ANODE MODULATOR POWER SUPPLIES FOR CONTINUOUS DUTY 500 KW KLYSTRONS (TH2103D) & 200KW GYROTRON (VGA8000A19)

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Abstract-- **Initial testing and commissioning of two high power Klystrons (TH2103D) and Gyrotron (VGA8000A19) have been carried out at our Institute. Each of the Klystrons is capable of delivering 500 kW at 3.7 GHz, to be used for non-inductive lower hybrid current drive (LHCD) in the Steady State Superconducting Tokamak (SST-1). The Gyrotron is capable of delivering 200KW at 28GHz, for breakdown and Electron Cyclotron Resonant Heating (ECRH) experiments on Aditya tokamak. The potential appearing at the anode point with respect to the cathode will turn-ON, turn-OFF and control the beam current. Thus these anode modulator power supplies control the out put power of the devices. Main input for both the power supplies is derived from the cathode power supply. A -2 kV bias power supply is connected between the modulator output and anode terminal to suppress dark current. The output pulse duration is adjustable from 50m Sec. to 1000 Sec. by the control system. Oil cooled tetrode YU155 is used as shunt voltage regulator in the klystron anode modulator power supply. A potential divider is made with the tetrode as a series element. It operates in its linear range and a variable voltage is available at the klystron anode by varying the impedance of the tetrode. As control grid voltage of tetrode is varied, the tube impedance changes from infinite to the required value. This change in impedance gives desired variable voltage from 0 to 60KV with respect to cathode (i.e. -65KV to -5KV with respect to ground). Two tetrodes are used for Gyrotron modulator power supply. This anode modulator power supply is capable of giving a two step voltage at the anode. One step for beam stabilization and the other for microwave power output. A potential divider is made with one tetrode as a series element and the other for shorting a part of the divider resistance, to obtain second voltage step. Both the tetrodes in this case are used as HV switches. This paper presents details of design, fabrication, and testing of both the anode modulator power supplies developed in house.**

I. INTRODUCTION

THE anode modulator power supply for 200 KW, 28GHz gyrotron (GAMPS) is required to pulse the anode voltage of the gyrotron from –2KV to +28KV with respect to its cathode, thereby controlling the beam current of the Gyrotron and bringing the Gyrotron from cut-off to conduction. The voltage pulse duration can be varied from control section from a few milliseconds to a range of few seconds. The power supply should be able to supply an anode current of 5 mA to the gyrotron during its conduction. The anode modulator power supply for Klystron (KAMPS) modulates the anode voltage from 0 to 60kV with respect to the cathode.

The GAMPS and KAMPS are fed through a high voltage cable by the external high voltage power supply (HVPS) capable of supplying maximum d.c. voltage of –70kV and 10amps. The required insulation level for the anode modulator power supplies of both klystron and gyrotron being 120kV, signals to and from the local control unit, which is at the ground potential, are transmitted through optical fibers to provide sufficient isolation between the controls and the power parts. For GAMPS power is supplied to the high voltage decks through epoxy cast H.V. isolation transformers. Each switching tetrode of GAMPS is connected to a high voltage deck where its filament biasing power supply, control grid circuit, screen grid power supply and interface electronics are mounted. The two power tetrodes are housed in a tank, the body of which is grounded to get rid of electrostatic charges. A potential divider is connected between the cathode and the collector of the Gyrotron. The potential divider is mounted by the side of high voltage deck and is kept air-cooled. All the control signals to Data Acquisition and Control unit from the local control unit are provided with potential free contacts.

