GA–A25778

HEATING AND CURRENT DRIVE POWER SYSTEMS FOR STEADY-STATE MFE DEVICES

by
J.F. TOOKER

MAY 2007

GENERAL ATOMICS

DISCLAIMER

GA–A25778

HEATING AND CURRENT DRIVE POWER SYSTEMS FOR STEADY-STATE MFE DEVICES

by
J.F. TOOKER

This is a preprint of a paper to be presented at the 5th IAEA Technical Meeting on Steady State Operations of Magnetic Fusion Devices, May 14-17, 2007 in Daejeon, Republic of Korea and to be published in the Proceedings.

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

GENERAL ATOMICS PROJECT 30200
MAY 2007

GENERAL ATOMICS

ABSTRACT

Steady-state magnetic fusion devices require many megawatts of heating and current drive (H&CD). The ITER design has 20 MW each of electron cyclotron (EC) and ion cyclotron (IC) H&CD, and possibly 20 MW of lower hybrid (LH) H&CD, with potential upgrades to 40 MW. The ITER EC system has twenty-four 170 GHz gyrotrons plus three startup gyrotrons. The IC system has eight tetrode rf sources. The planned LH system has 24 klystrons. The proposed configurations for the ITER EC and LH power supplies are similar, with 12 rf sources connected in pairs to a main high voltage (HV) power supply. The IC system has a power supply per source. Although the EC and LH power systems reduce cost by connecting multiple rf sources to a single main HV power supply, problems can arise when the sources, such as the ITER gyrotrons, are not designed to operate at the same voltage.

Each H&CD system has several requirements to fulfill in support of Magnetic Fusion Energy (MFE) device operations. For example, EC systems are used for plasma heating, current drive, and to control MHD instabilities, which would require the gyrotrons to turn on at different times for varying pulse lengths and power levels. The configuration of their power systems must have the versatility to meet these requirements, as well as operate one or more rf sources off-line for troubleshooting, etc. If possible, one would like to have a common architecture for the various H&CD power systems to maximize commonality and to avoid the expense of developing several designs.

An innovative power system architecture, initially proposed by General Atomics for the rf system of the linear accelerator for the Accelerator Production of Tritium project [R. Street, et al., "Advanced buck converter power supply `ABCPS' for APT," *Proc. 19th Int. LINAC Conf. (Chicago)* Eds CE Eyberger, RC Pardo, MM White (1998) pp. 216–218], can be readily adapted for the MFE heating and current drive systems. It maintains the versatility to control the voltage applied to each rf source that is provided by the traditional "power supply per source," and yet takes advantage of the economy of scale that is afforded by the need to power a large number of rf sources. It consists of unregulated main HV power supplies with multiple rf sources connected to each as in the ITER EC and LH H&CD systems. A HV power supply would produce a voltage appropriate for the class of rf sources (klystrons, gyrotrons, or tetrodes) to be connected to it. A separate solid-state IGBT-based pulse-width-modulated regulator is used for each rf source. By providing completely independent control of the voltage applied to each rf source, a very versatile power system is obtained that maximizes the support of device operations by being able to run any source in any of its possible modes of operation, while at the same time providing the capability to troubleshoot any source off-line.

1. INTRODUCTION

Steady-state magnetic fusion devices will require many megawatts of heating and current drive to initiate, sustain, and control the plasmas [1]. For example, the rf heating and current drive systems on ITER are being designed to deliver to the plasma:

- 20 MW of electron cyclotron heating and current drive (EC H&CD),
- 20 MW of ion cyclotron heating and current drive (IC H&CD), and possibly
- 20 MW of lower hybrid heating and current drive (LH H&CD),

with the potential to upgrade these to 40 MW in the future. The ITER EC system has twenty-four 1 MW 170 GHz gyrotrons, plus three 1 MW start-up gyrotrons. The IC system has eight 3 MW sources. The proposed LH system would have twenty-four 1 MW klystrons.

If the power systems for each of these follow the traditional practice, there would be an individual complete power supply for each of these rf sources. This leads operationally to the most versatile power systems, but it also leads to power systems that are very large physically and are the most costly. The costs and size of the power systems can be reduced if one could operate multiple sources from a single power supply by taking advantage of the economy of scale. Options being considered for the EC (or LH) power system on ITER do this by connecting 12 gyrotrons (or klystrons) each onto two large high voltage dc power supplies. However, there are operational issues and concerns with this that ITER is having to address.

