Moduladores Ressonantes de Alta Tensão para Alvo do ISOLDE

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***Abstract*—This paper describes a new solid-state resonant converter topology to increase the energy efficiency of the solid-state switching circuit being designed to replace the actual pulse transformer and thyratron based resonant modulator that supplies the 60 kV target potential for the ion acceleration of the On-Line Isotope Mass Separator ISOLDE accelerator. The results of an experimental prototype of 100 V are presented and discussed to validate the concept. The design of the materials, including the high-voltage coil, and switching times of the semiconductors proved to be critical to recover energy with high efficiency.**

***Index Terms*—Resonant converter, energy efficiency, accelerator power supply, energy recovery, high-voltage pulse circuit.**

I. Introduction

THIS paper describes and evaluates a new topology to replace the actual transformer thyratron based resonant modulator that supplies the acceleration voltage in the On-line Isotope Separator, ISOLDE, of the European Organization for Nuclear Research, CERN, taking the considerations and requirements imposed by the load and system operation in [1].

The ion source of the ISOLDE accelerator, located at the PSB – Proto-Synchrotron Booster, is connected to a thick target which is periodically bombarded by a proton beam. The ions produced in this step are accelerated to 60 kV before transport to the experimental area. To achieve the needed acceleration and high mass resolution in the downstream separator, both the target and ion source must be held at a precise and stable voltage with respect to a grounded extraction electrode as specified in [2].

Conventional topologies based on pulse transformers and thyratron [2] or two semiconductor stacks [1] were able to discharge to zero the capacitive load prior to ion beam impact and recharge it to the initial voltage afterwards using and auxiliary power supply. Such configuration does not allow energy recovery from the load, approximately 18 J and requires an additional 60 kV power supply to recharge the load.

Recent solid-state resonant topologies have been proposed to address the energy efficiency and recovery of the modulator where a coil is introduced to control the energy flow during charging and discharging of the load.

Such circuit was introduced in [3] by having an asymmetric bridge using three semiconductors Behlke and a coil, show in Fig. 1, that stored the energy from the load prior the beam impact and restored the voltage to 72% of the initial value (on the 1000 V experimental test). In this configuration, 18% of the energy is lost in the wire resistance, semiconductor conduction and switching periods, mainly due to the long period of time the coil is conducting while short-circuited to store the energy.

To compensate this voltage drop, an auxiliary power supply PSa was introduced in [4], as show in Fig. 2, which allowed to fully restore the voltage on the load to 6 kV for just 19 V. This topology has major benefits by meeting the requirements in [2] while recovering energy from the load and using a cheaper auxiliary power supply.

A novel approach to this resonant topology is achieved in this work by taking the lessons learned from previous work to develop a resonant converter with two switches and a coil.

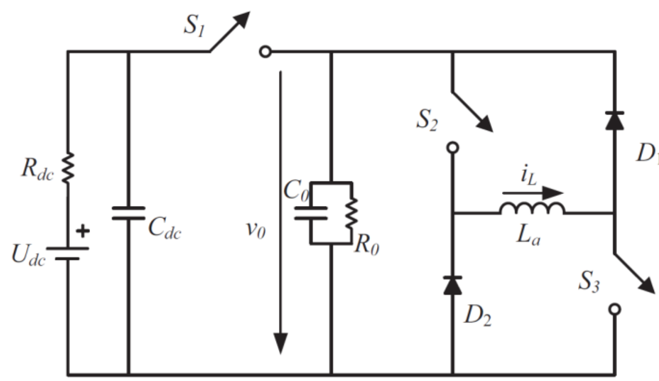

Fig. 1. Solid-state asymmetric bridge resonant converter circuit

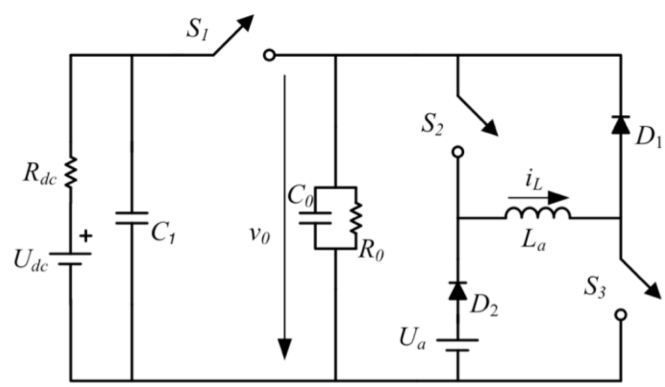

Fig. 2. Solid-state asymmetric bridge resonant converter with losses compensation circuit

