GA–A26447

MULTIPLE HIGH VOLTAGE MODULATORS OPERATING INDEPENDENTLY FROM A SINGLE COMMON 100 kV dc POWER SUPPLY

by
W.L. McDANIEL, P. HUYNH, D.D. ANASTASI,
J.F. TOOKER and D.M. HOYT

JUNE 2009

GENERAL ATOMICS

DISCLAIMER

GA–A26447

MULTIPLE HIGH VOLTAGE MODULATORS OPERATING INDEPENDENTLY FROM A SINGLE COMMON 100 kV dc POWER SUPPLY

by
W.L. McDANIEL, P. HUYNH, D.D. ANASTASI,
J.F. TOOKER and D.M. HOYT

This is a preprint of a paper to be presented at the 36th Symposium on Fusion Engineering, May 31 through June 5, 2009 in San Diego, California and to be published in the Proceedings.

Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698

GENERAL ATOMICS PROJECT 30200
JUNE 2009

GENERAL ATOMICS

Multiple High Voltage Modulators Operating Independently from a Single Common 100 kV dc Power Supply*

W.L. McDaniel, P. Huynh, D.D. Anastasi, J.F. Tooker, D.M. Hoyt
General Atomics
P.O. Box 85608
San Diego, California 92186-5608 USA
mcdaniel@fusion.gat.com

***Abstract.* This paper will describe a system where three gyrotrons can be independently operated, each with their own current, voltage and timing parameters, from a single 100 kV dc power supply. The supply enables each load to run simultaneously, sequentially, or by overlapping each other as long as the power rating of the dc supply is not surpassed. By taking full advantage of the capabilities of the front end power system, there is reduced cost, maintenance, and a lower number of high risk, high voltage components. The system also saves maintenance and complexity in lower level components thanks to a common safety and control system shared by each of the load regulators.**

Gyrotrons have a nonlinear voltage-current characteristic that need to be isolated from each other, so they each have their own modulators. By operating parallel modulators from a single supply, versus operating parallel gyrotrons from a single modulator, different operating modes can be obtained. For example, these modulators may be run simultaneously, where two gyrotrons can be run in parallel. They may also be 'phased' in and out so that they can be driven sequentially or by staggering the turn on and turn off times. This phased method will allow three gyrotrons operating, a number not otherwise supported by the rectifier power rating to be operated from a single 100 kV supply. In addition, different fault handling techniques, using a blended control system will be presented. This system implements a PLC for general 'Master' control, and 'slow' safety protections while relying on fast analog electronic logic circuits for the critical and potentially load damaging faults. Finally, there is acceptable risk of losing operation of all three gyrotrons simultaneously due to a single power supply fault. However, as presented in this paper, steps including fast logic control, and Tetrode 'blocking' have been implemented to mitigate this risk as much as possible.

Keywords: high voltage, gyrotron, modulators, control system, HVDC, power supply

I. INTRODUCTION

To provide sufficient heating of an ITER sized tokomak, particularly during very long pulses and near steady state operation, a large number of gyrotrons may be required [1]. Each gyrotron requires an expensive and complicated power system, generally consisting of a high voltage dc power supply, high voltage tetrode based modulator/regulator (mod/reg), independent fast analog control circuitry, and a relatively simple PLC-based control system. Efforts to save cost and simplify a gyrotron power system may be accomplished a number of ways.

From a gyrotron availability and flexibility standpoint, perhaps the most effective and least constraining method is by combining components from the high voltage dc power supply, and distributing the control system for each mod/reg.

II. SYSTEM COMPARISON

Recent operation at DIII-D has been conducted with six gyrotrons powered by three power systems, injecting into the same tokamak plasma. Four gyrotrons share two complete power systems, such that two gyrotrons are run in parallel from a single mod/reg. This has caused a few operational and reliability issues that were resolved in the design of the third system. First, when one gyrotron tube faults, the other running on the shared mod/reg must also be stopped from operating to ensure the power system protects the faulted gyrotron. Secondly, the impedance of the gyrotron tubes change as a function of voltage, occasionally causing a current loop that destabilizes the mod/reg itself. This restricted the stable current and voltage operating regime for the gyrotron [1]. In addition, each gyrotron must be pulsed at the same time and same voltage; one is always operated as 'slave' to the other. Finally, at mod/reg turn-on the rise time had to be increased in order to overcome excessive drop (sag) of the dc input voltage. This increases the amount of time at which the tetrode is at peak power dissipation, which coincided with an instability in the mod/reg.

