# A COMPACT 70MW, 250KV MODULATOR USING THYRATRONS

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## SUMMARY

A compact oil immersed modulator is described suitable for driving a 30MW output klystron and using two 70KV 2,500 Amp hydrogen thyratrons as switches. The design is a development of an earlier modulator using a 70KV triggered spark gap. This earlier model was limited to a maximum repetition rate of about 250 p.p.s. but the thyratron switches permit operation to over 1000 p.p.s. and a maximum duty cycle of .001. Complete oil immersion in a single tank results in compactness, economy, reliability and facilitates the use of a high charging voltage which, in turn, leads to a simplification in the pulse circuit, particularly in relation to pulse flattening and pulse length selection. A high current silicon clipper is described which is used to reduce the inverse voltage and which still permits rapid thyratron recovery time.

## INTRODUCTION

The design was commenced early in 1964, initially to fulfil the requirements of linear accelerators for the Universities of Toronto and Glasgow. Although the electrical performance called for new development, the physical arrangement was based on practice established for a previous generation of modulators having all components immersed in a single oil filled tank.

Experience had shown the advantages of this constructional form to be:-

1. Excellent reliability resulting from elimination of multiple high voltage bushings.
2. Compactness.
3. Economy in manufacture.
4. Simplicity of cooling and screening.

The use of a high charging voltage, in the region of 70KV, for the pulse forming network was also retained from existing spark switch modulator practice.

### Modulator Specification

The main parameters are as follows:-

| | |
|---|---|
| Peak Power Output | 70MW max. (57.5MW normal running level for TV2011 klystron) |
| Mean Power Output | 70kW. |
| Flat-top Pulse Lengths | 4.5 or 3.5,2.1,0.5μs selected by 3 position switch. |
| Pulse Repetition Rate | Up to 1000 p.p.s. max. (at 0.5μsec flat-top) |
| Pulse Flatness | ±0.5% over specified flat-top. |
| Pulse-Pulse Time Jitter | ±5ns max. |
| H.T. Stabilisation | Better than ±0.2% for ±3% mains variation. Response time less than 2 supply cycles. |

The modulator (Fig.1) is contained in a steel tank approximately 15ft. long by 3ft.9in. wide by 4ft.8in. high and at one end supports and accommodates the klystron, the cathode bushing of which is lowered into the tank.

Two free standing racks housing the klystron focus supply and the klystron cooling heat exchanger are installed in close proximity to the modulator. Other external items are the modulator control rack, which contains the instrumentation, trips and interlocks, and a separate motorised 100kVA a.c. regulator which can be installed in any convenient position.

## POWER SUPPLY

In the case of the TV2011 Klystron the values of pulse forming network impedance and pulse transformer ratio (15 ohms; 1:8) have been chosen such that for normal perveance tubes operating at 250-260kV the H.T. supply is 31-32kV. The power supply is designed to operate from 18kV (minimum) to cope with switch-on conditions, and may be run up to a maximum of 37.5kV to allow for end-of-life klystrons which may require pulse voltages up to 280kV.

It is necessary that the power supply is adjustable over this range and that at any setting it shall be stabilised automatically. A dual system is used, one part provides some 95% of the total power and is controlled by a continuously variable voltage regulating transformer, while the other part consists of a trimming circuit supplying the remainder. The trimmer is fed from a relatively fast acting a.c. controller employing thyristors, the conduction angles of which are determined by a circuit which compares a sample of the H.T. voltage with a reference voltage proportional to the chosen working level. Each of the two power supplies employs a three phase transformer and full wave rectifier, the combining being done by series connection of the d.c. outputs.

This system provides fast compensation over a range covering the working level and does not suffer from three disadvantages, associated with full power thyristor control:-

a. If controlled rectifiers are used, either as primary a.c. controllers, or as actual rectifiers on the secondary of the transformer, the d.c. output contains a high amplitude commutation spike except when the firing angles are set near to maximum output.

In the dual arrangement the trimmer normally operates at half voltage output and increases or decreases to compensate for mains variations but at no time is the spike output sufficient to present a serious smoothing problem, the L-C smoothing circuit (15H, 2μF) being common to the sum d.c. of both rectifiers.

b. Chopping the entire modulator input at levels in the range 50-100 kVA may lead to distortion of the supply waveform and when several modulators are run at slightly different conduction angles from a common source there is a risk of mutual interference with critical ancillary equipment.