II. Proposed Circuit

The proposed replacement circuit concept is show in Fig. 3, with actual 60 kV power supply U_{dc}, considering the internal resistor R_{dc} and boost capacitor C_{dc}, two auxiliary high voltage semiconductors switches (or semiconductor arrangements [5]) with a hold-off voltage of 60 kV.

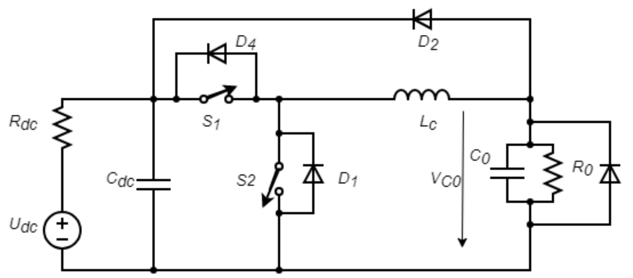

Fig. 3. Proposed replacement circuit topology concept for the ISOLDE target modulator.

To understand the circuit principles, the Fig. 4 shows the theoretical waveforms of the switch's S1 and S2 gate signals, voltage on the load C_0/R_0 and the current on the coil L_c.

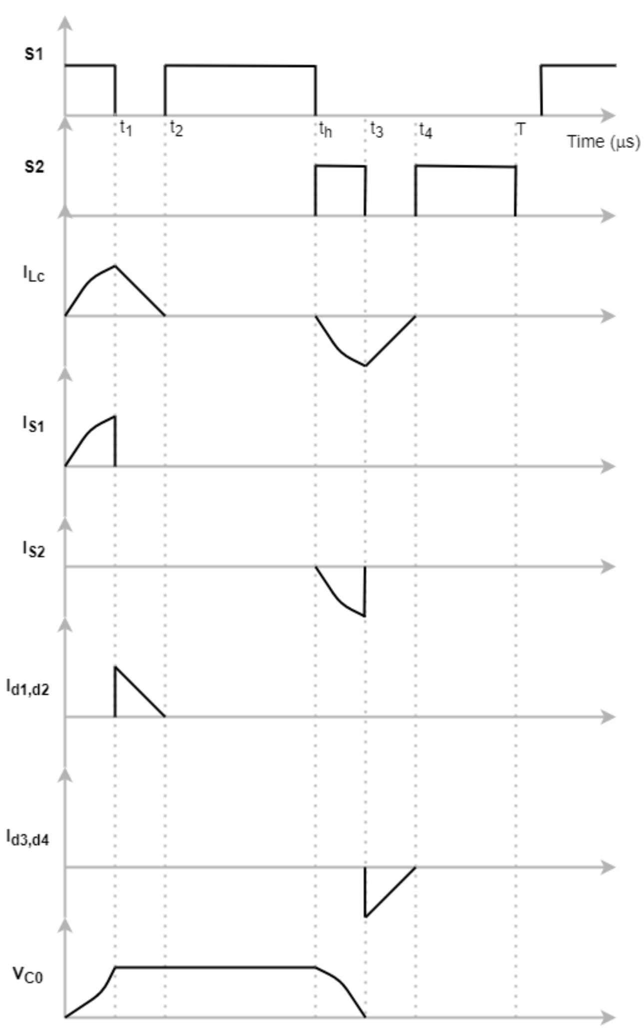

Fig. 4. Theoretical waveforms for the proposed replacement circuit topology for the ISOLDE target modulator of Fig. 3.

