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Operation of a Versatile Multi-power Supply System Driving Non-axisymmetric Coil Sets on the DIII-D Tokamak

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***Abstract*— We describe the development, and implementation of the DIII-D tokamak power supply system driving non-axisymmetric coil sets. The coil system operates in a broad range of 0 to 7 kA and dc up to 40 kHz using different combinations of power supplies. Three types of power supplies drive the tokamak's non-axisymmetric coil sets; variable unipolar quasi-dc SCR supplies, bi-polar switching power amplifiers, and linear amplifiers. The coils are used primarily for error field correction, resistive wall mode studies, and edge localized mode suppression. A versatile computer program generates the power supply — coil interconnections in the patch panel area for a specific experiment. Control of individual coils, or combinations of coils, is accomplished using the plasma control system (PCS). An upgrade to a precision response of the high current unipolar SCR power supplies has been under development. We discuss routine operation, coil control using the PCS, and challenges in maintaining this complex system.**

Keywords - power sypply; coil; linear amplifier

I. INTRODUCTION

The DIII-D non-axisymmetric coil sets require a versatile power supply system to meet the diverse needs of different tokamak experiments. Three types of power supplies are used in various combinations to drive these coil sets. Each type has different characteristics, i.e. high current, fast time response, etc. and are operated independently. The power supply system consists of: variable unipolar dc SCR supplies, bi-polar switching power amplifiers (SPAs), and linear amplifiers. The experimental setup has two types of coils shown in Fig. 1: internal coils (I-coils) and external compensating coils (C-coils). The coils are used primarily for error field correction, resistive wall mode (RWM) studies, and edge localized mode (ELM) suppression. The installation in the DIII–D tokamak of the I-coils allowed improved RWM and error field correction, but required additional power supply systems. The I-coil system is comprised of 12 individual low inductance magnetic field coils that can be rearranged in multiple configurations. The original purpose of the I/C-coils was to provide feedback stabilization up to the ideal wall beta limit without the need for strong plasma rotation and also to provide error field correction, although other experiments such as ELM suppression are now routinely carried out.

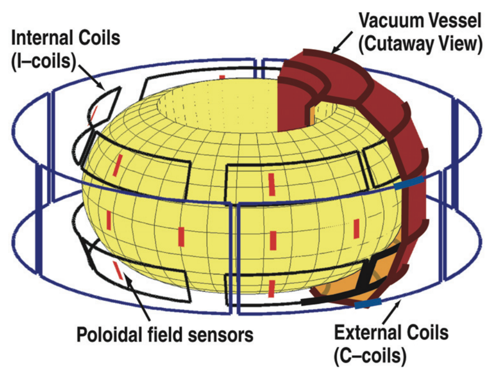

Figure 1. Non-axisymmetric external field coils.

Before the startup of each experiment, a versatile computer program generates the power supply — coil configurations and the corresponding patch panel interconnect diagram. Control during each shot of individual coils, or combinations of coils, is accomplished using the plasma control system (PCS). We discuss the successful integration of these various components, an upgrade to a precision response of the dc power supplies, routine operation, coil control using the PCS, and challenges in maintaining this complex system.

II. SYSTEMS DESCRIPTION

A. DC Power Generation and Delivery

The power supply system driving non-axisymmetric coil sets operates in a broad parameter range. For example if high current and slow response are required, the SCR power supplies (≤7 kA) are used. For intermediate response and current, the SPAs (2 kHz, 5 kA) are used. The highest frequency experiments require the linear amplifiers (≤40 kHz, 1.6 kA).

