ION CYCLOTRON RESONANCE HEATING TRANSMITTER OPENING SWITCH UPGRADE*

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Abstract

Diversified Technologies Inc. (DTI) has installed a high-power solid-state opening switch upgrade package to replace the mercury ignitron crowbars in the Ion Cyclotron Resonance Heating (ICRH) Transmitters at MIT Plasma Fusion Science Center's (PFSC) Alcator C-Mod, a Tokamak-type fusion experimental device.

INTRODUCTION

Diversified Technologies Inc. (DTI) has installed a high-power solid-state opening switch upgrade package to replace the mercury ignitron crowbars in the Ion Cyclotron Resonance Heating (ICRH) Transmitters at MIT Plasma Fusion Science Center's (PFSC) Alcator C Mod, a Tokamak-type fusion experimental device.

The speed of the series opening switch avoids the large fault currents on the transformer and power feed inherent with a crowbar. This improvement enables re-optimization of the Transformer/Rectifier (T/R) set, ultimately allowing increased power output and increased tetrode reliability.

FMIT HISTORY

The hardware developed was specifically optimized for the legacy FMIT (Fusion Materials Irradiation Test) transmitters, manufactured by Continental Electronics in the 1980s. The FMIT transmitters started out as "classic" 600 kW 80 MHz continuous wave units intended to power a linear accelerator for deuterons. The original systems had a triode low power amplifier, a tetrode driver stage and a high-power tetrode final amplifier. The legacy transmitters employed an EiMac 8973 FPA tetrode and a mercury ignitron crowbar.

After the FMIT program was cancelled, these transmitters were repurposed by the US DOE for various fusion laboratory research efforts such as for plasma heating, including the system at MIT. Over the past 25 years these systems have undergone progressive upgrades by the fusion community. The tetrode is currently the 4CM2500KG, capable of 2.5 MW.

GOALS FOR THE UPGRADE

A key concern in these transmitters is the possibility of ignitron explosion. Such explosions have occurred in the past, leading to the release of mercury into the cabinet and possibly the laboratory. This risk was unavoidable until improved protection switches, such as the solid-state opening switch, became practical. A second key concern is transmitter output power. The ratings of the existing high voltage power supply in the transmitter are a compromise between high output power (lower impedance required from the T/R set) and crowbar reliability (higher impedance required from the power supply to limit fault current).

DTI's opening switch upgrade replaces the mercury-filled ignitrons and safely allows the use of significantly reduced transformer impedance and lower droop, giving increased power. The kit applies DTI's proven high voltage solid-state switching technology to the plate and screen grid supplies of both the Final Power Amplifier (FPA) (Fig 1.) and Driver Cavity Amplifiers. A total of four opening switches are required: FPA Plate (30 kV/200 A); Driver Plate (17 kV/15 A); FPA Screen (2.5 kV/20 A); and Driver Screen (2.5 kV/5 A) (see schematic, Fig. 2).

The switch upgrade also improves tube protection; when a tetrode arc fault is sensed, all switches open in approximately 2 microseconds. This means that internal arc energy and gas evolution or plasma production remains small. Once plasma inside the tetrode has cleared sufficiently, voltage can be reapplied.

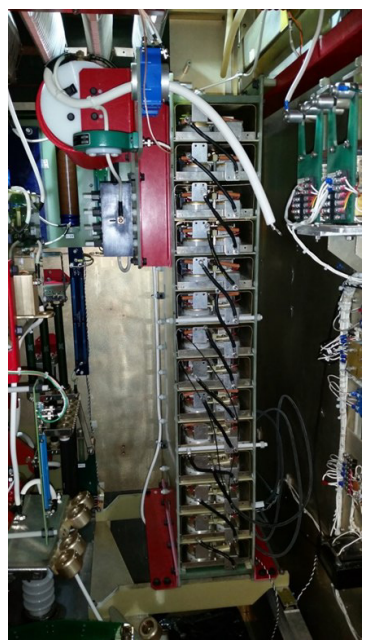

Figure 1: Final Power Amplifier High Voltage Switch Assembly. Switch consists of 14 IGBT switch plates and incorporates thick copper baseplates for inertial.

