf power sources. They have the merits of compact size, high-energy efficiency, high reliability, pulse width control and cost reduction. However, Marx modulators need a complex voltage compensation circuit if they are employed in long pulse applications such as the ILC. We describe here a novel scheme to compensate the HV droop of a Marx modulator by use of inductors and fast solid-state switches. The feasibility of the scheme was analyzed and proof-of-principle, low-voltage experiments were performed.

INTRODUCTION

Solid-state Marx modulators have been studied [1-8] as an alternative to conventional modulators that use hard tube switches which have a number of issues limiting their performance and application, e.g. large oil transformer for long pulse applications, being difficult to adjust and less reliable. A Marx generator using solid-state switches is a promising way of resolving these issues. The Marx, which produces HV pulses by switching the 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. More recently, with the advent of modern solid-state switching devices, the Marx application has now expanded into modulators. The current interruption capability of solid-state switches allows a Marx modulator to produce square-shaped output pulses at a very high repetition rate, and also changes its output pulse width from one pulse to the next, which gives Marx modulators the ability to adapt the alteration of load requirements rapidly. However, Marx modulators face great challenge when they are used to generate a long HV pulse such as that required by the ILC. The problem is intrinsic to the properties of a Marx generator. When discharging, the Marx voltage will decay with time. Either a small constant of the RC circuit or a long pulse width will lead to a larger voltage reduction at the end of a pulse. The ILC requires that voltage fluctuations, including voltage droops, be within ±0.5% in a 1.4 ms pulse flattop. An obvious way to limit the voltage droop for the Marx modulator is to increase the time constant of the modulator circuit. This would require a large capacitance of the Marx [8], as the impedance of Marx's load (klystron) cannot be changed arbitrarily. An expensive and bulky capacitor bank for the Marx modulator would need to be built. Another way is to build a voltage compensation circuitry. This research approach has been actively pursued [3-5, 8-9], although so far no satisfactory results have been reported.

Here we introduce a novel design scheme for the Marx modulator using low-cost circuitry designed to effectively compensate the voltage droop of the Marx main cell (MMC) output.

DESIGN SCHEME OF THE COMPENSATION CIRCUITRY

The central component of our compensation scheme is a HV charged compensation cell, called a modified vernier cell (MVC), by fully incorporating the high-speed solid state switches with their ability to resist current change in the inductive components. Because of its high stored electrical energy, the MVC can have a charge voltage as high as that of MMC, and can compensate the HV droop of the MMC for a longer time period, compared to that of the existing compensation vernier cells (VC) [4-5]. A simple topology of the MVC is shown in Figure 1.

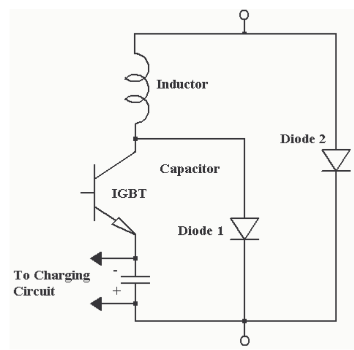

Figure 1: Configuration of a MVC.

The MVC shown in Figure 1 is in series with the ground end of the MMC bank. Its output voltage complements the voltage pulse output by the MMC bank.

Compared to the MMC in literature [10], the MVC shown in Figure 1 has additional components, i.e. an inductor and Diode 1, which are needed in the MVC to smooth abrupt voltage changes. During operation, the IGBT switch will be turned on if the voltage output by the MMC bank droops to a certain level. Voltage of the capacitor in the MVC will add to the pulse output by the MMC bank gradually due to the presence of the inductor. When the total voltage recovers its desired level, the IGBT will be turned off. Energy stored in the inductor will be released to compensate the voltage of the MMC bank and thus avoid an abrupt reduction of the voltage. The procedures can be repeated many times under a controlling device such as a commercial single-board computer so that the voltage droop in an entire pulse length (1.4 ms for ILC) can be compensated.

