# TOWARDS A PEBB-BASED DESIGN APPROACH FOR A MARX-TOPOLOGY ILC KLYSTRON MODULATOR*

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*Abstract*

Introduced by the U.S. Navy more than a decade ago, the concept of Power Electronic Building Blocks (PEBBs) has been successfully applied in various applications. It is well accepted within the power electronics arena that this concept offers the potential to achieve increased levels of modularity and compactness. This approach is thus ideally suited for applications where easy serviceability and high availability are key, such as the ILC. This paper presents a building block approach for designing a Marx-topology ILC klystron modulator.

## INTRODUCTION

In late 1994, the U.S. Navy initiated a 5-year research and development program [1] that would drastically impact the way power electronic converters, principally in the higher power and voltage ranges, are designed and manufactured today.

The idea was to develop an integrated systems approach for designing and manufacturing power electronic converters through the use of standardised building blocks (so-called PEBBs) to achieve increased power density, reduced costs, higher reliability, etc.

The PEBB concept is a platform-based approach and presents a valuable alternative to conventional power electronic converter design in terms of reduced complexity. The use of standardised building blocks with well defined functionality and interfaces leads to a simplification of converter design and assembly, thereby reducing overall engineering effort. Modular and hierarchical design principles are key in a PEBB-oriented design.

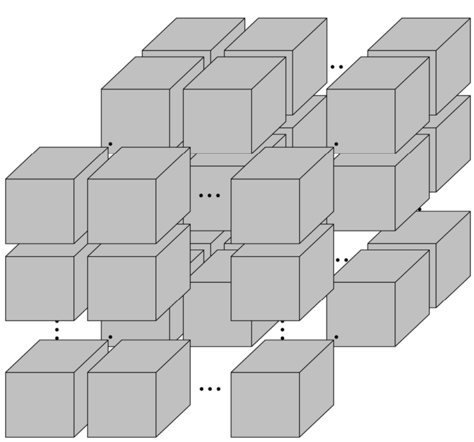

Figure 1: Illustration of PEBB concept.

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A PEBB typically includes power semiconductor devices, gate drivers, protection, power supply, passive components and sensors. PEBBs are configured together to form a system as illustrated schematically in Figure 1. The integration of these PEBBs has to produce the desired system behaviour and performance.

A PEBB-based design approach potentially leads to increased levels of modularity and compactness. This design paradigm tends to be perfectly tailored for applications targeting easy serviceability and high availability, such as the ILC.

The objective of this paper is to introduce a PEBB-oriented design approach for a Marx-topology modulator intended to power an ILC klystron; 120 kV, 140 A, 1.6 ms pulses at a repetition rate of 5 Hz. First a modular approach to droop correction is briefly proposed. Then initial considerations regarding the design of a Marx cell PEBB are given. Finally the conclusion is presented.

## PROPOSED MODULAR APPROACH TO DROOP CORRECTION

It is required that the voltage supplied to the cathode of an ILC klystron is kept within ±0.5% over the pulse duration. Conventional methods to compensate for the output voltage droop that results from the discharge of the storage capacitors in a Marx modulator are based on the use of delayed cells oftentimes in conjunction with additional Vernier cells. However, none of the methods described in the literature are modular in nature as such.

In order to fully exploit the potential benefits of redundancy and fault tolerance inherent to a PEBB-oriented design, a modular approach to droop correction is desirable.

Figure 2 shows how a main cell can be paired with a correction cell (in its most simplified way) to yield a modular approach to droop correction.

Pulse energy to the klystron load is predominantly provided by the main cell, as the name implies. Only a small portion of it is delivered by the correction cell.

The correction cell can be sitting at either the top (as shown in Figure 2) or the bottom of the main cell. The correction cell is topologically equivalent to the main cell, but operated at a significantly lower cell voltage. The correction cell can thus be seen as a Vernier-like cell, but unlike a Vernier cell, the correction cell is PWM regulated. It outputs a corrective voltage to compensate for the capacitor voltage droop on the main cell during its discharge, maintaining the combined output voltage of both cells within the specified flatness tolerance.

In this way, a fully modular approach to droop correction is achieved.