B. Non-axisymmetric Coils (C-coils and I-coils)

As described in Sec. I, the DIII-D tokamak has error field correction done by stabilization coils (I- and C-coils) shown in Fig. 1. The I-coil system comprises 12 individual in-vessel low inductance magnetic field coils that can be rearranged in multiple configurations. The power supply system can drive up to 7 kA in these low inductance coils to stop plasma rotation. The C-coil system consists of six external coils, symmetrical with the vessel midplane. For most experiments these coils are connected in pairs 180^o against, producing a toroidal n=1 mode number shown in Fig. 2. Each pair of C-coils is driven by one C-supply, has R = 11 mΩ and L = 240 uH. For typical hookups of I-coils, both SPAs and linear amplifiers are used, but they cannot be operated simultaneously on the same coil. We can run linear amplifiers to I-coils and SPAs to C-coils, however, most of our work is with n=1 "240 deg. quartets" where the top and bottom I-coils are phased 240 degrees from each other powered in groups of four coils. When typically running the 24 linear amplifiers (8 amplifiers/quartet) at 100 Hz, the I-coil quartets with cable leads have L = 46 uH and R = 31 mΩ. When using the three SPAs at 100 Hz, the I-coil quartets with their cable connections have L = 57 uH, R = 22 mΩ. The patch panel allows numerous combinations, hence, we can do n=2, n=3 and also drive each I-coil individually. However, most work is n=1 quartets as typical hookups, although other combinations have also been used.

C. Quasi-DC SCR Power Supplies

The power delivery system currently consists of five pulse-rated power supplies (C1-C5) with pulsed power rating of 350 Vdc, 5 kA, at 30 s. A six-pulse SCR (primary side) controlled rectifier output diode bridge can be connected in series to supply 350 Vdc, 5 kA or in parallel to supply 150 V, 7 kA. Three power supplies are directly connected to magnetic coils (parallel). The other two are in series configuration to provide input power to four 350 Vdc, 5 kA pulse rated SPAs.

D. Switching Power Amplifiers

A SPA's pulsed power rating is 350 V, ±5 kA, 10 s. Each SPA comprises three independent sub-cells. When configured in Single output mode the supply can deliver up to 5 kA to the load and when connected in triple output mode the supply can deliver three independent 1.7 kA outputs to the load. Each sub-cell contains twelve insulated gate bipolar transistors configured in an H-bridge configuration. The SPAs, when connected to the I-coils provide maximum current from dc to 300 Hz. The SPAs can operate up to 2 kHz at reduced current because of the inductance of the I-coils and their feed cables.

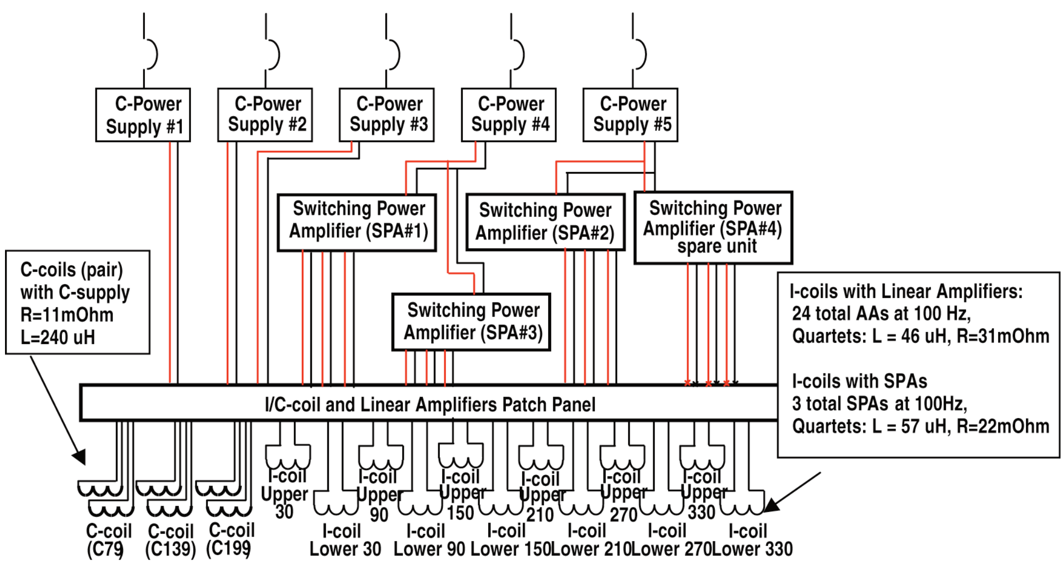

Figure 2. Typical Power distribution into patch panel and coils.