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#pchen1@sbcglobal.net

CALCULATIONS AND SIMULATIONS

We have calculated the minimum number of VCs to meet the ILC specifications of a voltage pulse (-120 kV high and ~1.4 ms long). The energy in VCs should at least make up the energy difference between the ideal pulse energy and the actual decayed pulse energy absorbed by a klystron. Voltage $V(t)$ output by a MMC bank with total capacitance C attenuates according to:

$$V(t) = V_0 e^{-\frac{t}{RC}} \quad , \tag{1}$$

where V_0 is dc charge voltage on the capacitor bank, t is discharging time, and R is the load of the MMC bank (i.e. the impedance of the klystrons, ~854 Ω for the ILC [11]). The output power $P(t)$ of the MMCs decays in a form of:

$$P(t) = \frac{V(t)^2}{R} \quad . \tag{2}$$

If $E(t)$ is the total energy dissipated on the load R, then:

$$E(t) = \int_0^t P(t)dt = \frac{1}{2} \times C{V_o}^2 (1 - e^{-\frac{2t}{RC}}) . \tag{3}$$

Since ILC requires a rectangular voltage pulse (amplitude of V_0), the energy $E_r(t)$ of the pulse loss in a load R is:

$$. \qquad E_r(t) = \frac{V_0^2}{R} \times t . \tag{4}$$

The energy stored in VCs should make up the difference between $E_r(t)$ and $E(t)$,

$$E(t) = \frac{1}{2} \times C_v {V_v}^2 , \tag{5}$$

where C_v is the capacitance and V_v is the charge voltage of the VC.

Table 1: Minimum Number of VCs Required for ILC Project in Different Designs

Design	Marx stage no.	Charge volt. (kV)	Stage C (uF)	VC's charge volt. (kV)	VCs' C (uF)	Pulse width (ms)	No. of VCs in existing scheme	No. of VCs in DULY's scheme
1	10	12	30	0.9	30	1.4	761	4.28
2	11	11	48	1.25	450	1.4	19.1	2.32
3	10	12	48	0.9	450	1.4	35.7	1.88
4	12	10	110	0.9	330	1.6	36.2	0.89

In Table 1, we estimated the minimum number of VCs required for different design parameters found in references [4-5]. The 8th column refers to the minimum number of VCs required for voltage droop compensation using design parameters given in the columns before. By comparison, DULY's scheme, in the 9th column, requires far fewer number of MVCs having the same capacitances and charge voltages as those of MMCs. The minimum number of required VCs in the traditional design is typically an order higher than the number of the cells of our scheme because of its much lower charge voltages compared to MMCs.

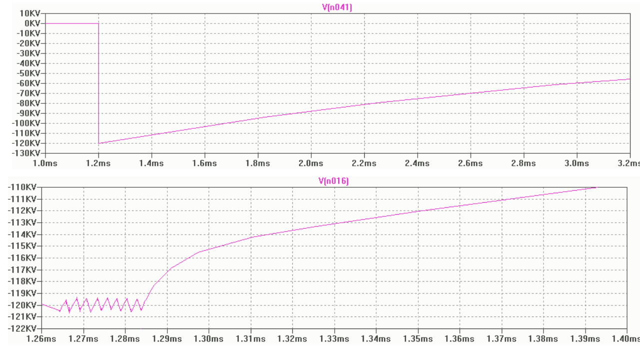

Figure 2: Above: Discharge curve of the Marx without compensation. Below: HV pulse of the Marx modulator in series of a MVC having inductance of 5.1 mH.

SPICE code simulations of the feasibility of the MVC were done with the Marx parameters shown in the 1st row of Table 1, using the MVC in Figure 1. Simulation results are shown in Figure 2, where the figure above is the MMC bank discharging curve and the figure below is the compensation result when the MMC bank is in series of a MVC that includes a 5.1 mH inductor. The results indicate that the fluctuations of the pulse flattop can be well controlled within ±0.5%. As real-time compensation is time-consuming, we only simulated compensation in a small time range. The MVC can compensate the voltage pulse in a much longer range. Similar results were obtained for the MVC with a 4 mH inductor in a shorter compensation interval. The results indicate that the parameters of the MVC need to be selected based on the response speeds of the controlling and switching devices such as the computer and the solid-state switches.

LOW VOLTAGE EXPERIMENTS ON THE MVC CIRCUITRY

Low-voltage experiments were performed for the MVC compensation circuitry. For simplicity, one stage Marx (C=3 μF) with charge voltage from ~55 V to 75 V was used and the charge voltage of the MVC (see Figure 1) was 6 V, roughly one tenth of MMC. The capacitance of the VC was 30 μF, similar to the MMC in reference [5].

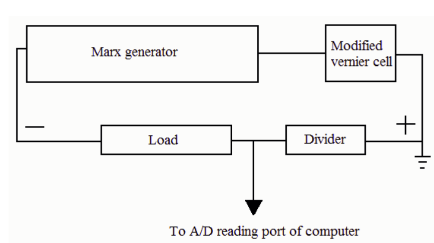

Figure 3: Diagram for the low voltage experiment.