The dual circuit has the advantage that because the greater part of the power input consists of a full cycle load the supply waveform is relatively clean.

c. A thyristor 'firing through' (due perhaps to breakdown or pick-up of spurious trigger) may lead to sudden increase in modulator output endangering the r.f. tube. In the event of such a fault in the thyristor trimming system the total output voltage cannot rise more than a few percent and serious malfunction of the modulator is avoided.

The main d.c. supply has been designed with sufficient margin to permit full power operation of the klystron without the trimmer if necessary.

### Rectification and Smoothing.

For both the main and trimming rectifiers strings of 1000V silicon avalanche diodes are employed. Over-current protection in the event of short circuit is provided by fast fault sensing to open the main contactor (common to both circuits). Also 9% reactance has been introduced into the supply transformers to ensure that on short circuit the d.c. drawn from the rectifiers does not exceed 28 Amps. The $I^2t$ rating for the diodes permits this current for a period of 100m.sec following normal full load current, but the circuit is arranged to clear in about 50m.sec, thereby giving a 2:1 safety factor.

To achieve this it was necessary to make tests of contactor opening times and to devise thyristor control for the contactor opening coil. The thyristor logic includes duplication for reliability and easy manual check out by push button.

### The Trimming System

The trimming system and H.T. supply is shewn in Fig.2. The H.T. line is monitored by a potentiometer immediately after the rectifiers, to avoid the phase shift and time lag of the L-C filter. It was found necessary to shield this potentiometer from stray fields, it consists of a chain of resistors arranged approximately non-inductively in a cylindrical can 23" by 5" dia. contained within the modulator tank, the output being brought out by a double-screened cable. The d.c. sample is compared with a reference potential derived from a potentiometer mechanically ganged to the main a.c. regulator and fed from a stable d.c. source. Thus, as the regulator is raised the reference rises and the sample from the H.T. line should rise proportionally. Any difference constitutes an error signal which is fed via a chopper type d.c. amplifier to a three-phase thyristor controller to advance or retard the thyristor firing angles. The a.c. regulator runs up in about 25 sec until the drive motor is stopped by a relay circuit which also controls visual indicators on the modulator control panel and main accelerator control station. These relays are controlled by a bistable transistor circuit which sense both the reference potential and the modulator mean current. Thus the H.T. runs up to a predetermined level irrespective of the load current imposed by widely different duty cycles.

As the regulator runs up, the load current increases approximately linearly and the H.T. voltage sags slightly due to power supply impedance (mainly transformer reactance). A sample of the modulator mean current is fed to the error signal amplifier to ensure that the trimming circuit operates in the centre of its range at all levels and at all duty cycles. During modulator tests, a rig consisting of three large wattage resistors, shunted by a three pole contactor, is inserted in the mains supply line to produce, at will, a step of 3% in the input voltage and with the trimmer working a change of less than 0.2% is seen on the klystron voltage pulse

## PULSE CIRCUIT

### Charging

The resonant charging system is connected to the 'back end' of the p.f.n. in order to reduce the stray capacitance seen by the switch tubes. (Fig.3.) A single choke of 3.0H is used for all repetition rates, the necessary hold-off being achieved by a stack of silicon diodes consisting of 160 devices each rated at 1000V. Each diode is shunted by a capacitor and resistor but selected low leakage diodes were chosen to allow the sharing resistors to be as high as possible, thereby reducing the back leakage and charge loss at low repetition rates.

### Pulse Forming

With modulators designed to produce very flat pulses it is not unusual to make the mean pulse length longer than the flat-top required, by a factor of perhaps 2. This is an advantage in that heavy despiking can be used to round off the leading edge without exciting the resonances attributable to stray reactances. Alternatively, if the despiking is less severe, the first part of the pulse top - having some ripple may be ignored. That these methods are wasteful of power is of little significance in low P.R.F. applications. In our case the maximum possible P.R.F. was required at each pulse length but because of klystron mean power limitations it was not permissible to waste any appreciable part of the pulse.