E. DIII-D Parallel Audio Amplifier Power System Description

The DIII-D I-coils must provide fast response to plasma conditions for some experiments. To meet the specified goal, three types of commercial modular linear amplifiers were tested for configurability, power capability, and reliable system integration functionality. The AE Techron 7780 Linear Amplifer, 5 kW rms CW, 140 Vpk max, and 200 A max, for 10 s max from dc to 40 kHz met this goal. A system of 24 linear amplifiers connectable in various series/parallel output configurations was developed, with a focus on maximizing current output. A linear amplifier current sharing is achieved through matched output impedances using equal length output leads joined through the linear amplifier patch panel to the separate I-coil patch panel. The I-coil patch panel physically locks out other power supply inputs when the linear amplifiers are used.

The 24 linear amplifiers system is typically connected in three groups of eight parallel linear amplifiers in an operational group capable of 1.6 kA into 0.1 Ω load (four I-coils in series), dc to ~1 kHz. Each group has a single master with seven slaves, with the master distributing the command signal through the intermediate stage drive signal. A system feature is the automatic designation of master/slave status via a 25 pin DB connector patch panel that routes the plasma control system commands, links the master/save interlocks, and selects the linear amplifiers master/slave mode by physical jumper connections. Group interconnected interlocks prevent parallel operation if any of the group linear amplifier's trip output overload, thermal overload, or input circuit breaker trip.

F. Regulation PCS, CAMAC, PLCs, cRIO

Data acquisition for the I-coil system is implemented with a cPCI digitizer system of 96 channels. Data is acquired at a rate of 50 to 100 KS/s throughout the entire 5 to 10 s DIII-D plasma shot and stored on a local cPCI i86 computer. Post-shot, the data is uploaded via Ethernet to the shot database. Parameters acquired include coil currents, coil voltages, and power supply currents and voltages for the five large dc supplies and four switched power amplifiers. The PCS commands, as received at the power supply room are also digitized for diagnostic purposes. A local control system is used to coordinate the operation of the linear amplifiers with the DIII-D machine control. The linear amplifier control system interlocks the 208 volt power to the amplifiers with the machine access control system for personnel protection and safety. Additionally, it synchronizes the arming of the supplies to the shot cycle and directs PCS command voltages to the correct amplifiers. A low-level signal patch panel is used in concert with the amp output patch panel to assign master-slave status to the linear amplifiers in a set. The status of this patch panel is reported to the DIII-D control computer by an Ethernet connected server with 96 discrete inputs, scanned once per second. The server device also reports ready and fault conditions for each amplifier

G. Patch Panels — Distribute Power

A typical interconnection, distributing DIII-D power from power supplies through patch panels, to the coil sets, is shown in Figs 3 and 4. In this case, linear amplifiers are not connected. They have a separate patch panel shown in Fig. 3, and cannot be run on the same coil if other supplies are used, although an upgrade is being considered to allow this capability. From hundreds variations of I/C-coil patch panel connections about 40 have been tried in various plasma experiments. The patch panel diagram is generated by the operations computer before each experiment. An example of a typical 240 quartet is shown in Fig. 4. A specific hookup is connected in less than 10 minutes. Standard connections are made with copper jumper straps between SPA subsections and/or I-coils. Preformed cables are used for non-standard connections and between supplies and coils.