The waveforms showed in in Fig. 4 start when the target was impacted by the beam and the voltage needs to recover to the initial value 60 kV +/- 1V for detection. During this time, $t \in [0, t_1]$ (1), S1 is *on* and the target is charged resonantly through L_c.

$$t_1 = \frac{T}{4} = \frac{\pi\sqrt{L_c C_0}}{2} \tag{1}$$

When the load reaches the maximum voltage V_{max}, at the instant t_1, the current in the coil L_c reaches the peak value I_{max} (2). This energy stored in the coil returns to the power supply during the interval $t \in [t_1, t_2]$, raising the voltage at C_{dc}, through the diodes D_1 and D_2, and having S1 *off*.

$$I_{max} = \frac{V_{max}}{Z_0} \tag{2}$$

$$Z_0 = \left(1 + \frac{1}{Q}\right)\omega_{res} L_c \approx \omega_{res} L_c \tag{3}$$

$$\omega_{res} = \frac{1}{\sqrt{\frac{L_c}{C_{eq}}}} = \sqrt{\frac{C_0 + C_{dc}}{L_c C_0 C_{dc}}} \tag{4}$$

In (3) it is considered a quality factor Q of at least 200, which is a crucial design parameter to achieve high efficiency in this topology.

The time needed for the coil to completely discharge can be calculated given that $C_{dc} >> C_0$ the current falls at constant voltage (5), and t_2 is given by (6).

$$\frac{dI_L}{dt} = \frac{U_{dc}}{L} \tag{5}$$

$$t_2 = t_1 + \frac{L\, I_{L,max}}{U_{dc}} \tag{6}$$

By completely discharging the energy in the coil to the power supply, C_{dc}, the semiconductor S1 is switched *on* again at precisely t_2 to stabilize the voltage at the target until t_h, allowing scientists to perform measurements.

Due to the oscillatory nature of this topology, it is crucial to trigger S1 *on* and *off* at the precise times mentioned to achieve a stable and fast voltage on the target.

After measurements are completed at t_h the voltage at the target needs to be modulated to zero during the interval $t \in [t_h, t_3]$. So, the semiconductor S2 is switched *on*, allowing the load to charge the magnetic energy in the coil. When the voltage at C_0 reaches zero, at t_3 given by (7), the current at L_c is reaching the peak value and the current will now flow through D_3, allowing the voltage to stabilize at zero.

$$t_3 = t_h + t_2 \tag{7}$$

At t_3, the magnetic energy in the core of L_c needs to return to the power supply, C_{dc}, to optimize the energy recovery. So S2 is switched *off* during $t \in [t_3, t_4]$ allowing the current to flow through D_4, returning the energy to the power supply. If the semiconductors are ideal, there is no need to trigger S2 *on* again at t_4, given by (8). However, it was observed that the current in

L_c could revert and increase the voltage in the target by forcing the semiconductor S1 to conduct negatively. To prevent this effect, S2 is switched *on* during $t \in [t_4, T]$, stabilizing the voltage of the target at zero during the beam impact.

$$t_4 = t_h + t_2 \qquad (8)$$

III. Experimental Results

A laboratory level prototype of the Fig. 3 was assembled to validate the proposed concept at 100 V. For the switches S1 and S2 a SiC - *Silicon Carbide* MOSFET – *Metal Oxide Semiconductor Field Effect Transistor* N-Channel ST Microelectronics SCT30N120, rated at 1200 V and 45 A, was selected. For diodes, the Silicon Carbide Power Schottky Diode, model GB05SLT12-220, from GeneSiC, rated at 1200 V and 12 A, was selected.

The switches were commanded by a Hybrid Dual MOSFET Driver, model SKHI 21A (R), from Semikron. The control signals were generated in a PI 18F2331 microcontroller and send via opto-couplers the input gates, to better insulate the switching noise.