I. SYSTEM REQUIREMENTS

The maximum gun anode voltage of gyrotron is specified at 32 kV positive with respect to the cathode voltage while the cathode voltage is specified at 80kV dc. Maximum gun anode current is specified to be 5mA. Typical operating parameters are 28kV @ less than 0.5mA for VGA-8000A19. The gun anode voltage may be pulsed in two steps. After the beam voltage is switched on, the gun anode voltage is either switched or ramped to a value of 15-20 kV positive where it is held for about 30-60 seconds while emission cooling stabilizes the beam current. Finally the gun anode is pulsed all the way to its normal value of 28 kV positive with respect to its cathode. The schematic of a typical pulse is shown in **Fig1**. The output voltage of KAMPS should be continuously settable from 0 to 60KV with respect to cathode. (i.e. -65KV to -5KV with respect to ground). The voltage pulse duration is to be adjustable from 50m Sec. to 1000 Sec. by the LHCD control system. At the time of arc fault the voltage at modulating anode point of the klystron should become zero within 10μSec. Duty factor of the anode pulse also is required to be variable.

II. CIRCUIT DESCRIPTION

To design the anode modulator of the Gyrotron a potential divider of total resistance 1.3 Mohms is designed to carry 50mA current. Two power Tetrodes (TH5188) are used, one as a series switch in the path of the divider and the other as a bypass switch, which crowbars a part of the divider and hence

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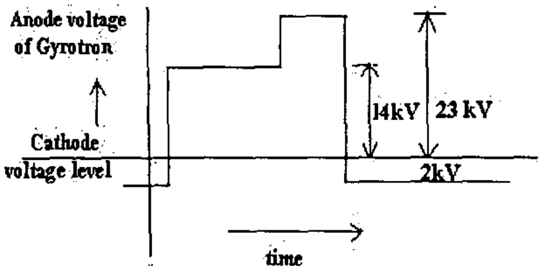

Fig 1: Typical pulse output of anode modulator of gyrotron

is parallel across that part of the divider (**Fig 2**). The control grid bias of a power tetrode has been selected on the basis of its plate current and plate voltage. Keeping in view that the plate current of the power tetrode can be as high as 200 mA during transients and that the dc plate voltage of the power tetrode is –70kV, the control grid bias of TH5188 is selected to pulse between –500V dc to +100 Vdc. The screen grid bias is 1000Vdc. The filament boost is 7.5Vac and filament current 35A. The operating regime has been selected from the constant current characteristics of the tetrode TH5188. The tetrodes TH5188 are rated for 120 kVdc plate voltage and 10kW plate dissipation. The screen grid voltage is 1000V keeping in view that 5mA is the specified anode current drawn during conduction.

Each power tetrode has been pulsed at its control grid using two BEL tubes in totempole configuration. The dc power supply for the control grid of the power tetrode is bipolar. During ECRH shot the control grid of power tetrode is biased positive for full conduction by switching 'ON' one BEL tetrode and simultaneously switching 'OFF' the other BEL tube. The control grid voltage of a BEL tetrode is pulsed between –200Vdc and +75 Vdc for biasing it from complete cut-off to full conduction. The screen grid voltage of a BEL tetrode is supplied by a dc power supply of +500V, 1A rating. The filament heating is provided by a 5V, 14Aac voltage source. The current limiting resistor 2.5k, 200W is added in the control grid path to limit the control grid current of the power tetrode to 200 mA.

The BEL 400 tubes are rated for 4kV plate voltage and 400 W plate dissipation. During testing the control grid cut-off bias is kept at –100Vdc for the complete cut-off of the BEL400. The constant characteristics of BEL tubes are the source behind the selection of these parameters.

Pulsing of control grid voltage of each BEL400 is accomplished using IGBTs (IRGBC40U) of International Rectifiers. The gate driver circuits are designed to provide optocoupler isolated 7V level signals and proper current drives to the IGBTs. The control grid current for the BEL400 tetrode at 75V as calculated from the constant current characteristics is 630 mA. A current limiting resistor of 500 ohms is required to limit the control grid current of a BEL tube to this value. Selected IGBTs are rated for a collector-to-emitter voltage of 600V and a continuous collector current of 40 A. The rise time and fall time are of the order of nanosecond, maximum value of fall time being 120 nanoseconds. The gate driver circuits are connected to the optical signal conditioning circuit that in turn is connected to the controls of the GAMPS through fiber optic links.