At 3.5μs flat-top the mean pulse length is only 4μs and the P.R.F. 250 p.p.s. Nevertheless a departure from flatness of about ±0.5% is achievable over the specified flat-top by careful adjustment of the P.F.N., the use of minimal despiking and a pulse transformer designed for low leakage inductance. The latter is important since one of the main causes of ripple during the start of the pulse is thought to be due to resonance of the leakage inductance and the klystron cathode/ground capacitance; reduction of the leakage substantially reduces the amplitude and duration of the oscillation.

The P.F.N. is rated for continuous operation at 72kV and consists of two parts: one has five sections for the short pulse (0.5μsec) and the other has eleven sections for the long pulse (3.5μsec) tapped at the seventh for the medium pulse (2.1μsec). The inductive element consist of self supporting coils arranged horizontally above the capacitor banks. The coils have tapping clips which permit individual adjustments for inductance and mutual coupling.

Change of pulse length is accomplished by a specially designed three position switch which selects either the short line or the long line and in the latter case puts seven or eleven sections in circuit. Contacts are included which modify the seventh section inductance according to whether it is the end section for the medium pulse or the seventh section of the long pulse, to give optimum flatness for each. The contacts also route the charging feed and end-of-line inverse diode clipper to the back end of the selected portion. The body of the switch is constructed of $\frac{3}{8}$" thick acrylic sheet and is perhaps best described by its resemblance to a large slide rule about a metre in length. The sliding member is operated by a lever from above the lid of the tank.

### Pulse Transformer

A leakage inductance of about 2μH is achieved by careful arrangement of the windings around several d.c. biased uncut loops of 0.002" hypersil, an arrangement designed for consistent performance over long periods, in that repeated thermal cycling will not affect the core characteristics as can be the case with gapped cores. The secondary winding is tapped to provide 35 and 40kV outputs for the linac gun if required.

## CONTROL OF THYRATRON INVERSE VOLTAGE

During initial thyratron tests an inverse diode circuit was connected across the thyratron to stabilise the resonant charging circuit against variations of load impedance. Its effective forward resistance was about 400 ohms. When thyratrons were first operated at low repetition frequencies, arc-back was frequently encountered when the peak anode voltage was raised to the region of 60kV. There was also evidence of unexpectedly high thyratron dissipation when the P.R.F. was raised. Excessive inverse current was suspected. The peak inverse voltage was found to be about one half of the peak forward anode voltage. (Fig.4.) Also the distribution of inverse voltage between the two thyratron gaps was observed during the period immediately following the pulse and it was found that inverse voltage appeared initially only on the gap adjacent to the anode.

An analysis was therefore made, both theoretically and by means of an electrical scale model of the origin of this inverse voltage. Both methods indicated that the principal cause was the leakage inductance of the pulse transformer but that reducing it within the range of practicability, would have the effect mainly of reducing the duration of the inverse voltage rather than its peak value. It was therefore decided to fit a low impedance end-of-line clipper circuit and to modify the pulse transformer so as to reduce the mean dissipation in the inverse diode load resistor from 8kW to 3kW. To overcome difficulty with thyratron recovery, a non-linear C.R. network was used with an extended foil paper capacitor.

With a diode load resistor of 4 times $Z_0$ (60 ohms), which was as low as was considered safe with the avalanche silicon diode stack, the thyratron inverse voltage was reduced to the region of 20kV. At this level, operation free from arc-back was obtained.

## DEVELOPMENT OF THE SWITCHING THYRATRON

Development has been concentrated on the CX1168 thyratron. When the first tube was operated there was difficulty in withstanding the full H.T. voltage on the short pulse length at high gas pressures even at low P.R.F. Monitoring of the potential of the gradient-grid, which was connected to the centre of a high resistance potentional divider between anode and cathode, revealed that its potential rose during the early part of each charging cycle to almost the peak anode voltage and later fell back to its proper half-way level. This was due to insufficiently rapid recovery of the top gap, and was confirmed by negatively biassing the upper part of the gradient grid with respect to the lower. In tests carried out before the introduction of the end-of-line clipper, excessive grid heating was observed even when the valve envelope was effectively cooled by air-blast. As a result, in a typical case, the reservoir range fell steadily with increase of H.T. voltage and P.R.F. until at 60kV, 500 p.p.s. satisfactory operation was obtained only at a unique reservoir setting. The inverse voltage immediately following the pulse was reduced by the introduction of the end-of-line clipper and the design of the thyratron was modified to reduce the recovery time of the gradient grid and to improve its cooling. Operating at up to 1000 p.p.s. was then possible. However, at high P.R.F. severe corona developed on the outside of the top ceramic. It was therefor decided to immerse the valve in transformer oil. This also solved the cooling problem by natural convection, with a consequent gain in reliability.