TABLE I
Experimental Control Signal's Timings

Instant	Value [µs]
t_1	50
t_2	100
t_h	354
t_3	410
t_4	440
T	540

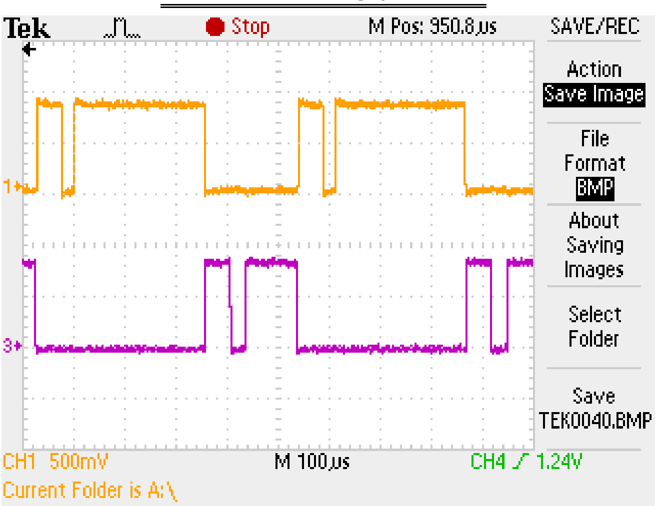

Fig. 5. Experimental control signals for Fig. 3 circuit operation. 100 µs / div. Trigger signals for S1 (top) and S2 (bottom).

The main power supply U_{dc} used was a conventional low voltage power supply, with a buffer C_{dc} capacitance of 4 µF. The load consists of 0.44 nF capacitor in parallel with a 10 MΩ resistor.

The coil was assembled for 1000 V, with 2.5 mH, using a core material ETD59-3C90 from Ferroxcube.

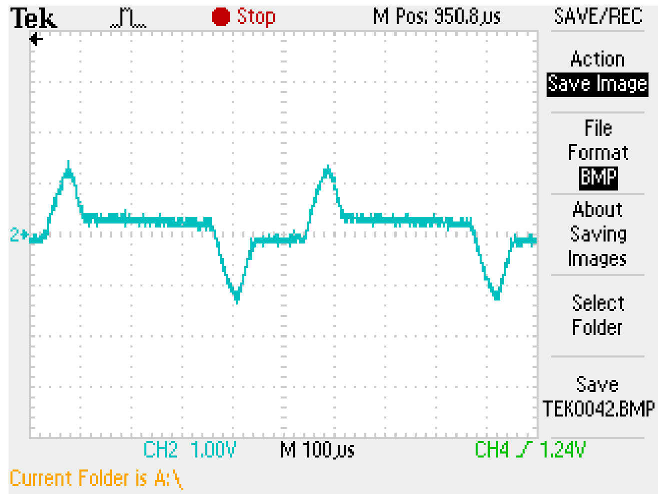

Fig. 6. Experimental current waveform at the coil Lc for Fig. 3 circuit operation. 100 µs / div.

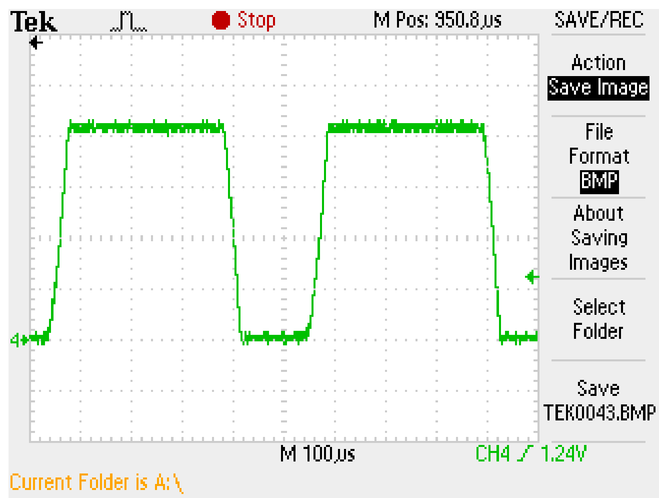

Fig. 7. Experimental waveform ate the load for Fig. 3 circuit operation. 100 µs / div. Oscilloscope voltage scale 10x. Voltage probe scale 20x.

To measure the current in the coil, a Tektronix A622 current probe was used, and to measure the voltages a conventional voltage probe with 20 times voltage reduction. The results were visualized in a Tektronix TDS 2024 oscilloscope.

The control signals for semiconductors S1 and S2 were configured to achieve the timings shown in Table I, with a frequency of 1785 H_z. The waveforms of the control signals are presented in Fig. 5.

With this configuration the waveforms of the current in the coil L_c were obtained in Fig. 6, having a peak current of 0.57 A, and for voltage on the load in Fig. 7. The measured load time to fall to zero was 14 µs.

