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Thyratron-PFN, IGBT Hybrid, and Direct Switched Modulator R&D As it Effects Klystron Protection

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Abstract

Modulator development is an ongoing program at SLAC. The Stanford Linear Accelerator with its approximately 240 klystrons and modulators operates for 6000 plus hours a year. This operation gives SLAC an important insight into component and system reliability in the High Voltage environment. The planned NLC is approximately 10 times the size of SLAC and the High Voltage Modulator Klystron systems are one of the largest cost drivers. This paper will contain a brief progress report on the optimized Line Modulator and touch on Solid-State advances, which make Solid State, High Power pulse modulators the wave of the future. Klystron protection remains a critical issue along with modulator reliability, efficiency and cost. Configurations whereby multiple klystrons are paralleled on a single modulator may exacerbate the problem. The majority of this paper will discuss tests at SLAC of klystron arcs on Line-type modulators with single and double klystron loads. This talk may introduce and refer to other talks at this conference and other conferences by National and Foreign Laboratory collaborators and Industry, specifically in relation to DOE SBIR programs.

History & Configurations

The majority of the high voltage, high power klystron modulators have been Line-type, using thyratron switches. The history at SLAC has shown these modulators to be reasonably reliable. Presently at SLAC, thyratrons have an average life of over 20K hours and the klystrons have an average life of greater than 45K hours.

End of life for a klystron usually appears as an inability to hold voltage or as cathode material depletion shown by requiring high heater power.

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Line-type modulators also tend to be about 50% efficient. The NLC program requires modulators of higher efficiency and excellent reliability.

The initial cost model modulator for the NLC was a conventional line-type, thyratron modulator optimized to operate two 500kV PPM-klystrons with an overall modulator efficiency of between 60 and 65%. The relatively compact modulator, built in a single oil tank for the klystrons and modulator was designed for depot maintenance. Due to funding issues, and the selection of a solid state design for the NLC, this modulator is just reaching completion of construction and should be tested in July. Figure 1 shows the modulator platform extended from the tank.

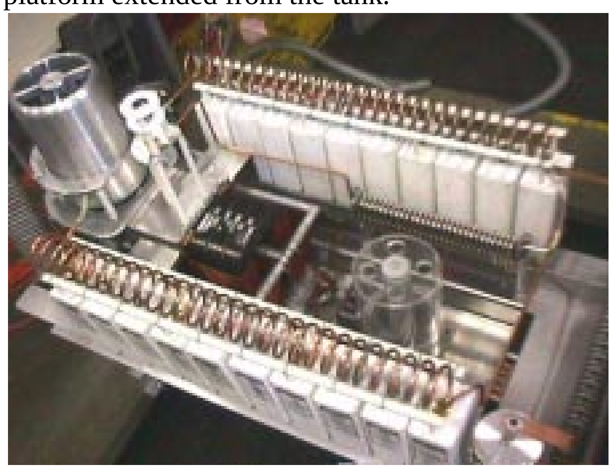

Figure 1. Thyratron-PFN Modulator Platform

High voltage, high power IGBT's (Insulated Gate Bipolar Transistor) are used extensively in the traction motor industry. Tests of these devices for fast switching applications by industry and laboratory engineers including Dick Cassel at SLAC has produced positive results. The present modulator of choice, is an induction type design with the best projected efficency and lowest projected cost per klystron. Being built under a collaboration between SLAC, LLNL (Lawrence Livermore National Laboratory) and Bechtel-Nevada, this modulator drives eight PPM klystrons to take advantage of the switching power of the high voltage IGBT's. Dick Cassel will present this concept later in the symposium.

Diversified Technologies Inc. have been building series IGBT switched modulators in recent years up to approximately 160kV. They will be working towards increasing this directly switched voltage toward 500kV under an SBIR from the DOE. This approach eliminates the pulse transformer but requires a full voltage (500kV) power supply.

A Hybrid modulator concept, a series IGBT switch into an optimized pulse transformer, will be further developed and produced under a Phase II SBIR from the DOE by Diversified Technologies Inc. In this case the pulse transformer can be used to match the peak IGBT switching power to the load and therefore be optimized for cost with a dual klystron load.

Klystron protection is an issue in all of these designs, especially with increasing cathode voltage. Line-type modulators, are inherently current limited but must dump the full pulse energy and count on the impedance mismatch to transfer the energy to an end of line clipper. An IGBT switched modulator has the capability of having the pulse terminated using high speed sensing. How fast this can be done is still an open question as is the peak current that will be delivered into an arc. These questions should be answered within the next year.

Klystron Arc Studies

Examination of failed 5045 klystrons has not shown significant damage due to arcing at the gun although small damage is visible even on klystrons that hold voltage but have failed for another reason. In general this has been attributed to the current limiting (approx. 2 times operating) inherent in a line-type modulator design. In addition, the inductance of the pulse transformer, which can be a limiting factor in rise time, can actually help delay the buildup of the arc current.
However, when two klystrons are operated from the same line-type modulator, the modulator impedance is one-half of a klystron impedance and therefore the current in an arc is limited to four times operating. It would follow that more energy is dumped into the arc, which could create more damage. How much energy is too much and is energy (joules) the proper measure, remains a question we are attempting to answer.