The third and newest power system developed at DIII-D combines the high voltage dc power supply and the power supply control system, but designates a single mod/reg and its control system for each gyrotron. This enables completely isolated and independent gyrotron control and operation, while combining major high voltage components; consequently only a power supply fault will interrupt all connected gyrotrons from operation (Fig. 1). This configuration solves three of the above discussed issues. Since each mod/reg has its own interface with ECH control, there are no 'slave' gyrotrons (Fig. 2), and their non-linear characteristics do not interfere with one another. The initial dc input voltage sag was kept from drooping too low by adding 50% more capacitance to the input filter circuit (compare Figs. 3 and 4).

*This work was supported by the US Department of Energy under DE-FC02-04ER54698.

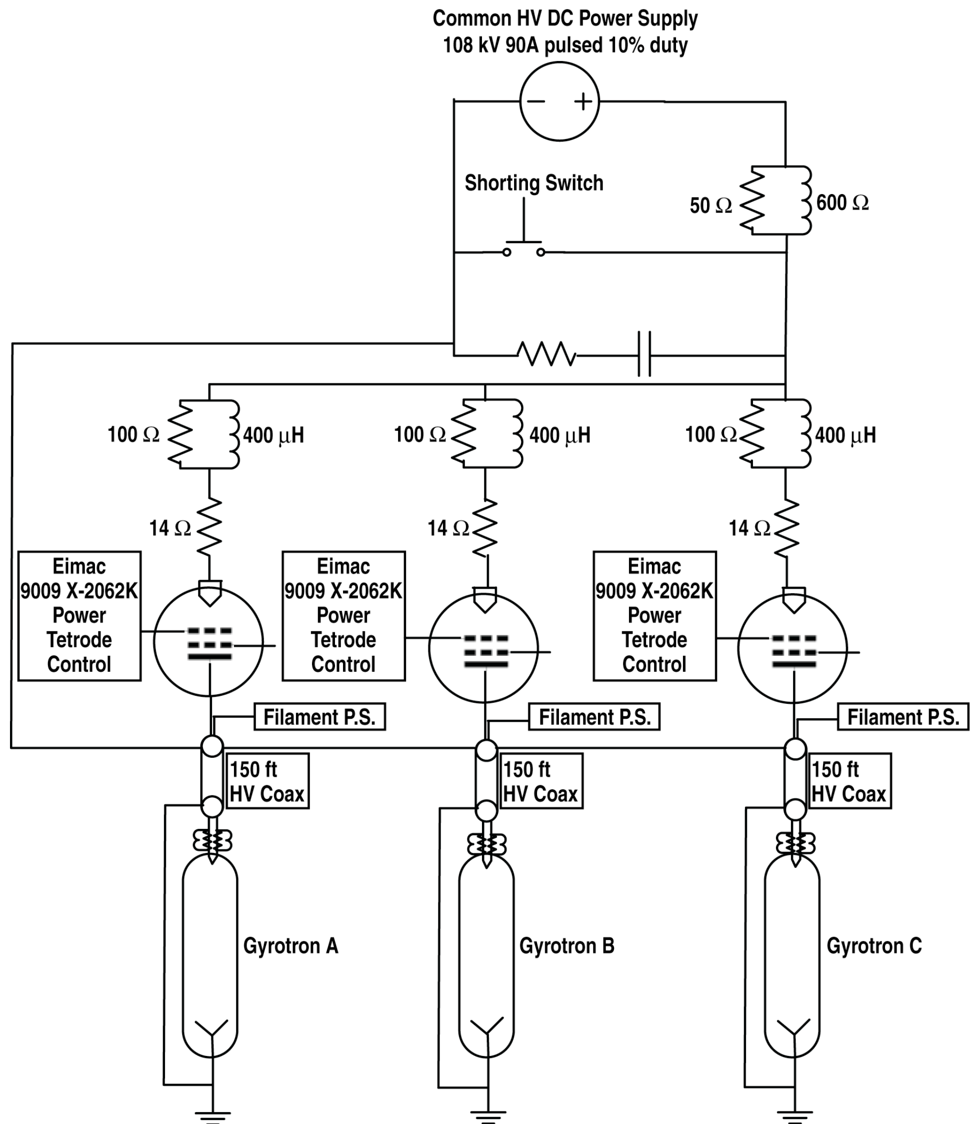

Figure 1. The basic layout of three mod/regs and three gyrotrons, run by a single HVDC power supply.