It is possible to observe the expected behavior of the resonant circuit for the ISOLDE target modulator, by achieving a stable voltage at the target prior to the beam impact when the voltage should be zero and after impact when the voltage should be restored in less than 33 µs while stabilizing at the maximum value, while recovering the energy at each stage.

However, this topology requires additional analysis and configuration to be applied for the 60 kV target modulator.

The precision of the switches control signals is crucial to achieve the highest efficiency. To demonstrate this, the topology was tested in the same conditions without the second signal *on* for S2 during the time $t \in [t_4, T]$. In this scenario, when the coil discharges completely through D_4 to the power supply, the S1 is switched *on* due to the non-idealities, reversing the energy flow and charging the target again. This effect is shown in Fig. 8.

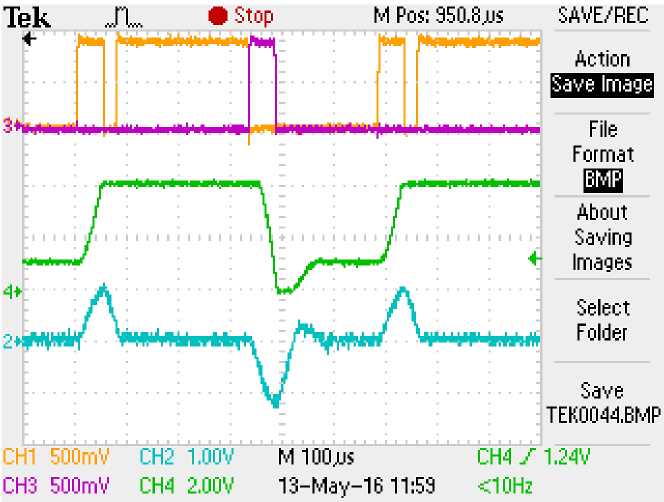

Fig. 8. Experimental results when S2 is switched *on* during t_4 and T. Trigger signals for S1 (orange top) and S2 (violet top). Load voltage waveform (green middle). Coil current waveform (blue bottom).

IV. Conclusion

The increased number in resonant topologies for the ISOLDE target modulator show that there is room for improvement in the target voltage stabilization and modulation to zero in a short amount of time.

The topology presented in this paper presented a new approach to improve energy recovery to the main power supply and improving the overall efficiency. The preliminary results of a 100 V laboratory prototype show the concept is valid, but it needs careful design and assembly, especially the precision of the control signals, to decrease losses.

Acknowledgment

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References

[1] L. M. Redondo, J. Fernando Silva, H. Canacsinh, N. Ferrão, C. Mendes, R. Soares, J. Schipper and A. Fowler, “Solid-state Marx based two switch voltage modulator for the On-Line Isotope Mass Separator accelerator at the European Organization for Nuclear Research”, Review of Scientific Instruments 81, 7, pp. 074703, Jul 2010.

[2] D. C. Fiander and A. Fowler, "A 60 KV MODULATOR FOR THE TARGET VOLTAGE OF AN ON-LINE ISOTOPE SEPARATOR," *Twentieth Conference Record on Power Modulator Symposium*, Myrtle Beach, SC, USA, 1992, pp. 173.

[3] L. M. Redondo, J. F. Silva, H. Canacsinh, J. P. M. Mendes, M. A. Rodrigues and T. Fowler, "Resonant converter topology for the new ISOLDE/CERN modulator," 2014 IEEE International Power Modulator and High Voltage Conference (IPMHVC), Santa Fe, NM, 2014, pp. 119-122.

[4] L. M. Redondo, H. Canacsinh, J. F. Silva and A. Fowler, "Resonant Converter Topology With Losses Compensation for the ISOLDE/CERN Modulator," in IEEE Transactions on Plasma Science, vol. 45, no. 12, pp. 3265-3270, Dec. 2017.

[5] L. M. Redondo, J. F Silva, P Tavares, E Margato, “All Silicon Marxbank topology for high-voltage, high-frequency rectangular pulses, Power Electronics Specialists Conference”, 2005. PESC'05. IEEE 36th, pp. 1170-1174.