To design the anode modulator for klystron a potential divider has been made with tetrode YU155 as a series element that works as a shunt voltage regulator (**Fig 6**). We get variable tube resistance if control grid voltage is varied at fixed screen grid voltage. Thus varying the tube resistance varies the voltage available at the tap point. The tube is biased to cut-off by applying -800 volts to the control grid with respect to cathode As control grid voltage is varied from -800 volts to -80 volts the tube resistance changes from infinite value (cut-off) to 130KΩ. This change in resistance gives us a desired variable voltage from -65KV to -5KV at the output of the anode modulator power supply. The output voltage is tapped across the tetrode and connected to modulating anode of the Klystron through 2KV floating bias power supply. A 20KΩ current limiting resistor is provided to limit the anode current at the time of arc fault. Tetrode requires filament power supply, Screen grid power supply and control grid power supply. Two separate power supplies are made for filament and screen grid and a power module is used for control grid. These are floating type power supplies. Isolation transformers are used to get the floating voltages. A precision potential divider is used for output voltage measurement. Optical isolation circuit isolates control and measurement signals. The entire power supply system except –2kV bias and the optical transmitter circuits is housed in an oil tank.

One of the most important factors affecting the life of YU!55 and ultimate performance is the filament voltage as measured directly at the filament pins that should be 7.5 volts. Variation in filament voltage must be kept within the range of (5% of the rated voltage. The tetrode's initial cold heater resistance is such that current in excess of 2 to 3 times operating current can damage the filament. A soft start circuit is used for initial current limiting. The filament voltage is always lifted at 70 KVDC voltage. To serve the purpose of isolation, an isolation transformer with 120kVdc isolation level between primary and secondary is used. Secondary side leads of the isolation transformer are directly soldered with filament pins of the tetrode YU155. A servo voltage stabilizer is used on primary side of the isolation transformer that will take care of both line and load regulation.

The selected screen grid voltage for YU155 is 500 Volts dc. This screen grid power supply is also a floating power supply. The ratings of the 120kVdc isolation transformer used for this are 230/355 Volts, 355 VA. The secondary of the transformer is connected to a bridge rectifier, R-C filter circuit and a bleeder resistor. This supply gives 500Vdc output voltage with 1% ripple factor.

A power module is used as a control grid power supply for YU155. Using isolation transformer and optical isolation circuit respectively isolates the input voltage and control signal of this module. MOVS and zener diodes provide protection against input surges and control signal surges respectively. The

ON and OFF status of the power supply goes to Data Acquisition and Controls (DAC).

signal so that if crowbar is triggered in the middle of the shot, the suitable power tetrode is driven into cut-off mode. The gun