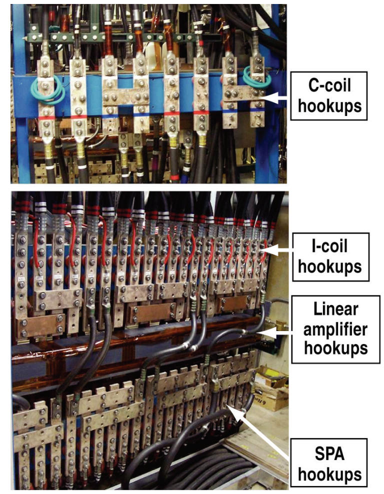

Figure 3. Actual Patch panel photos showing coils connections.

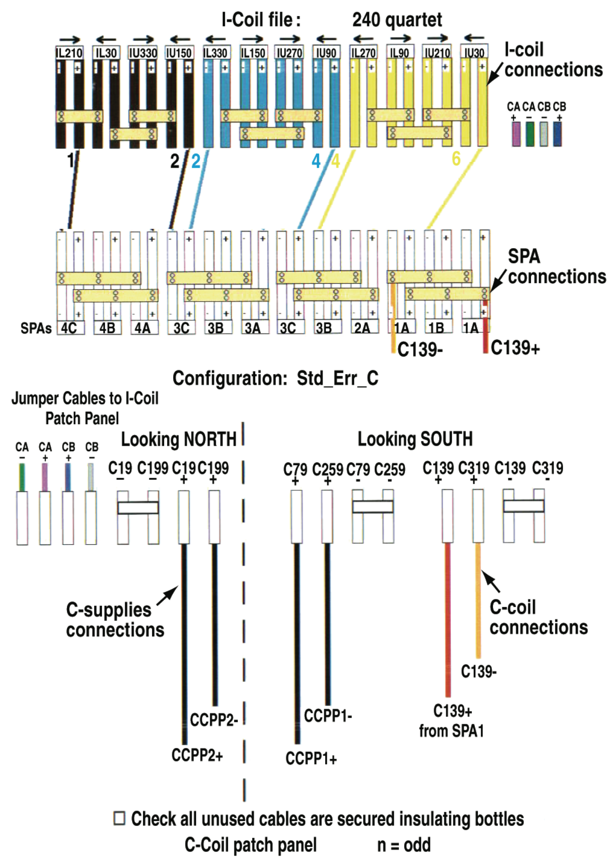

Figure 4. Typical computer generated patch panel connections.

III. UTILIZING THE TOKAMAK'S VERSATILE C/I-COILS EXPERIMENTAL CONFIGURATIONS

There have been several interesting physics experiments conducted showing the versatility and effectiveness of this power supply-coil system. The physics requirement was to power each C-coil separately, in pairs, or all together, and for the I-coils individual connections or the ability to interconnect the I-coils in a variety of combinations. The physics requirements have been — dc to 300 Hz operation up to 5–7 kA for 10 s pulses (the design limit of the I-coils is 7 kA). The coils usually operate at full current up to 300 Hz powering each I-coil individually or interconnecting the I-coils in a variety of combinations. The latter requirement allows the I-coils to be configured to produce n = 0, 1, 2, or 3 magnetic fields, where n is the toroidal mode number. In addition the poloidal mode spectrum of the magnetic fields produced by the I-coils can be varied by changing the phasing between the six upper coils and the six lower coils. This enables better feedback stabilization of plasma using PCS with no rotational stabilization.

A. The Hardware Capabilities have been Continuously Expanded to Meet Physics Goals

- 1986–1988 saddle loops for locked mode detection.
- 1989 single n=1 coil for error field compensation.
- 1994 C-coils, six external compensating coils to optimize field correction.
- 1998 RWM experiments using C-coils and F-coils chopper power supplies. Discharges rotationally stabilized.
- 1999 SPAs for RWM feedback stabilization.
- 2004–2005 I-coils, 12 internal coils installed.
- 2005 versatile patch panel installed.
- 2006 24 audio amplifier system installed.