Modern instrumentation, namely digital storage oscilloscopes and computers have given us the opportunity to capture and examine klystron arcs in some detail. At SLAC, we have captured arcs and transferred the data to 'Excel' for analysis. Data on 5045 klystrons was manipulated to calculate arc current using the arc voltage and klystron perveance. Some XL4 klystron data includes collector current enabling the calculation of arc current. We have looked at the fall of the klystron cathode voltage and the rise of the arc current and calculated the energy and peak power delivered into the arc. We have calculated energy levels dumped into an arc that previously were believed would destroy a klystron. Of course we don't know how close we are to klystron failure due to these arcs. We have run two klystrons on a single modulator and examined measured arcs. All of these tests have been made using a line-type modulator. We hope to continue the study using new solid state modulators under design and construction. These tests should begin in the fall of this year.

Table 1 is a simplified compilation of some of the arc data taken to date showing the calculated arc energy. It includes data on 5045's, a 150MW S-Band tube, XL4's, plus XL4's and 5045 Diodes in a two tube configuration. As the data shows, the peak voltage and current alone does not account for the variation of the calculated energy dumped

Klystron	Peak Voltage (kV)	Peak Current (kV)	Energy (joules)
5045 (7)	300.9	550	46.4
5045 (10)	368	525	35.9
CPI DESY	423	700	47.5
XL4-5A (1)	449.8	600	66.5
XL4-5A (7)	454	300	59.5
NLCTA-2 (1739)	443	900	68.5
NLCTA-2 (1747)	430	900	61
NLCTA-2 (KL4)	430	1400	60.4
NLCTA-2 (KL7)	394	1200	23

Table 1. Simplified Arc Data

into the arc. Examination of the arc voltage and current shows that the fall of the cathode voltage and the rise of the arc current can vary from arc to arc and between different configurations. Figure 2 depicts the waveforms during an XL4 Klystron arc in the Test Lab. Notice the slow fall of the cathode voltage and relatively slow rise of the arc current. Figure 3. is a set of waveforms taken during an arc of a 150MW S-Band klystron built by CPI for DESY in Hamburg, Germany while under test at SLAC. This is a higher perveance klystron

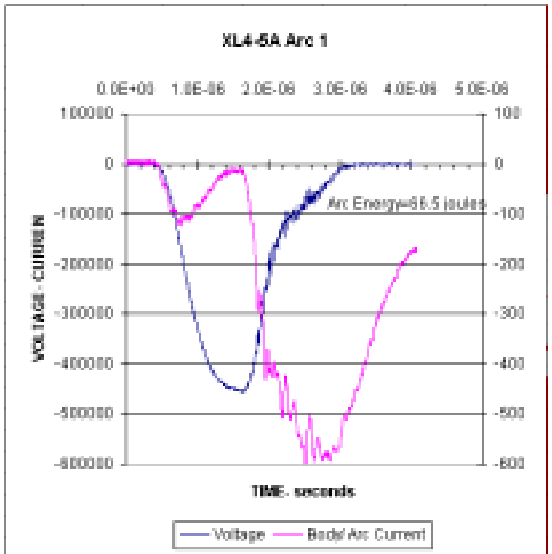

Figure 2. XL4 Arc Waveforms

running on a modulator with lower driving impedance. The voltage seems to fall faster and

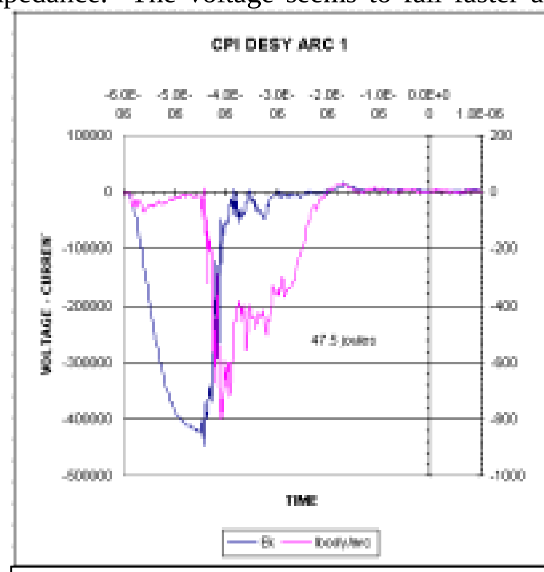

Figure 3. 150MW (CPI-DESY) Arc Waveforms

the current rises somewhat faster. However, it still takes several hundred nanoseconds for the voltage to fall, not the nanoseconds over which people expect the arc to form as in a normal spark gap.

These klystrons operate in extremely good vacuum (10^{-8} or 10^{-9} torr) and are designed with electric fields capable of holding off the voltage. There is no overvoltage condition and therefore the arc formation is slow in transcending the gap.