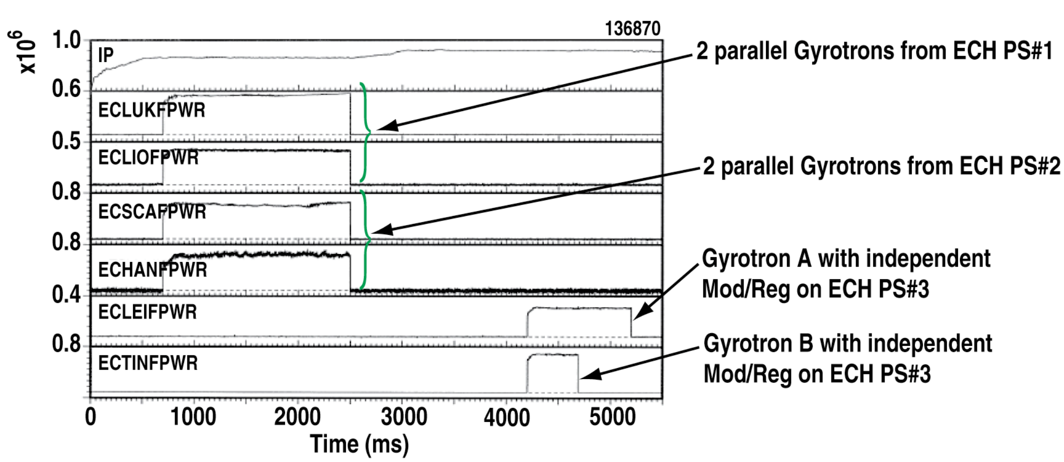

Figure 2. Six gyrotrons running into the same plasma shot. The lower two waveforms are two gyrotrons running from independent mod/regs, with the same HVDC power supply. Notice one gyrotron faulted early and the second gyrotron continued a full length shot.

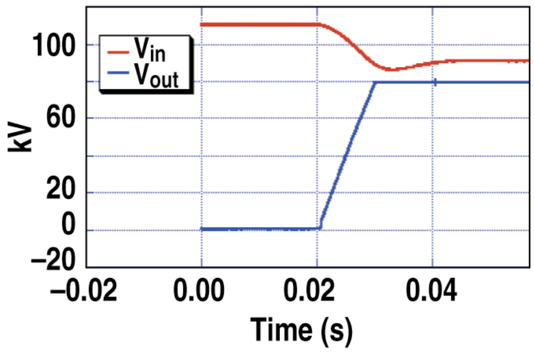

Figure 3. Plot of V_{in} vs. V_{out} of a typical gyrotron shot on the original gyrotron power systems. The voltage sag on V_{in} undershoots as the tetrode turns on, due to a 'softness' on the HVDC power supply. Input capacitors were added in the past, reducing this excessive voltage sag, but not enough.

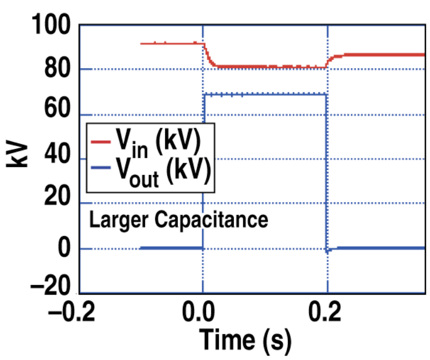

Figure 4. Plot of V_{in} vs. Vout of a typical gyrotron shot on the new gyrotron power system described in this paper. The voltage sag on V_{in} no longer undershoots as the tetrode turns on. Input capacitance was increased by 50% on the new HVDC power supply. The HVDC supply is now much 'stiffer' during mod/reg turn-on.

This new power system uses the same Eimac 9009 X-2062K tetrodes that are used in the neutral beam mod/regs throughout most the DIII-D facility and is rated for 50 amps pulsed. This allows for 150 amps with three mod/regs, however, due to the faceplate rating of the HVDC rectifier of 90 amps at 10% duty cycle, three gyrotrons cannot be operated at full parameters, simultaneously. However, 2 gyrotrons can run at the same time, and a third can be run or conditioned asynchronously. With only a total system cost increase of 15% for adding the third mod/reg, a cost savings can be obtained when the third mod/reg is used asynchronously for gyrotron conditioning in-between DIII-D shots. Now conditioning can be accomplished during a normal work shift, rather than during a second shift, and weekend man-hours. Flexibility of operation is also possible allowing for three 'phased' gyrotrons to inject energy into a single plasma shot, staggered so that a maximum of two are running simultaneously. In designing a new ignitron-based crowbar, cost was reduced by installing 50 kV isolation transformers in series between each stage of the crowbar (Fig. 5), rather than using four 100 kV isolation transformers separately feeding each stage.