This paper will present considerations that the configuration of these power systems must take into account. A generic power system architecture is proposed that can be readily adapted to a variety of heating and current drive systems. The more specific issues and considerations for the ITER EC system will be used as an example, and the proposed solution will be tailored for the EC power system.

2. POWER SYSTEM CONSIDERATIONS

If one wants to energize multiple rf sources from a single high voltage power supply, one cannot assume that they will all operate identically. The preferred operating point for each could be different. Although a subset of the sources will operate at the same power supply settings, others will need to operate at different settings to achieve stable operation. This can become a bigger issue if multiple vendors provide the "same" rf source, and they are designed to operate at completely different voltages. This is occurring in the ITER EC H&CD as three different partners provide the 170 GHz gyrotrons and each has different voltage requirements. In early 2005 the vendors of the 170 GHz gyrotrons under development for ITER were asked to list the requirements for the power supplies to run each of their gyrotrons. Table 1 summarizes those requirements. The three start-up gyrotrons are now to be provided by India and there is no design for them at this time.

Table 1
Power Supply Parameters for Each ITER Gyrotron

Parameter	Units	Gyrotron Russia	Gyrotron Japan[(a)]	Gyrotron Europe
Max beam voltage	kV	105	100	100
Nominal cathode voltage	kV	–70	–60	–60
Cathode voltage range	kV		–45 to –65	–45 to –65
Cathode current	A	35	50	80
Acceleration voltage range	kV	0 to +35	0 to +40	0 to +40
Acceleration current	A	0.1	0.2	0.15

[(a)]Uses –60 kV cathode-collector power supply with a 100 kV cathode-body power supply; also requires anode voltage set by a resistor/zener diode network.

As can be seen, the set of gyrotrons from each vendor operates at different power supply settings. One could try to force the gyrotron vendors to design the gyrotrons to a common set of power supply specifications, but this is not likely given the amount of effort and cost expended to-date in the development of these gyrotrons. One option being considered for the EC H&CD power supplies has 12 gyrotrons connected to each of two HVdc power supplies. These 12 gyrotrons will have the same cathode voltage. Therefore, some of the gyrotrons will be operating at their design voltages, while others will be operating with lower voltage, and therefore lower output power. One might think to adjust the body power supply to compensate for a different cathode voltage in order to obtain the correct beam voltage for a given gyrotron. At best this will change the depression voltage and alter the efficiency of the gyrotron. At worst, the gyrotron will not be able to operate due to electrons being reflected back toward the cavity from the collector because of too high of a depression voltage.

With multiple rf sources in the H&CD systems of steady-state MFE devices, all of them will not be fully operational all the time. An rf source could have had a degrading internal fault and need to be reconditioned. A source could have developed an operational problem, which needs to be investigated and remedied, so that it could be returned to service as quickly as possible. After replacement of a failed rf source, the replacement will need to be started from low voltage and current setting and reconditioned before being able to support operation of the MFE device. Alternately, during a pulse into the MFE device, the termination of a pulse of a rf source (due to a fault such as an internal arc, overcurrent, vac-ion over current, rf drop-out, etc.) should not result in the termination of one or more rf sources that are running without a problem. The configuration of the power system needs to be such that it maximizes the availability of the gyrotrons for operation of the MFE device, as well as maximize the capability to operate one or more rf sources off-line from MFE device operations for troubleshooting, reconditioning, and the like.

The H&CD system can have more than one role in support of MFE device operations. For example, EC H&CD systems are used for plasma heating, current drive, suppression of unwanted plasma modes, transport studies, etc. In support of this multi-function role, the EC power system should have the capability to operate the gyrotrons independently, either in groups or individually, to turn on different gyrotrons at different times, for different pulse lengths, or to modulate or otherwise control the output power.

All of these issues need to be considered when developing the design for the power supplies of a H&CD system. Furthermore, the design needs to consider that future rf sources will likely operate at parameters different from those of present day units. One would not want to limit rf source development, or force that development in some way due to limitations in the operational capability of the associated H&CD power system, or to have to incur a very costly upgrade to the H&CD power system to be able to run future sources.

3. POWER SYSTEM CONFIGURATION

If the power systems for the H&CD systems had an individual complete power supply for each rf source, then operationally the most versatile configuration for the power system would be obtained, but it also is the most expensive configuration and would also be very large physically. The costs and size of the power systems can be reduced if one could operate multiple sources from a single power supply by taking advantage of the economy of scale. This is especially true of the front-end of the power system in which the incoming ac line voltage is converted to high voltage dc. However, the configuration of the power system must preserve the individual control of the voltage applied to each rf source, or the operational versatility of the H&CD can be severely comprised. This is the dilemma the power system for the ITER EC H&CD is now facing.