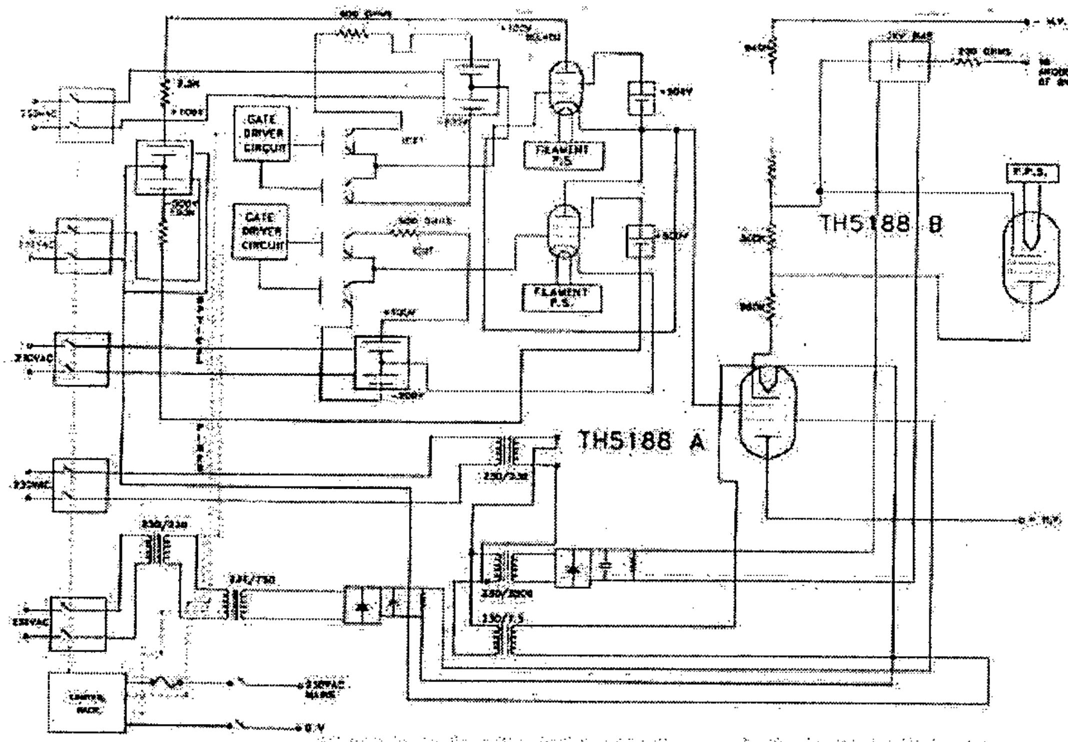

Fig 2: Anode modulator power supply for gyrotron

III. CONTROLS AND PROTECTIONS

For GAMPS gun anode current is viewed by sensing current across a series resistance of value 200 ohms, then using voltage-to-frequency conversion and a fiber optic link. The 0-5V signal monitoring 0-10mA current is fed to a meter as also to DAC. The sequential switching of theIGBTs, BEL tubes and power Tetrodes is done through solid-state timers and relay switches. To monitor the output voltage of anode modulator power supply of klystron a 100KVDC potential divider is made. To achieve this isolation level optical isolation circuit consisting of transmitter, fibre optic cable, receiver and signal processing unit has been used. After isolation this signal goes to a dc meter and DAC for monitoring and control. For monitoring anode current of the modulator power supply of klystron a 0 to 5 volts signal is tapped across current limiting resistor. After isolation this signal goes to DAC for monitoring purpose.

The protection requirements for GAMPS call for removal of both the beam and gun anode voltage to zero within 10μs. This is achieved by a rail-gap based crowbar protection system. The pulse from Data Acquisition and Controls for 'ON' and 'OFF' of the power tetrodes has an interlock with crowbar triggering anode current signal has been interlocked with crowbar trigger circuit so that if anode current exceeds 5mA the crowbar is triggered.

The interlocks provided in the KAMPS are a) filament warm up time interlock b) applied voltage sequence interlock c) turn on and turn off interlock. The protection for the power supply demands that the tetrode should go into cut off mode in following conditions: a) at the time of crowbaring b) at the time of any type of fault occurring on klystron side c) at the time of applying and removal of main cathode voltage. In all these conditions the power module receives a 10 volts signal from DAC which drives tetrode to cut-off mode.

IV. CONCLUSION

A typical shot taken during Gyrotron commissioning is shown in **Fig 3** in which upper trace shows the anode voltage to be 22kV positive w.r.t. cathode voltage and lower trace shows the cathode voltage at –40kVdc. The anode modulator power supply has been tested at a floating voltage of -60kVdc The shot obtained is shown in **Fig4.**

The anode modulator power supply for klystron has been tested for 1000 seconds at –55kVdc. **Fig 5** shows a klystron shot of duration of about 1second, the upper trace being control sign from DAC and lower trace being output voltage of power supply measured across a 10000:1 divider. measured across a 10000:1 divider.

