COMPARISON AMONG ELIGIBLE TOPOLOGIES FOR MARX KLYSTRON MODULATORS

C. Abbate, G. Busatto, F. Iannuzzo, C. Pagliarone, G.M. Piacentino,
University of Cassino, Cassino, Italy
F. Bedeschi, INFN, Pisa, Italy

Abstract

The possible issues related to the use of last-generations Insulated Gate Bipolar Transistors (IGBTs) switches into a Marx-topology klystron modulator are discussed. Experimental results obtained from two cells Marx prototypes using two different solutions, including single device and series connected devices both hard-switched, are presented. The use of single high voltage device per cell allowed us to obtain lower on-state voltage drop but much slower switching times. On the other side the series connection of lower voltage IGBTs results in much faster commutations and lower devices costs accompanied by a larger on state voltage drop.

INTRODUCTION

The International Linear Collider (ILC) is a High Energy Physics particle accelerator that will give physicists a new cosmic doorway to explore energy regimes beyond the reach of today's accelerators [1]. ILC will complement the Large Hadron Collider (LHC), a proton-proton collider at the European Center for Nuclear Research (CERN) in Geneva, Switzerland, by producing electron-positron collisions at center of mass energy ranging from 200 GeV to 500 GeV.

It consists of two linear accelerators (linacs), 31 kilometers long, facing each other, plus two damping rings each with a circumference of about 6.7 kilometers [2]. The accelerating gradient, for the ILC main linacs, will be supplied by 16000 pure niobium superconducting 1.3 GHz accelerating cavities, with a nominal gradient of about 31.5 MeV/m, powered by 576 10 MW RF Stations, each with a Modulator, a Klystron and a RF Distribution System. Another 86 similar stations will be used for the e+ and e- sources and Ring to Main Linac (RTML) bunch compressors. Each of the 10 MW L-band ILC Klystron will require a Klystron Modulator capable to provide 120 kV, 140 A, 1.6 ms (27 kJ) pulses at 5 Hz repetition rate, within a specified flatness tolerance below 1 % [2].

The existing Baseline Configuration Document (BCD) modulator is a transformer-based topology. The large size, weight, and cost of this transformer, owing to the long pulse length, have motivated research into alternative topologies that do not employ power magnetics as for example the the Marx Modulators [3].

A Marx modulator is essentially a high-voltage pulse generator that uses a set of N capacitors, charged in parallel to a low input voltage, Vin, and discharged in series to apply a high voltage Vout= NxVin to the target load. In recent years, the classical Marx layout has been improved by using semiconductor switches that increase control, efficiency and pulse form [4, 5]. In a Marx design, the danger of overvoltage is minimized because switches don't hold-off large potentials and remain isolated within the subsystems. In many cases the improvements consist solely of replacing traditional switches (e.g. spark gaps) with solid-state devices, but traditional passive elements (inductive chokes of resistors) are kept to provide charging paths and stage isolation.

The present ILC Marx modulator uses solid-state switches and isolation elements to connect capacitors in parallel while charging but in series during discharge to generate the required high voltage output without the use of a transformer. This has several advantages over the conventional klystron modulator designs as it is physically smaller, there is no pulse transformer (quite massive for the needed voltages and currents), no need of large energy storage capacitor banks, owing to the active droop, it is oil-free, the voltage hold-off is achieved by using air insulation, it is air cooled and any secondary air-water heat exchanger is physically isolated from the electronic components.

Each cell of a Marx-topology klystron modulator includes at least two high-voltage switches to be used one for the charge of the capacitors and the other one for the fire of the output pulse. The optimal combination between the number of cells and the number of switches per cell, results from a trade-off in terms of reliability/ robustness/efficiency/cost constraints.

The objective of this paper is to present the experimental results taken from two cells Marx prototypes where last-generations of Insulated Gate Bipolar Transistors (IGBTs) switches are used. Two different solutions are analyzed: in the first one a single 6500V - 400A IGBT module is used for the two swithes whereas in the second solution four sections each made of two paralleled 1700V - 75A discrete IGBT are connected in series in order to achieve 6800V blocking capabilities.