The CX1168 thyratron is used at 70kV, 2300A, 50 p.p.s., 1μs mean. One tube is used at pulse lengths up to 5 microseconds at 2300A peak current, with an average current limit of 2.5A. Between 500 and 1000 p.p.s. two thyratrons are used switched alternately.

The design of the tube alleviates dissipation problems at the grids because the control grid G2, which is heated by the cathode, receives no inverse dissipation. On the other hand, the gradient grid, which is subject to inverse dissipation, is about 3" away from the control grid. This permits the introduction of a copper structure to conduct heat away from the centre of the gradient grid effectively. Fig.5.

## DEVELOPMENT OF AN INVERSE DIODE STACK USING CONTROLLED AVALANCHE SILICON DIODES

The performance required of the diode stack is as follows:-

| | Normal | Fault |
|---|---|---|
| Peak Current | 400A for 1μs 1000pps. | 75k |
| | 250A for 5μs 250pps. | 1400A |
| Peak Inverse Voltage | 75kV | 120kV approx |

Protective circuits limit the fault condition to isolated pulses separated by several seconds.

The diode stack is immersed in oil in the main modulator tank, where the maximum temperature is 50°C. On the basis of pulse tests on individual diodes, Mullard BYX-25-800R was found to be the most suitable controlled avalanches diode. A stack of 100 such diodes having 1.2kV avalanche voltage was judged adequate. It was desired to avoid the need for sharing capacitors in the interests of economy and reliability. However, calculations indicated that capacitance to earth would lead to excessive average avalanche dissipation in some diodes unless the stack was screened.

Using a cylindrical geometry resistance network analogue to solve Poisson's equation, it was found possible to design end-caps which would ensure freedom from avalanching during the normal charging cycle (Fig.6.).

Diode stack of this design have given satisfactory service in the modulators, both on resistance load with intermittent short-circuits applied for a few successive pulses and with klystrons as loads.

## ACKNOWLEDGEMENTS

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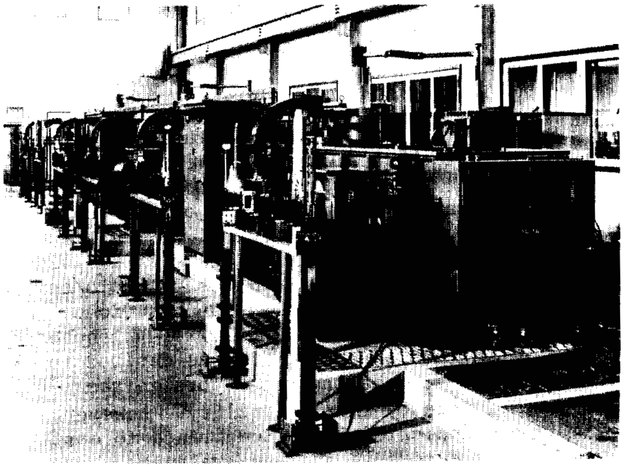

Fig. 1. View of modulator (at Glasgow).

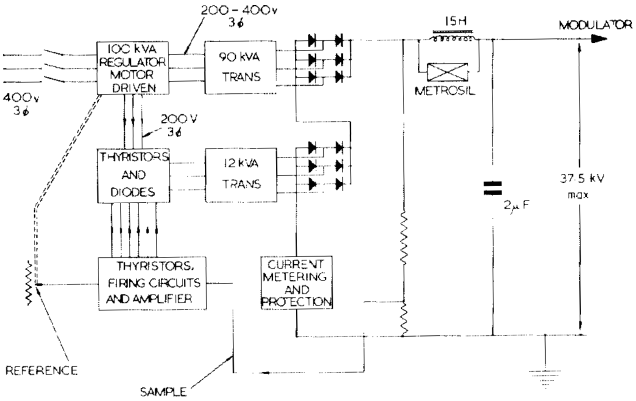

Fig. 2. Modulator Power Supply.