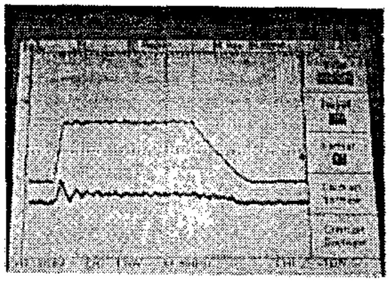

Fig 3: upper trace (ch1): 22kV pulse on the anode of gyrotron lower trace(ch2) : cathode voltage at –40kVdc

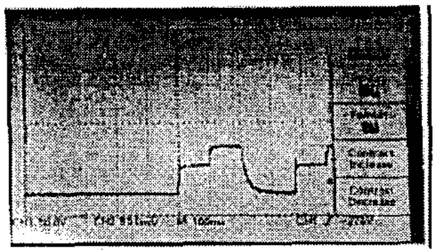

Fig 4: Two step pulse at the output of anode modulator power supply Of gyrotron, the power supply being tested with an input of –60kVdc floating voltage

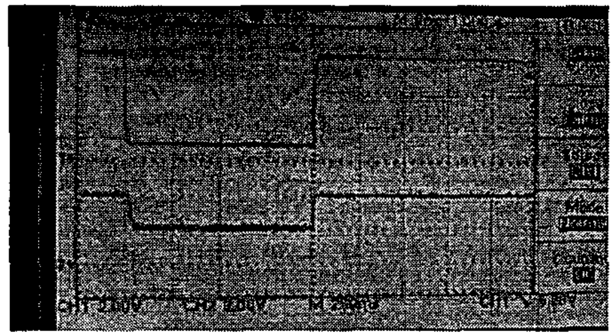

Fig 5 : upper trace: control signal from DAC lower trace: output voltage of anode modulator power supply

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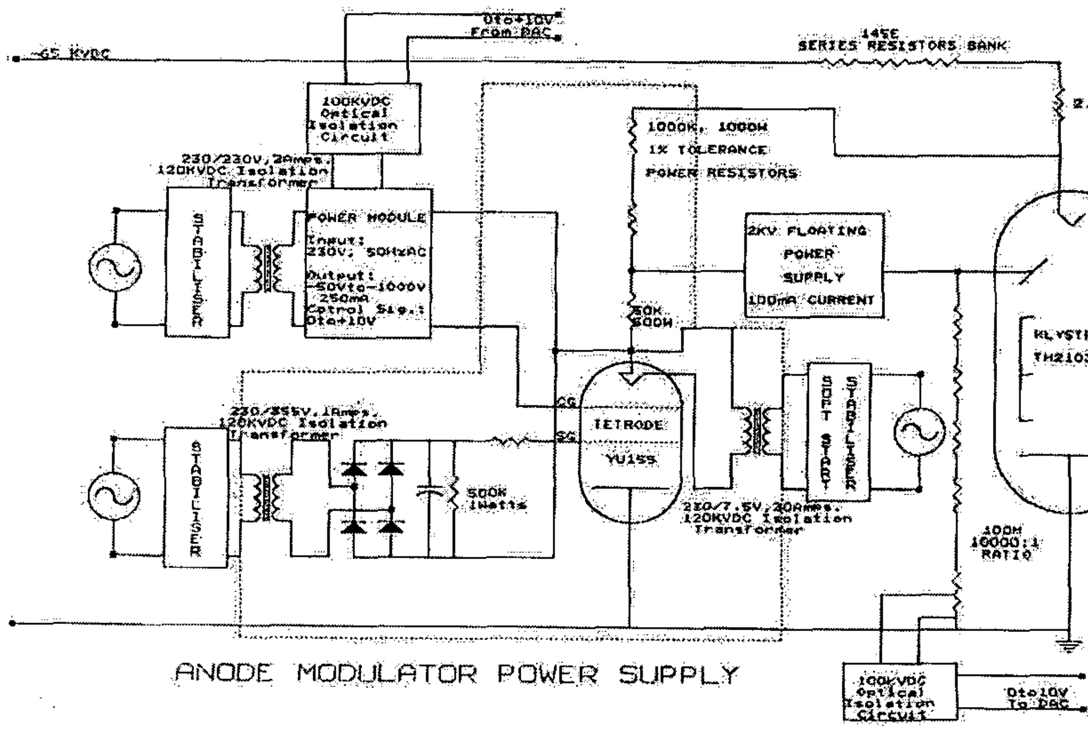

Fig 6: Anode modulator power supply for klystron