It is less expensive to have a single, larger HVdc power supply, consisting of switchgear, transformer, rectifier, and filter, feeding a set of “N” rf sources, than having “N” smaller HVdc power supplies, one for each rf source. Normally for the smaller HVdc power supplies, the incoming line voltage is stepped down to an intermediate voltage, which is then stepped up to the required HVdc by each power supply. The larger HVdc power supply can go directly from the incoming line voltage to the required HVdc, further reducing cost and complexity by eliminating the intermediate ac voltage distribution equipment. One option under consideration for the power system for the ITER EC H&CD has 12 gyrotrons connected to a single HVdc power supply, with the primary of the transformer at the incoming ac line voltage. Pairs of gyrotrons are connected to and disconnected from the HVdc by IGBT switches. A second option, essentially a power supply per pair of gyrotrons, requires the step-down transformer to produce an intermediate ac voltage and the associated distribution equipment.

The architecture for the H&CD power supply proposed here converts the incoming line voltage directly to the HVdc and is sized for “N” rf sources. There are “N” regulators, one for each rf source, to independently control the voltage applied to each rf source. A simplified block diagram of this configuration is shown in Fig. 1.

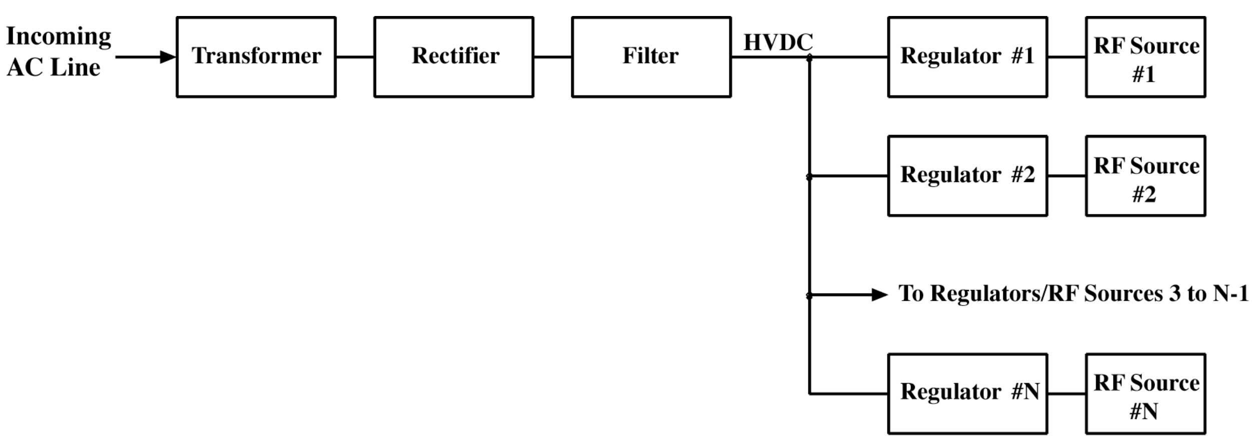

Fig. 1. Simplified block diagram of configuration for power system.

This architecture was initially proposed by General Atomics for the 244 klystrons in the rf system of the linear accelerator for the Accelerator Production of Tritium project [2]. With the advances in high voltage, high power solid-state devices and in the design of power supplies that are taking advantage of their capabilities, an isolated gate bipolar transistor (IGBT) pulse-width-modulated (PWM) regulator can be a viable and better option, especially over regulators that employ high voltage, high power tetrodes.

The DIII-D tokamak facility has an EC system [3–5] with six 1 MW-level gyrotrons and three power supplies. Two of the EC power supplies can operate two gyrotrons each with the voltage controlled by a single tetrode, not unlike that proposed for ITER. The "weaker" or operationally "more problematic" of the two gyrotrons dominates the operation of the two. For that reason, these power supplies normally run one gyrotron for conditioning or troubleshooting. When running two gyrotrons in support of DIII-D operations, the operating point of both is determined by the one with the lower stable voltage, limiting the power that can be delivered to the plasma. In addition, a fault of one gyrotron terminates both, with the concurrent negative impact on the physics experiment. The third EC power supply energizes three 1 MW level gyrotrons using three tetrode-based modulator-regulators connected to a common HVdc power supply. This power supply has run three gyrotrons at different voltage levels to maximize the power to the plasma. If one faulted, the others continued to operate.