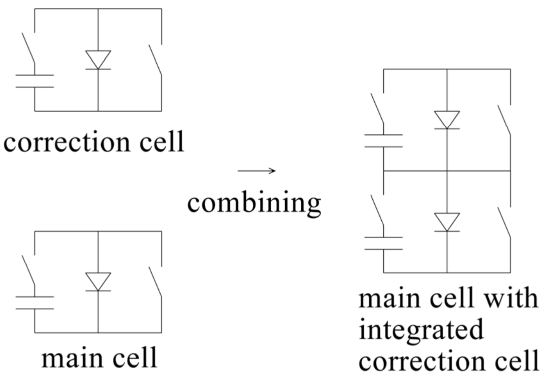


Figure 2: Schematic representation of the proposed droop correction concept. Both cells consist of an energy storage capacitor, a charge switch (right switch), a discharge switch (left switch) and a bypass diode.

The main cell with integrated correction cell as drawn in Figure 2 defines the PEBB also referred to as the Marx cell PEBB in the remainder of this paper. The Marx modulator is built around N such stacked PEBBs.

## IGBT-BASED MARX CELL PEBB – INITIAL DESIGN CONSIDERATIONS

### *Choice of Cell Operating Voltage(s)*

*1) Selection of Semiconductor Devices:* It is desirable to operate the PEBBs at the highest voltage possible (but without making use of any switch assemblies that consist of series connected semiconductor devices) to limit the number of PEBBs required to construct the Marx modulator.

Driven by the continual evolution in performance and characteristics since its introduction in the early 1990s, the IGBT has become the device of choice for a wide range of medium to high voltage applications.

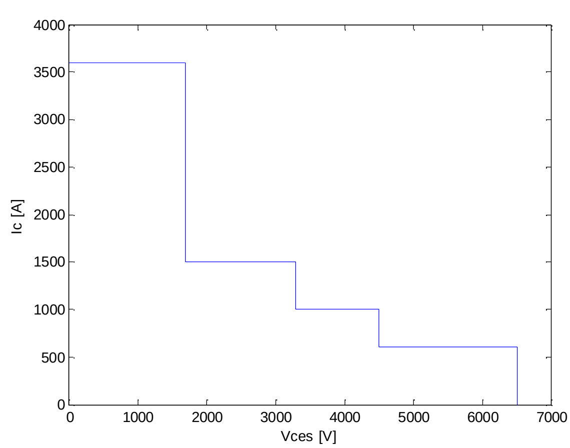


Figure 3: Voltage and current ratings range of commercially available high voltage IGBT modules.

Today 6.5 kV IGBT modules up to currents of 600 A are commercially available as illustrated in Figure 3. The lowest current rating is 200 A.

It is well known that the life of high voltage semiconductor devices can be drastically shortened when exposed to high blocking voltages due to a failure mechanism initiated by cosmic rays. This limits the maximum allowable DC blocking voltage for high voltage semiconductor devices to far less than $V_{ces}$.

Figure 4 shows the predicted failure rate as a function of DC voltage for a number of 6.5 kV IGBTs.

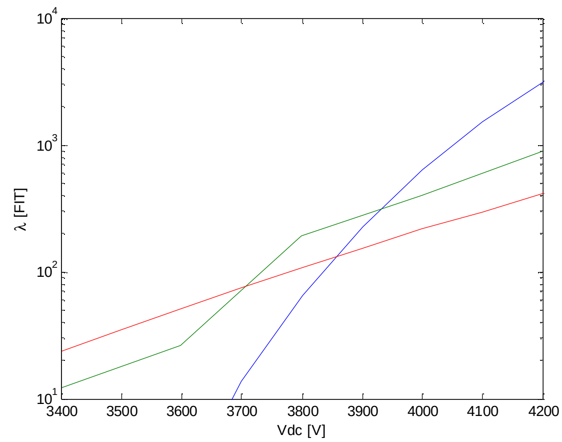


Figure 4: Failure rate versus DC voltage at 25ºC and sea level.

From Figure 4 it is clear that a suitable voltage for the main capacitor (refers to the capacitor in a main cell, likewise correction capacitor refers to the capacitor in a correction cell) of a Marx cell PEBB ranges typically between 3400-4000 V, assuming sufficiently low failure rates for the 6.5 kV IGBTs.

For instance, a curve fit to the blue graph in Figure 4 yields the following expression to estimate the DC voltage $V_{dc}$ for a given failure rate $\lambda$

$$V_{dc} = C_1 - \frac{C_2}{\ln\left(\frac{\lambda}{C_3}\right) - \frac{25 - T_j}{47.6} - \frac{1 - \left(1 - \frac{h}{44300}\right)^{5.26}}{0.143}} \qquad (1)$$

where $T_j$ is junction temperature, $h$ is altitude, and $C_1$, $C_2$, and $C_3$ are curve fit parameters.