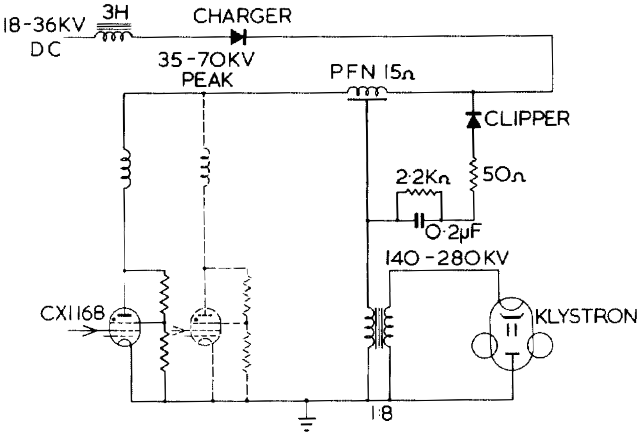

Fig. 3. Modulator Circuit.

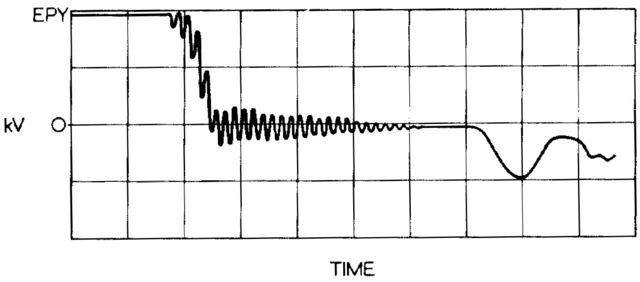

Fig. 4. Thyratron Anode Volts.

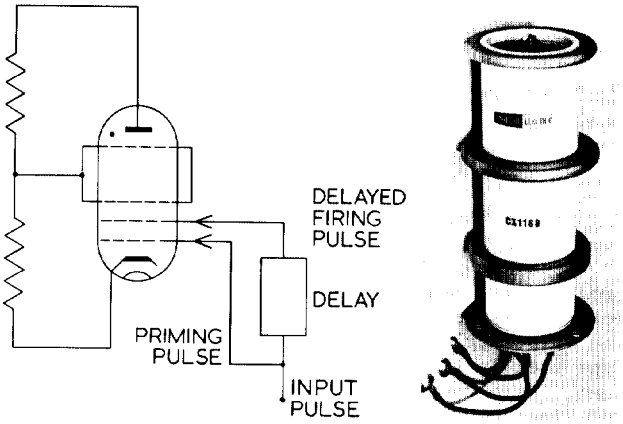

Fig. 5. CX1168 Thyratron.

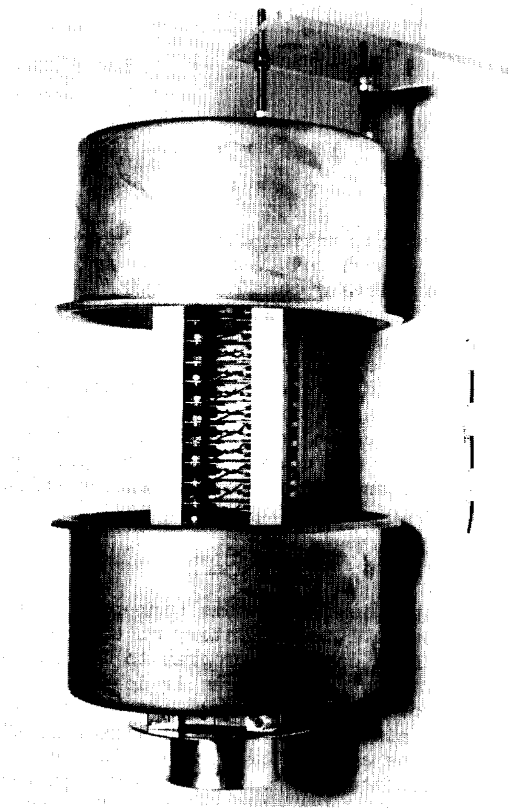

Fig. 6. Diode Assembly.