A NOVEL SOLID-STATE MARX MODULATOR TOPOLOGY WITH VOLTAGE DROOP SELF-COMPENSATION*

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Abstract

A novel topology of the solid state Marx modulator is described for raising its electric energy utilization ratio (EEUR) and suppressing voltage droop. The topology allows Marx cells to store a large amount of electric energy and utilize it efficiently. Theoretical analysis and initial experiment show that the Marx modulator with the new topology, under proper control of energy release, is able to significantly enhance its EEUR.

A NEW TOPOLOGY

In November 2007, we submitted an SBIR proposal to DOE for studying how to efficiently counteract the voltage droop of solid-state Marx modulators (Marx in short) and was funded April 2008 [1]. In the proposal, we proposed a new Marx compensation cell (NMCC). To our knowledge, this is the first time to use inductors in compensation cells (CCs) to prevent abrupt voltage addition on a Marx cell (MC) bank voltage. During follow up experiments, we realized that it was necessary to perform an overhaul on the Marx to raise the low value of its EEUR, defined as the available electric energy that can be dissipated in a Marx's load during one pulse, or one discharge period, over total electric energy stored in the capacitors of the Marx at start of the pulse. We thus design a new topology for the Marx described below.

For the Marx with a number of MCs [2], electric energy E_t stored in the Marx relates to the MCs by a relation of $E_t=n\times C\times V^2/2$, where n, C and V are the number of cells, the capacitance and the charge voltage of the MC's capacitors in order. During discharge, the maximum energy dissipated on the Marx's load, E_u, is:

$$E_u=n\times C\times(V^2-V_d^2)/2 \qquad (1)$$

where V_d is the residual voltage of the MC's capacitors after discharge. The EEUR is given by:

$$EEUR=E_u/E_t=1-(V_d/V)^2 \qquad (2)$$

From Eq. 1 & 2, an EEUR is low if V_d closes to V. So we have to greatly increase E_t in order to obtain adequate energy supply to the load. For example, if V_d is required not to be lower than 99% of V, EEUR is equal to 1.99%, which means more than 98% energy in Marx's capacitors cannot be utilized. By just being stored there, it occupies a large stack of capacitors. To raise the EEUR so that voltage droop can be mitigated, CCs were studied. Currently, using vernier cells (VCs, one kind of CCs) are the prevailing method to compensate voltage droop [2], though there are some variations such as combining a VC with a MC [3]. EEUR of the Marx is increased effectively by this way and the energy stored in MCs [3-4] is reduced from 1.5 MJ to ~100 kJ, corresponding to an EEUR ~25%. However, the method is expensive, limiting further improvement of EEURs, since each VC is built as an integrated cell and has limited compensation ability [5-6].

New Topology of the solid state Marx modulator

From above, we attribute the root cause of low EEURs of a simple Marx to insufficient separation of the final voltage (use voltage) after discharge from the initial charge voltage of the MC capacitors. A moderate increase of the charge voltage to higher than the final discharge voltage can greatly improve the EEUR. For example, if the charge voltage of the MC [3] is raised from the original 4 kV to 6 kV but its final voltage after discharge remains at 4 kV, then the EEUR becomes 56%, roughly twice that above. However, the paradigm of enlarging the difference between initial charge voltage and the final voltage cannot be implemented on a conventional MC [2] because its main capacitors are part of the discharge circuit loop and any change of the capacitor voltage directly affects the one on the load (e.g. klystron) which does not accept large voltage changes. Therefore, another capacitor that can hold charged energy but is not in the discharge loop of the Marx is needed. Our design concept of a high EEUR Marx modulator is illustrated in Fig. 1.

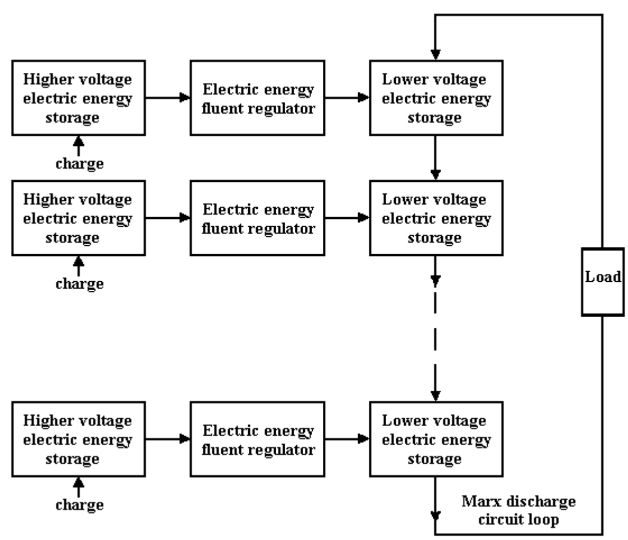

Figure 1: Diagram for designing a new Marx modulator.