B. Future Developmen of the Experimental System

We have been upgrading the C-/I-coil power supply control card system. A sharp rise-time and good control of the current waveform throughout a shot is needed. The maximum rise time of the power supplies directly to C-coils is now about 100 ms. This is driven by R/L parameters of the coil and because the I-coils have lower R/L parameters, they require better current regulation of the SCR control card preferably with 10 ms. Furthermore, the C-coils being directly connected to power supplies shall be regulated better. We would like to increase the regulation span of a coil current from about 2–7 kA down to tens of amperes.

IV. SYSTEM OPERATION

The implementation of these power systems has allowed a variety of experiments to be carried out on the DIII-D tokamak, and we discuss one example here. Dynamic error field correction was developed to compensate for magnetic field errors that cannot be fully predicted in a feedforward mode, especially in the presence of a RWM [2]. The error field response is detected and summed with the pre-programmed correction and applied to the C-coils. A fast growing RWM is further stabilized by the high-speed linear amplifiers powering the I-coils. A schematic of this circuit is shown in Fig. 5, and the time response in Fig. 6.

V. CONCLUSION

Many DIII/D physics experiments have been conducted showing the versatility and effectiveness of this patch panel/power supply system. The system enables over 40 different experimental combinations and the recent addition of 24 high bandwidth linear amplifiers provides a wide range of current & bandwidth supplies to meet the research needs.

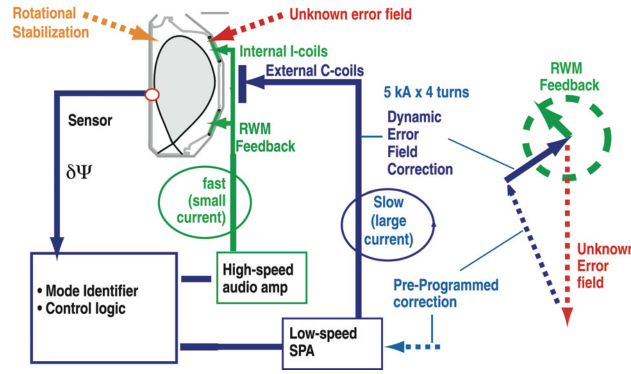

Figure 5. Two independent power supply combination is effective and efficient for improving n=1 RWM stabilization.

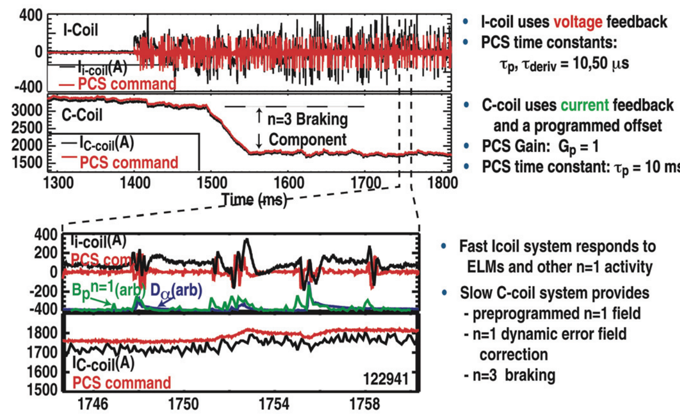

Figure 6. Example of I/C-coils feedback regulation.

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REFERENCES

[1] G.L. Jackson, et al., “Experiments and modeling for feedback system development in DIII-D,” Presented at the 10th Workshop on MHD Stability Control, Madison, Wisconsin, 2005.

[2] A.M. Garofalo, et al., “Sustained stabilization of the resistive wall mode by plasma rotation in the DIII-D tokamak,” Phys. Rev. Lett. **89**, 235001 (2002).

[3] G.L. Campbell and D.H. Kellman, "DIII-D CAMAC infrastructure maintenance experience and upgrade plans," Proceedings of the 22nd IEEE/NPSS Symposium on Fusion Engineering (SOFE), Paper P3-18, 2007.