The main advantage of a tetrode-based regulator over a solid-state regulator is the regulation speed. However, a tetrode-based modulator has several disadvantages compared to a solid-state regulator. A tetrode needs screen, grid, filament and VacIon power supplies along with associated electronics to control and monitor them, as well as a high water flow for cooling. Not only does this add to the cost and complexity of the modulator, tetrodes at the voltage and power levels required to operate the rf sources are very expensive. Additionally, tetrodes have limited operating life. If the regulation speed of a tetrode-based regulator is not required, such as for the cathode power supply of depressed collector gyrotrons, a solid-state regulator is a more cost-effective, less complex, and more reliable alternative.

A simplified diagram of an IGBT PWM regulator is shown in Fig. 2. There are enough IGBTs connected in series to provide the necessary voltage hold-off. The IGBTs in the PWM regulator switch at a frequency around 15 kHz and an L-C (inductor-capacitor) filter with a free-wheeling diode filters the output. Regulation of 0.25% or better can easily be achieved. A crowbar is needed to limit the energy deposited into the gyrotron from the filter if the gyrotron has an internal arc.

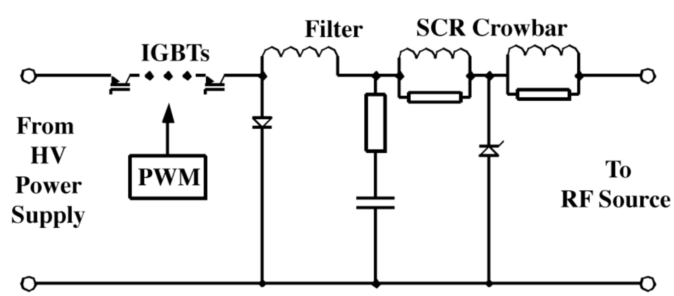

Fig. 2. Simplified diagram of an IGBT PWM regulator.

The voltage generated by HVdc power supply is determined by the voltage needed for the rf source with the highest voltage, plus some additional amount for future sources. For rf sources that need to operate at lower voltages, the PWM control would simply reduce the pulse width of the IGBTs to regulate at a lower output voltage without substantially increasing the power dissipated in the power supply, unlike that of a tetrode-based regulator.

A simplified one-line diagram of this proposed configuration as a gyrotron power supply for the ITER EC H&CD system is shown in Fig. 3. It maintains the configuration of the first option for ITER with a main HVdc cathode power supply and 12 gyrotrons (or 15 including the start-up gyrotrons) per power supply. However, instead of an IGBT switch connecting pairs of gyrotrons to the main HVdc, the architecture is revised by converting the IGBT switches to solid-state IGBT-based PWM regulators, with one regulator per gyrotron.