III. Fast Fault Handling

In order to protect the gyrotron, each mod/reg is equipped with its own set of fast analog control circuits. A number of protection functions pertaining to the mod/reg components are performed on the high voltage deck itself such as grid and screen over-voltages and over-currents. These faults are then sent via digital fiber to its own ground level control system for fault handling. Fast analog fiber optic links are also used to communicate between the high voltage control system and the ground level control system for monitoring waveforms and implementing redundant fault logic control through the mod/regs PLC. Most faults, especially gyrotron faults such as body current, will simply generate a block, turning off the tetrode, and effectively shutting off energy applied to the

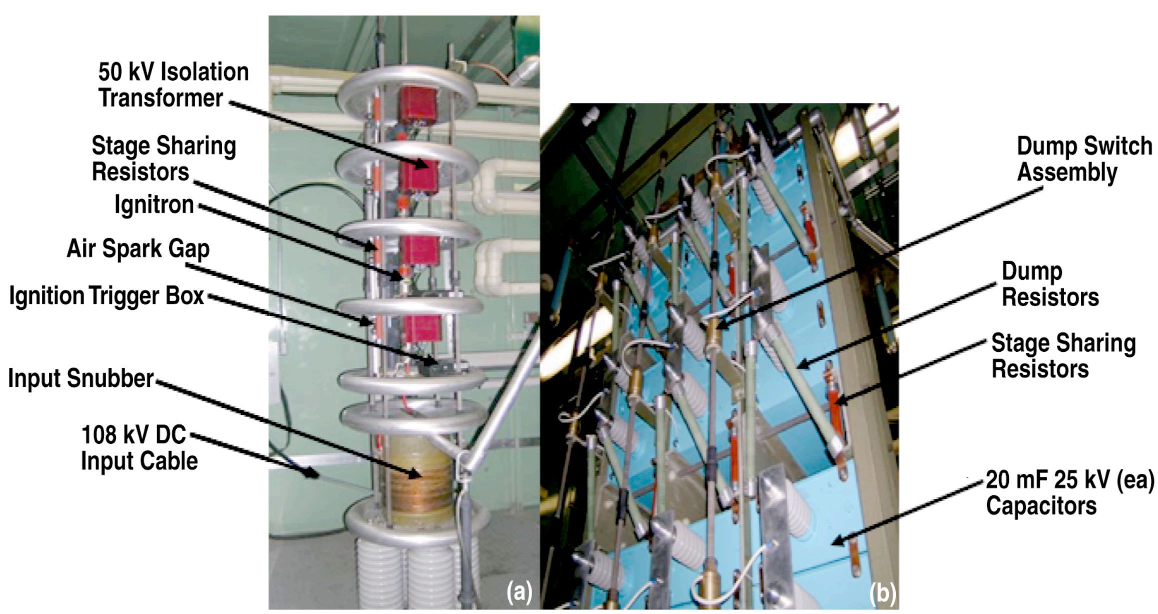

Figure 5. (a) New ignitron based crowbar arrangement with series isolation transformers and SCR trigger boxes. (b) HVDC input capacitor circuit, total capacitance is 30uF and series resistance is 34 ohms.