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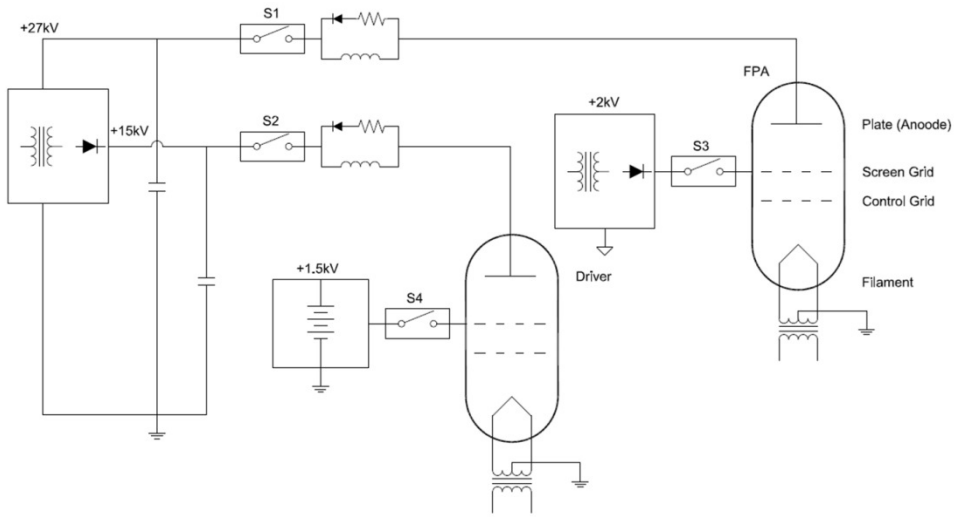

Figure 2: High Voltage Upgrade Schematic.

SWITCH DESCRIPTION

The DTI high voltage switch is fundamentally a number of high power IGBTs in series configured to operate properly as a fast opening or closing switch with high reliability. This switch can be commanded to toggle with sub-microsecond response time. The particular switches used in this upgrade employ a proven DTI magnetically-coupled drive arrangement leading to a very simple and robust configuration. Each switch assembly incorporates a series snubber inductor to limit the rate of rise of current during faults.

The large FPA opening switch is comprised of 14 switch plates in series, each of which holds a large dual 3300 V / 400 A IGBT module and associated control and protection circuitry. The system is conservatively designed for nominal 30 kV operation and 200 A, 8 second pulses, with a fault current nominal limit of 500 A.

The switch plates are designed with an "inertial cooling" concept using a heavy copper heat spreader without fins. The tradeoffs between copper and aluminum as well as fins versus no fins were investigated early in the design, leading to the selection of the simple copper plate. The temperature of this heatsink increases during the long pulse and is cooled off by a number of fans mounted on the back of the switch housing. DTI also delivers finned or liquid-cooled switch plates for continuous duty applications. DTI switches are conservatively designed and individual stages operate with a short circuit failure mode, so the stack continues operation seamlessly if an IGBT fails.

INSTALLATION AND OPERATION

DTI was first funded by the DOE under an SBIR to develop this upgrade kit in 2008. In 2012 the system was tested at DTI with dummy loads at full voltage and peak current under continuing DOE funds. In 2016, DTI installed and tested the upgrade with the help of MIT personnel under Alcator C-Mod operation funds (Fig 3).

During operation, any fault will cause all four switches to open within 2 microseconds. Assuming the fault is cleared, the switches may be reclosed immediately. The screen grid switches are commanded to close slightly after the anode switches (approximately 100 ms) to prevent application of screen voltage before plate (anode) voltage. Each time the plates are commanded to close a soft-start pulse burst is delivered. This rapidly and progressively charges up the cable and load capacitance downstream of the switch to minimize voltage overshoot. The 1 ms burst consists of a number of short pulses which are created on the main control board.

DTI's opening switch kit can readily be adapted to any similar transmitters as an upgrade from a crowbar.

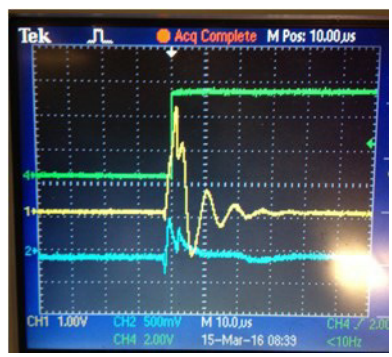

Figure 3: Full voltage Wire Test at Alcator C-Mod. Waveform shows data from the FPA at 31.4k kV. Green: Fault Detection. Yellow: Switch Current. Once current threshold of 170 A is crossed, fault logic toggles to high and opens the switch. The current reaches 320 A before the switch opens.

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