A buck regulator meets our requirements when it is incorporated with a MC, forming a new Marx cell (NMC, see Fig. 2), which also is one topology of our NMCCs but with different control. The buck regulator here is not a

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conventional one that uses switching frequency to control its output voltage. In fact, its switch may cut off energy flow at any time during a compensation pulse. In Fig. 2, Line AB separates NMC into two parts: left is a buck regulator circuit and right is a MC. The buck regulator has four components, i.e. high voltage (HERV) Capacitor 1, high voltage (HV) Switch(es) 2, Diode 3 and Inductor 4. In operation, as the energy in lower-voltage (LERV) Capacitor 6 is dissipated, its voltage quickly reduces due to its limited stored energy. Once the voltage approaches a preset value, switch 2 is turned on by an intelligent control (a computer) and the energy in HERV capacitor 1 flows to LERV capacitor 6 rapidly, compensating its energy loss and raising its voltage slightly above the preset value, when switch 2 is off and energy transfer is ended temporarily till the voltage of LERV capacitor 6 is low again. Since the NMC can maintain its output voltage, it is called a self-sustainable NMC.

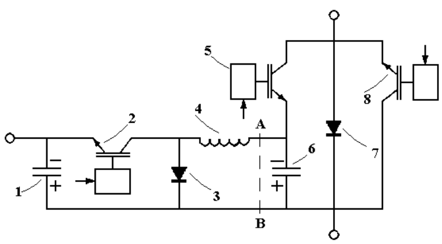

Figure 2: The topology of a NMC.

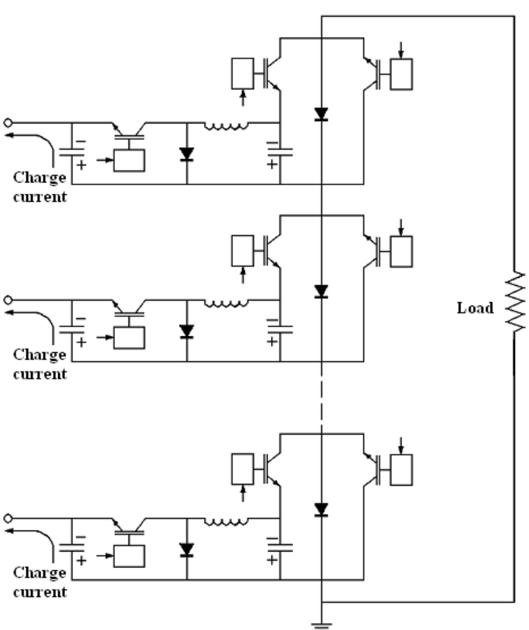

Figure 3: New topology for Marx modulators.

Two factors greatly impact the energy transfer process. The first one is the switching ability of Switch 2, including its speed, voltage rating, etc. Solid-state switches such as HV IGBTs are commercially available [7], with their switching speeds (< 1 μs) fast enough in ms application. During each switching time, one NMC releases a large part of the stored energy equivalent to that of a VC. Switches 2 need not switch too many times, alleviating its load working in HV. One IGBT can release multiple portions of energy, indicating the ability to replace several VCs. The second factor is Inductor 4, which needs a proper value for matching energy regulation speed. A new topology of the entire Marx is shown in Fig. 3, built with self-sustainable NMCs.

Calculations of energy storage capacity and New Marx modulator simulations

Here we show how the size of the Marx's capacitors is materially reduced as EEUR is increased. The electric energy, E_c, in a simple two-parallel-electrode capacitor is:

$$E_c=(1/2)\times C\times V_c^2=(1/2)\times(S/d)\times\varepsilon\times(E_f\times d)^2\,, \qquad (3)$$

where C is the capacitance, V_c is the voltage across the capacitor, S is the electrodes' area, d is the gap distance between the two electrodes, ε is the dielectric constant of the capacitor's filling material, and E_f is the capacitor's internal electric field. From the equation it follows:

$$E_c=(1/2)\times\varepsilon\times V_s\times E_f^2, \qquad (4)$$

where V_s=S×d is the volume of the capacitor. The energy in a capacitor is proportional to V_s if ε and E_f are fixed. Now, if we only increase the electrodes' gap to 1.5d and reduce the surface area of the capacitor's electrode proportionally so that the volume of the capacitor is not changed, the energy stored in the capacitor should be the same as before. But the voltage of the capacitor has been increase to 1.5Vc. From prior calculation, we know that the EEUR will be raised to 56% if the capacitor discharges from 1.5Vc to Vc, 27.9 times of the EEUR of 1.99% computed before, which means the Marx with 56% of EEUR is capable of outputting as many as 27.9 times the electric energy of the conventional Marx with only 1.99% of EEUR. In another word, the energy stack volume of the Marx modulator that needs 1.5 MJ will be diminished to 53.76 kJ if its EEUR is raised from 1.99% to 56%. Also note that the Marx modulator having VCs still need to store ~100 kJ energy. Since E_f is constant, there is no risk of internal HV breakdown. Our topology needs two energy storage capacitors for each NMC, but the size of our two capacitors together is still much smaller than the single capacitor used in a VC-compensated Marx because LERV Capacitor 6 is very small (see the model in simulations). In fact, when we analyse the two energy storages of our new topology, it is easy to realize that the charge voltage variations will not impact the output voltage of LERV Capacitor 6 as the voltage depends on the switching that regulates the energy fluent. Thus, LERV Capacitor 6 will not need a highly accurate charge voltage source, further reducing cost.