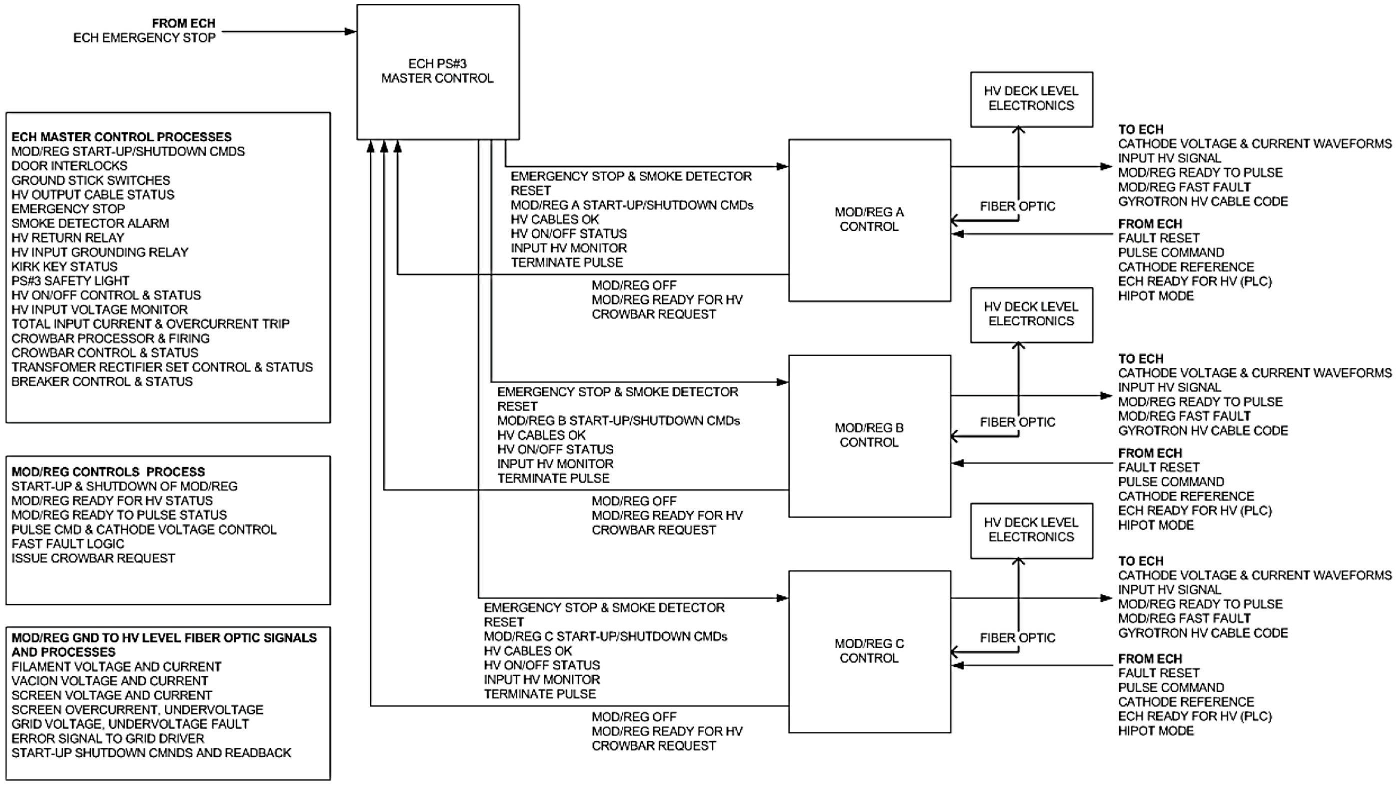

Figure 6. Block diagram of processes and communication signals between the various sections of the distributed control system.

corresponding gyrotron. At the ground level control system, each of the mod/regs' control systems then communicates with a master control system, which is responsible for controlling the input high voltage and associated safety interlocks. The master control system and mod/reg control systems each send and receive status signals, faults, and requests. For example; a 'Crowbar Request' is received by the master from a mod/reg control system; it fires the crowbar, and then controls and monitors the breakers. Each mod/reg control system can communicate directly with main ECH control to obtain and feedback different control parameters and faults, however the master control system is connected to ECH only by an 'emergency stop' signal (Fig. 6). This limits the potential for inadvertent events causing a loss of high voltage. Ultimately, the only fault that causes a mod/reg to issue a 'crowbar request' to quickly remove high volts is when the tetrode 'fails to block' and power may be seen at the output of the mod/reg when it is not requested.

IV. Limitations and Areas for Improvement

Due to the short time frame between project initiation and required operation of the system, much of the design for the new system was copied from existing systems. Some issues were discovered in testing and early operation of the power system. Using three mod/regs means there are three times more opportunity to generate a power supply fault, emphasizing the importance of having two series HV breakers for equipment protection. Also, running multiple loads from a single HVDC power system compromises the sensitivity allowed on some of the fault protection. For example, a single gyrotron running on a single mod/reg, connected to a single HVDC power supply will allow for primary power fuses and dc overcurrent limits set to 45–50 amps. However, running two gyrotrons simultaneously will require the dc overcurrent limit and fuses to operate at 80 amps if simultaneous operation is then required. In future systems, an upgraded primary power supply, with higher ratings, would further 'stiffen' the dc input voltage, and could allow for more parallel mod/regs operating more asynchronous and independent gyrotrons.

V. Summary

This paper, described the new gyrotron power system at DIII-D and its advantages over the existing systems based on flexibility of use and cost parameters. Changes and improvements implemented during assembly of the HVDC power system were discussed as well as additional 'problem' areas for future power system development. The primary HVDC power supply has been stiffened significantly. However, DIII-D has not yet run three gyrotrons from this power system as is still intended. When the third modulator regulator is tested and certified for operation and the HVDC power supply is driving a third larger load, the step-up transformer used in the yard may need to be replaced with a more substantial unit.

References

[1] C. J. Pawley et al., Stability of high voltage modulators for nonlinear loads, Fusion Engineering, 2003. 20th IEEE/NPSS Symp. on Fusion; Published: 14-17 Oct. 2003, Page(s): 387 - 389.