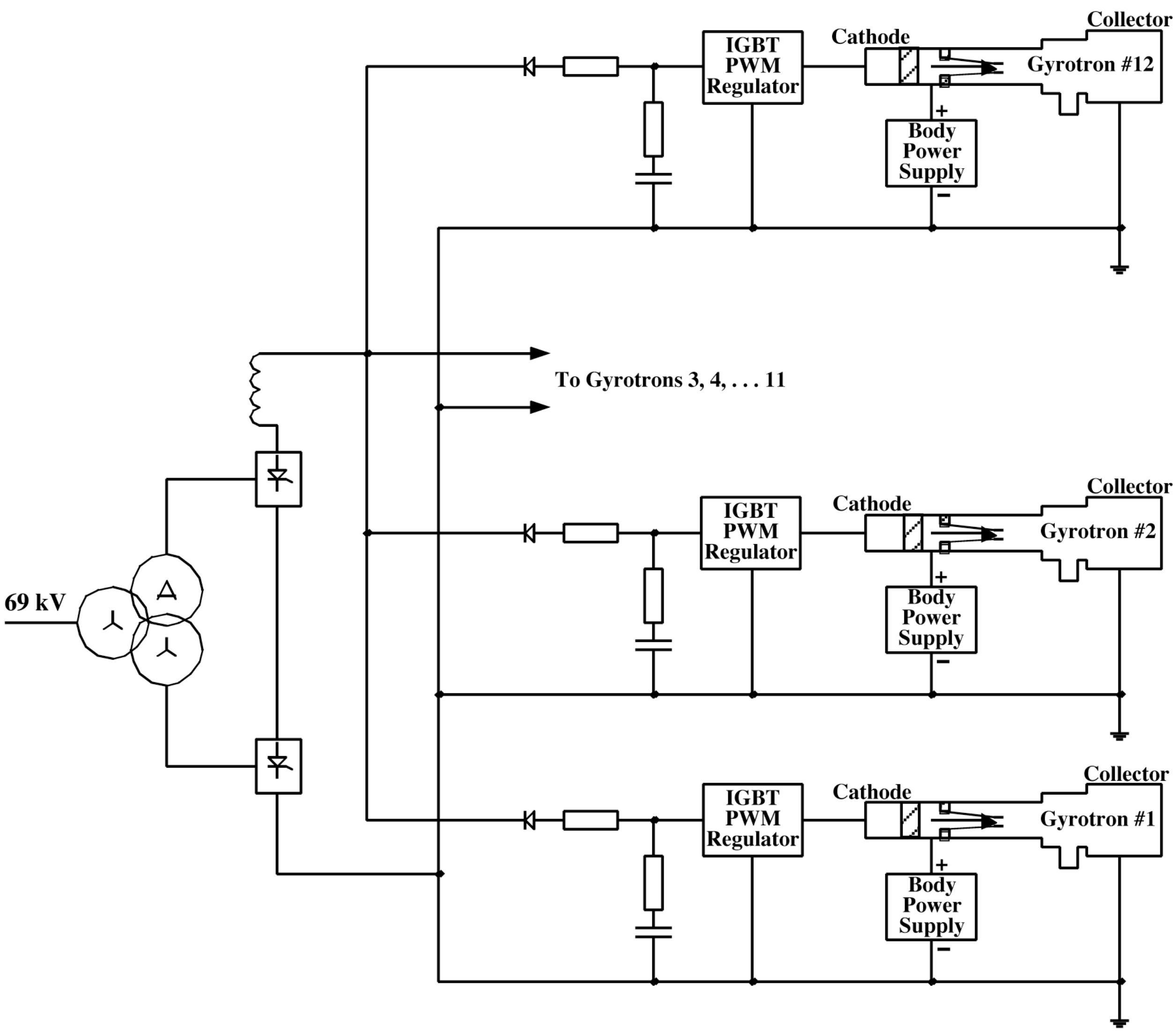

Fig. 3. One-line diagram of proposed architecture as an ITER EC H&CD power supply.

This configuration is readily adaptable to the various H&CD systems of steady-state MFE devices. The output voltage of the HVdc power supply would match that of the particular class of rf source, plus some head-room for the regulator to control the voltage applied to the sources (70 kVdc for EC gyrotrons, 95 kVdc for the LH klystrons, and 30 kVdc for IC tetrodes). The rectifier diode stacks can be modular, with more or fewer in series depending on the voltage required for the rf source, and use the same diode for all the power supplies to achieve commonality of components. A few IGBTs (four for example) can be assembled into modules, with more or fewer modules in series, depending on the required voltage hold-off. The number of rf sources connected to each power supply can be selected to achieve a convenient combination. For example, an option for the ITER EC and LH power systems has 12 rf sources per HVDC power supply. The HVdc power supplies can be located outside. Only the regulators need to be inside, in the vicinity of the rf sources, to limit the energy stored in the cable between them.

4. CONCLUSION

A configuration for the H&CD power systems of steady-state MFE devices has been developed that can operate multiple rf sources with completely independent control of the voltages applied to each rf source. A very versatile power system is obtained for the H&CD systems required for steady-state MFE devices that maximizes the support of physics and operations by being able to simultaneously run each rf source at its most appropriate voltage and in any of its possible modes of operation, while at the same time providing the capability to run any source off-line for troubleshooting, conditioning, or similar activities.

REFERENCES

[1] ITER Physics Expert Group on Energetic Particles, Heating and Current Drive 1999 Chapter 6: Plasma auxiliary heating and current drive, Eds ITER Physics Basis, *Nucl. Fusion* **39**, 2465–2539.

[2] Street R, Overett T and Bowles E 1998 Advanced buck converter power supply "ABCPS" for APT *Proc. 19th Int. LINAC Conf. (Chicago)* Eds CE Eyberger, RC Pardo, MM White p 216–218.

[3] Lohr J, *et al.,* 2005 *Fusion Sci. Technol.* **48**, 1226.

[4] Lohr J, Callis R W, Ellis R A, Gorelov I A, Kajiwara K, Ponce D, and Tooker J F 2006 *Proc. 14th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating (Heliotopos)* Ed A Lazaros p 418.

[5] Callis R W *et al.* 2003 *Nucl. Fusion* **43** 1501.

ACKNOWLEDGMENT

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