Initial simulations are performed on the Marx with the new topology, using the LTspice code. The Marx is modeled as having only one NMC. HERV Capacitor 1 and LERV Capacitor 6 are 30 μF and 1 uF individually. The inductor is 11.66 mH, and the load is 1069 Ω. HERV capacitor 1 is assumed to have a charge voltage of 400 V while LERV Capacitor 6 outputs a voltage pulse with initial amplitude of 178.5 V (use voltage). The simulation results show that the output voltage of the Marx can be well balanced between 177.4 V and 179.3 V, without any voltage droop, during 1.2 ms.

Preliminary experiments on the new topology

To further verify the viability of the new topology, we performed preliminary experiment on the Marx having the same circuit parameters as the simulations, except the voltage on LERV Capacitor 6, which is regulated by IGBT switch under computer control. By switching the energy fluent, the voltage droop of the Marx should be compensated and stabilized within a small range of fluctuations. We adopted an open-loop control algorithm, taking advantage of the fact that the Marx load is a high power resistor having stable resistance value.

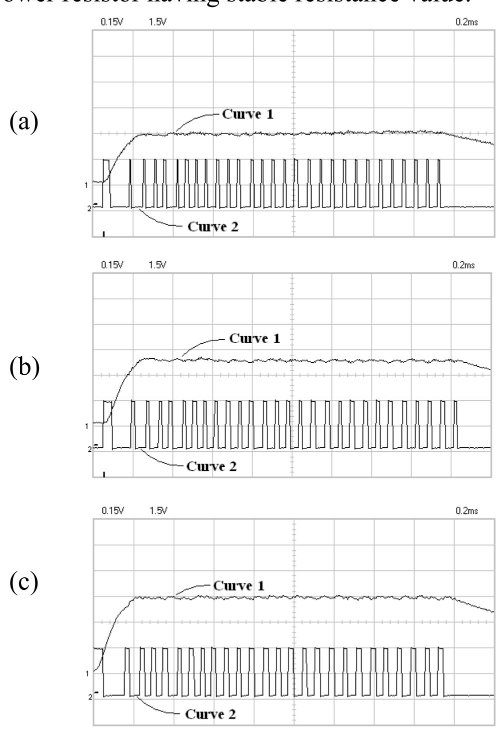

Figure 4: Initial experimental results.

Initial experimental results are shown in Fig. 4a to c. In Fig. 4, Curve 1 is the voltage pulse output by the new Marx. Curve 2 is the computer control pulse. For Curve 2, a HV level (~ 3 V) indicates the IGBT is turned on and energy is transferred from HERV Capacitor 1 to LERV Capacitor 6, while LV level (0 V) means that IGBT is off and no energy transfer occurs. When we changed our control software to alter the IGBT turn on time and duration time (comparing Curve 2 from Fig. 4a to 4c), we obtained three different output voltage amplitudes, i.e. 116.9 V, 153.8 V and 178.5 V, shown as Curve 1 in Fig. 4a-c, from the new Marx. Flattop fluctuations of all three curves are suppressed to 6% of their individual pulse amplitude. The fluctuations can be improved to smaller than 1% as required by the ILC in two ways: (1) Make a Marx modulator with multiple cells in series [6]; and (2) Tune the computer control program more finely than our preliminary experiments.

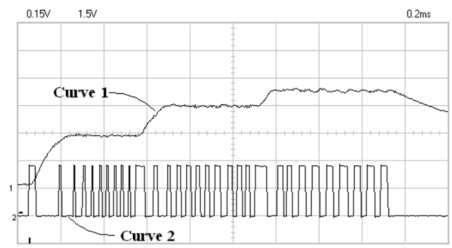

Figure 5: Terrace voltage pulse output by the new Marx.

The relatively slow rise and fall times shown in Fig. 4a to 4c are due to the algorithm in the control software because so far we have not tried to accurately control the IGBT switches. But we will do so in next experiments. The ability to change the output voltage pulse waveform by modifying a control program is another merit of this new type of Marx modulator. To further demonstrate the versatility of the control software, we have conducted an experiment for outputting a terrace voltage pulse by exploiting a simple program to regulate the energy fluent. The experimental result is indicated in Fig. 5, where Curve 1 is the terrace voltage pulse and Curve 2 is the computer control signal.

CONCLUSION

Although it is clear that the EEUR in the new Marx is considerably higher than other topologies, so far we have not measured its precise value in our preliminary experiment. This task, together with high voltage experiments (~4kV) is under preparation. Our theoretical analysis, simulation data and initial experimental results indicate the new topology for Marx modulators is feasible and has many important merits, bringing us to the edge of a breakthrough in the Marx technology. Success of the project will not only materially foster the applications of Marx modulators in the high-energy accelerator field, but also expand our modulator design paradigm and horizon greatly.

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