In our tests, IGBT (rated at 100V) switches were driven by driver circuits and controlled by a single-board computer. The voltage of the divider was sent to the computer for computing the entire voltage of the Marx modulator. Compensation with a single VC and regulated by the computer was observed in the initial experiments (see Figure 4), where the overall voltage pulse was 1.7 ms long. The compensation actions (Curve 2, Fig. 2) made small ripples on the overall voltage pulse (Curve 1, Fig. 2) and maintained its level up to t=500 µs. After that, the overall voltage pulse decayed as the stored energy of the MVC was exhausted.

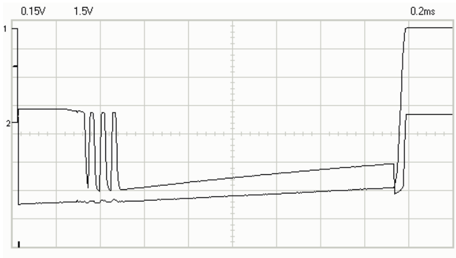

Figure 4: Compensation actions observed.

Next, the Marx capacitance was changed from 3 µF to 6 µF while the MVC was still maintained at 30 µF and 6 V charge voltage. The compensation ability of the MVC increased (see Figure 5) and the overall voltage pulses obtained longer compensation actions.

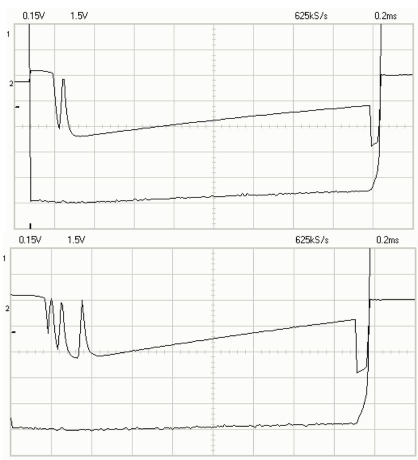

Figure 5: Compensation Curvesfor Marx C=3µF (Upper) and 6µF (Bottom).

In the next experiments, we changed the charge voltages of the MMC from 57.98 V to 61.02 V, 66.96 V, 70.28 V while keeping the charge voltage of the MVC. We found that the compensation ability of the MVC weakened gradually, a phenomenon already indicated in our prior calculations. Further, we found that the compensation intervals needed to be cut when we employed smaller inductance in the MVC, which agreed with our simulations well. The experimental results above illustrate that the MVC design scheme is viable at low voltage.

TOPOLOGY DISCUSSION

To prevent klystron arcing, we also studied another topology of the compensation circuitry (see Figure 6). The circuitry consists of two parts. The first part, including an inductor (L_1), a diode (D_1), a capacitor (C_1) and a solid-state switch (IGBT SW1), is actually a configuration of a buck converter. The second part that embraces the rest of the components is a MMC used in reference [10]. The voltage across C_2 can be compensated in real time by the energy of the buck converter under a controlling device such as a computer. If the two ends connected to C_2 exchange their positions, the MVC will start from a negative biased. But the cost of this connection should be figured out carefully since more MMCs will be needed.

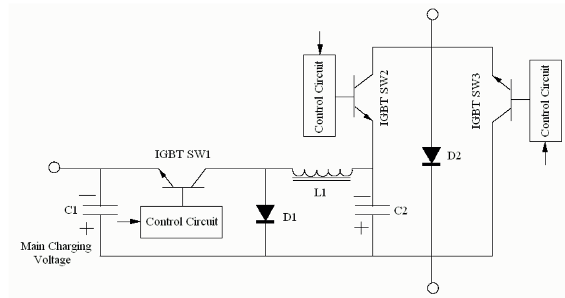

Figure 6: The second configuration of the MVC.

The merits of the circuit in Figure 6 are: 1) It has two switches (IGBT SW1 & 2) to cut down any energy path to the klystron when the klystron is arcing; 2) Inductor L1 is not in the circuit of the discharge path of the MMCs. It has a light current load. So do IGBT SW1 and Diode 1. Although it looks like that the configuration in Fig. 6 has more components, it is far less expensive than the previous Marx modulator designs because 1) the compensation strength of one MVC will be equivalent to that of several VCs charged in low voltage, and 2) some of the components in the configuration are light load. It should be pointed out that the topology of the MVC in Figure 1 is a special case of that in Fig. 6 (when C_2=0).

In summary, the viability of the simplified compensation circuitry design has been demonstrated by calculations, simulations and low voltage experiments. Further experiments are needed to completely confirm its feasibility for high voltage applications.

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