CIRCUIT DESCRIPTION

The schematic of two cells out of the N cells of the Marx-topology klystron modulator is reported in Fig. 1 [3]. Each cell includes a charge IGBT, a fire IGBT, a main capacitor, C, a bypass/clamping diode, a charge diode and an isolation diode. During the first phase, the "fire IGBTs" are in the off state and all the "charge IGBTs" are in the on state so that a practically null voltage is applied to the load. At the same time the ground potential is applied to one side of the capacitors whereas the other side of each capacitor is connected to the power

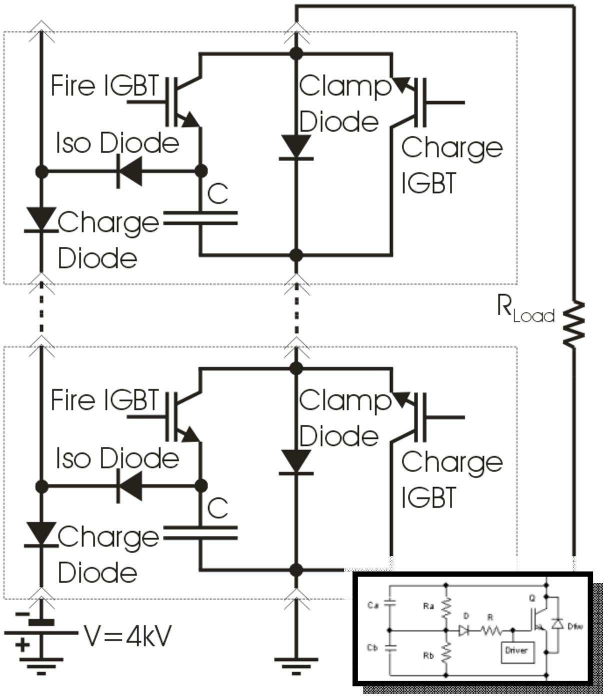

Figure 1: Schematic of two cells of Marx-topology klystron modulator. Inset: balancing circuit used in the series solution.

supply through the isolation and the charge diodes so that these capacitors are charged in parallel to the negative voltage given by the power supply, V. When the charge IGBTs are turned off and the fire IGBTs are turned on, all the capacitors are connected in series by the fire IGBTs. Hence a negative voltage, N x V, is applied to the load.

In our project we have chosen a 4kV power supply. The main capacitor C is realized by the series connection of two 400μF 3200V capacitors. Two solutions have been tested for the IGBTs: single 6.5kV 400A module and 4 series connected 1700V, 2x75A discrete IGBTs. For dynamically sharing the voltage across the series connected IGBTs, a passive balancing circuit, discussed in [6], has been here used for the first time in Marx topologies, which is able to limit the overvoltage across each device during transients, whose sketch has been included into the inset of Fig. 1.

With the above numbers, at least n=30 cells are required to achieve 120kV pulses necessary for the ILC klystron.

In Fig. 2 a picture of the apparatus is reported. It clearly shows the two main capacitors and the mother board which hosts the power modules. For its construction, a double layer PCB was used with a 1.6mm-FR4 isolation layer and a 105μm thickness of the copper layer that was defined in order to be able to withstand current pulses of 140A. The layout of the circuit was designed by using a bus-bar technique which allowed us to reduce the stray inductances of the circuit in the main path of the current. This inductance may induce a dangerous large overvoltage on the power device at its turn-off. In the picture are also recognizable the drivers of each IGBT, the

Figure 2: A picture of the experimental apparatus when a single 6500V – 400A IGBT module is mounted

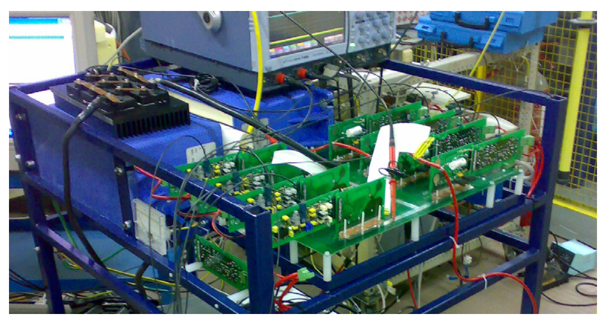

Figure 3: A picture of the experimental apparatus when series connected 1700V – 2x75A IGBT devices are mounted with the balancing external circuit

single module and the four series connected IGBTs. An FPGA circuit is used to define the control sequence of the devices gate signals. The isolation between the control circuit and the power IGBTs is guaranteed by optical connection obtained by means of optic fibers.

In Fig. 3 a picture of the experimental apparatus is reported when the four series connected IGBTs are tested with the respective balancing circuit used for the dynamic good sharing of the applied voltage.