To achieve a negligible failure rate of 100 FIT (1 FIT=1 failure in $10^9$ operating hours) it follows from (1) that the DC voltage should be limited to 3833 V.

The corresponding repetitive blocking voltage $V_{dr}$ can be calculated as follows

$$V_{dr} = 1.5 V_{dc} \qquad (2)$$

and equals 5749.5 V.

Both of the other curves in Figure 4 clearly show failure rates of 100 FIT at similar voltages.

*2) Fault-Tolerant Operation:* In order to achieve fault-tolerant operation of the modulator, redundancy has to be incorporated into the design. As mentioned earlier, a PEBB-oriented design is ideally suited to achieve that objective.

Based on the assumption that the DC voltage should be around 3800 V for reliable long-term performance, a 32-cell design is considered to generate the 120 kV pulse.

For an assumed cell reliability, $R_{cell}$, of 99%, the reliability of a 32-cell Marx modulator, $R_{marx}$, drops to 72.5% if no failures can be tolerated as seen in Figure 5. However, if one failure can be tolerated the reliability increases to 95.93% (which is still below the reliability of one cell) and if two failures can be tolerated the reliability increases to 99.6%.

Tolerating two PEBBs to fail implies that the remaining 30 PEBBs operate at 4000 V. This increased voltage falls within the range as indicated above.

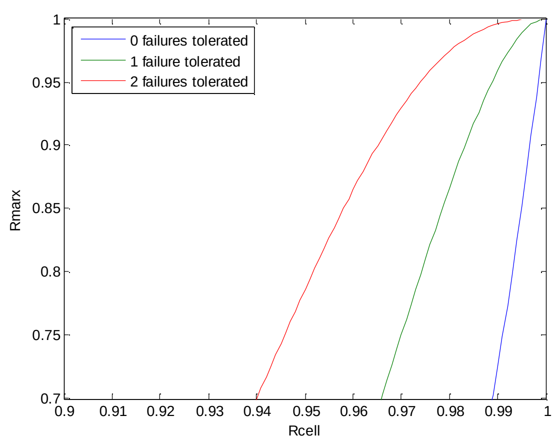


Figure 5: Reliability of a 32-cell Marx modulator versus the reliability of one basic Marx cell PEBB.

In view of the above considerations, a 32-cell design with (N+2) redundancy is chosen. The corresponding voltage on the main capacitor of a Marx cell PEBB is 3750 V.

As indicated previously, the correction cell is operated at a significantly lower voltage as compared to the main cell. It is found that a charge voltage of 1050 V is sufficient for the correction capacitor to provide droop correction on the corresponding main capacitor. In consequence, 1.7 kV IGBTs can be selected.

It should be noted that appropriate fault detection, isolation and reconfiguration mechanisms are key to achieve fault-tolerant operation.

### *Required Stored Energy*

An ILC klystron requires 26.9 kJ delivered every pulse.

The main capacitors are dimensioned to deliver most of that energy. The correction capacitors, however, are sized to deliver only the energy needed to correct for the voltage droop on the main capacitor in their respective Marx cell PEBB. In this way the size of the main capacitors can be kept within affordable limits.

A smaller main capacitor requires more correction, but a larger capacitor increases its costs. Typically, a 20-40% droop in voltage yields a cost-effective design.

The required size $C$ of the energy storage capacitors can be calculated as follows

$$C \geq \frac{\tau_p I}{\delta V} \tag{3}$$

where $\tau_p$ is pulse duration, $V$ is capacitor voltage, $I$ is current supplied to the klystron load, and $\delta$ is voltage droop.

The values obtained for main and correction capacitors using (3) are 350 µF and 875 µF, respectively, assuming 100 µs rise and fall and accounting for 5% age loss and ±5% tolerance.

Consequently, the main capacitor stores 2460.9 J and the correction capacitor stores 482.3 J.

In short, this design allows 28.6% of the total stored energy in the 32-cell Marx modulator, 94.2 kJ, to be delivered in the output pulse, 26.9 kJ, while keeping the droop within a ±0.5% range.

## CONCLUSION

This paper has briefly introduced a concept to achieve droop correction in a fully modular manner. In addition, initial design considerations for a Marx cell PEBB have been addressed.

## REFERENCES

[1] T. Ericsen, "Power Electronic Building Blocks - A systematic approach to power electronics," in Proc. IEEE Power Eng. Soc. Summer Meeting, Seattle, WA, 16-20 July 2000, pp. 1216-1218.