Ray Larsen at SLAC had suggested looking at the arc power or energy as a function of time. Table 2 follows Table 1 by exchanging voltage and current amplitudes for time, and energy for peak power. Richard Adler of North Star Research, during a

Klystron	Voltage Fall (ns)	Current Rise (ns)	Peak PWR (MW)
5045 (7)	3000	400	88.4
5045 (10)	1200	200	113
CPI DESY	600	300	147
XL4-5A (1)	1300	800	115
XL4-5A (7)	1600	600	76
NLCTA-2 (1739)	1000	400	273
NLCTA-2 (1747)	1100	300	269
NLCTA-2 (KL4)	850	1100	120
NLCTA-2 (KL7)	400	1200	76

Table 2. Arc times and Peak Power

breakdown study, compiled a database of articles on vacuum arcs[1]. He believes, for short pulses the first stage of breakdown is plasma electron emission (private communication). The current increases monotonically until the expanding plasma reaches the anode. The velocity of this expanding plasma tends to be 2-3 cm/microsecond or slower. This is in somewhat agreement with the rise of arc current measured at SLAC.

The two XL4 arcs (1739&1747), which occurred at NLCTA in a two tube, single modulator configuration, indicate significantly larger peak power, but total energy in the discharge similar to other arc measurements. The two 5045 Diode arcs (KL4&KL7), which also occurred at NLCTA in a two tube, single modulator configuration, indicate peak arc power closer to a single tube configuration. The arc powers are shown in Figures 4 and 5 respectively. Rise and fall time of arc current and cathode voltage contribute to both energy and peak power. Faster rise of current can add to peak power but if integrated over less total time can equal the same energy as an arc with less peak power but over a longer time period. Which case actually causes more damage to the klystron internal surfaces is not clearly understood at this

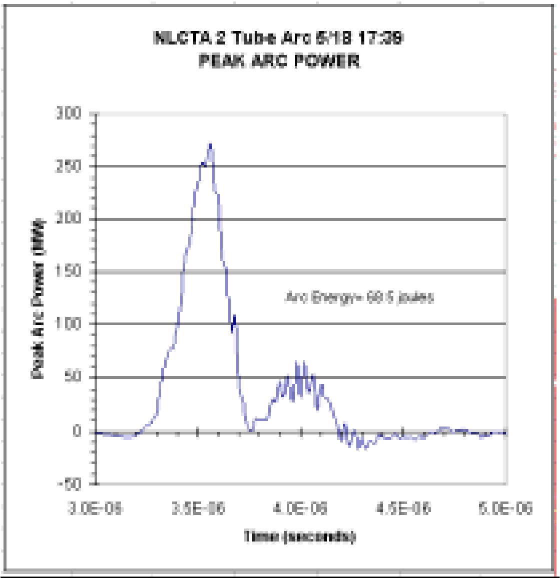

Figure 4. XL4 Arc in Two Tube Configuration

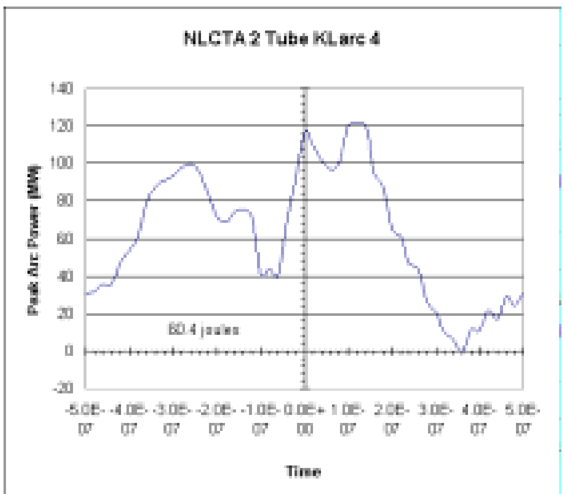

Figure 5. Diode Arc in Two Tube Configuration

time.

Conclusions

To date, we have insufficient data to draw any real conclusions as to what type of discharge into a klystron causes enough damage to stop operation or what cumulative damage will render the klystron inoperative. Arc data taken to date seems to indicate a change in slope of the arc time formation and sometimes a re-increase in voltage after the voltage nears a minimum. During this time more energy is delivered into the arc. However, this energy is delivered over a longer time period and the arc therefore is delivered a lower peak power. Evaporization of material alone does not seem to be enough to stop the klystron from being used. Perhaps high peak power delivered in a shorter time period concentrates the damage over a smaller area causing deeper damage.

Examinations of old klystrons indicate that small amounts of surface material are vaporized during an arc and these points of vaporization occur over the life of the klystron. An ideal situation would allow examination of electrodes after a few arcs of high energy or high peak power, but this can only occur if a special diode is built for this purpose. Measuring and analyzing arcs, in klystrons on IGBT modulators with fast rise times and short pulse widths, should also help to understand external factors effecting a klystron arc. We plan to look at these arcs on the induction modulator in the fall of this year.

Acknowledgements

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References

1. R.J. Adler, D.E. Voss; "Field Emission and Breakdown with Application to RF and Pulsed Devices"; North Star Research Corporation.

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