EXPERIMENTAL RESULTS

The switching waveforms of the single 6.5kV module have been reported in Fig. 4, with the following test parameters: V=4kV, Iload=120A, Rgate,on = RGate,off = 5.6Ω.

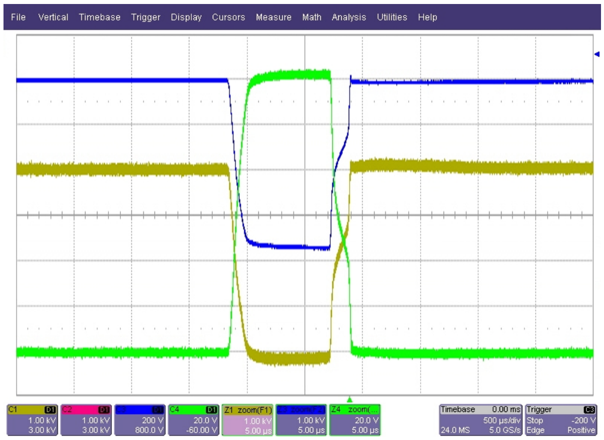

Figure 4: Switching waveforms for the commutation of a single 6500V 400A IGBT module. Yellow: device voltage (1kV/div); Green: device current (20A/div); Blue: load voltage (1kV/div).

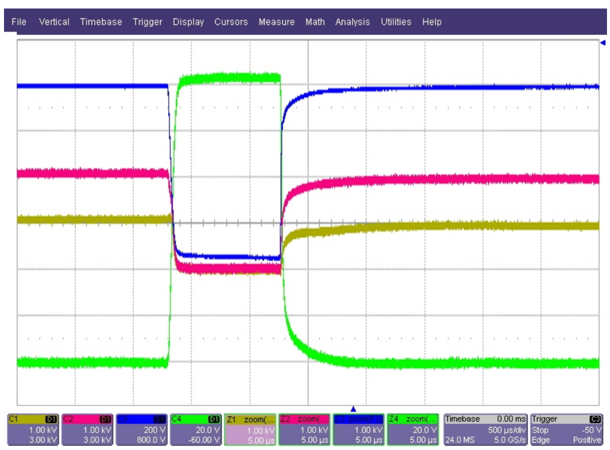

Figure 5: Switching waveforms for the commutation of the series connected 1700V IGBT discrete devices. Yellow: single device voltage (1kV/div); Purple: two series (of 4) device voltage (1kV/div); Blue: total device voltage (series of 4) (1kV/div), coinciding with the load voltage; Green: device/load current (20A/div).

For the sake of comparison, in Fig. 5 the switching waveforms in the case of the four discrete series-connected 1700V – 2x75A IGBT have been reported.

The comparison has been done on several aspects. From the forward voltage point of view, the solution of a single 6.5kV module exhibits a 3.2-3.8V with respect to 4x3.5V = 14V of the series solution.

On the other hand, on the transient side, a better behaviour has been observed in the series solution. In fact, if Fig. 4 and Fig. 5 are compared, much sharper commutations are observed in the series case, where current gradients of dI/dt, rise = 352A/µs and dI/dt, fall = 180A/µs have been measured, whereas dI/dt, rise = 104A/µs and dI/dt, fall = 82 A/µs have been observed in the single module case. Moreover, a large current tail has been observed in this latter case, very typical of high-voltage IGBT modules, that could significantly affect the overall commutation of the Marx modulator.

On the cost evaluation side, though, the 4xIGBT discrete solution resulted strongly cheaper, with an expense of about 200$ with respect to 1000$ of the single module solution, where the above totals include the driver costs in both cases.

Finally, from the reliability point of view, it is widely shared that two opposite effects should be considered: the increased number of components reduces the overall MTBF (mean time between failures), but the voltage derating (1.0kV over 1.7kV and 4kV over 6.5kV) increases the MTBF. For this reason, it is not possible to conclude definitively that the single-module solution is better than the other one.

CONLUSIONS

Two Marx cells prototypes using two different solutions, including single device and series connected devices, both hard-switched, have been presented. The use of single high-voltage IGBT module per cell allowed us to obtain a very lower on-state voltage drop but much slower switching times. A significant drawback of this solution is the cost, resulted about five times the series-connection solution.

The reliability of the series connection of several lower voltage IGBTs results not so much reduced, if one thinks to the strong MTBF increase due to the voltage derating of such solution.

It is worth to point out that a novel solution for the voltage sharing among the series connected devices, including passive components only [6], has been adopted for the first time in Marx applications with significant results.

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