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ABSTRACT

With the recent installation in the DIII–D Tokamak of the internal resistive wall mode (RWM) stabilization coils (I-coils), upgrades to the existing RWM and error field correcting power supply systems were necessary. The new I-coil system is comprised of 12 individual low inductance magnetic field coils that can be rearranged in multiple configurations with the main purpose of providing feedback stabilization up to the ideal wall beta limit without the need for strong plasma rotation. This paper will discuss the power supply system upgrades needed to drive up to 5 kA in these low inductance coils.

The power supply system is now comprised of (5) 300 V dc, 5 to 7 kA pulse rated power supplies which can either be connected directly to magnetic coils or else provide input power to (4) 300 V dc, 5 kA pulse rated Switching Power Amplifiers (SPAs). The SPA actuators, when connected to the I-coils provide maximum current from dc to 300 Hz and can operate up to 2 kHz at reduced current, limited by the inductance of the I-coils and their cable feeds. We will present the details of the upgraded power system including instrumentation, data acquisition, multiple SPAs powered by a single dc supply, a versatile patch panel, and low inductance cabling.

1. INTRODUCTION AND PHYSICS DESIGN REQUIREMENTS

A new coil set has recently been installed in DIII–D consisting of 12 picture frame coils inside the vacuum vessel [1]. The primary purpose of these internal coils (I-coils) is for experiments to stabilize resistive wall modes at low rotation near the ideal wall β limit [2] which is an important demonstration for future burning plasma devices utilizing advanced tokamak scenarios. A versatile patch panel allows for many different interconnections of these coils. These coils are an enhancement to an existing 6-coil external set (C-coils) and both coil systems are often operated simultaneously. Hence, significant upgrades to the existing DIII–D C-coil power system were required.

The physics design requirements for this power system were: (a) DC operation up to 5 kA for 10 sec pulses (the design limit of the I-coils is 7 kA), (b) A-C operation at full current up to 300 Hz, (c) ability to power each I-coil individually and (d) ability to interconnect 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 6 upper coils and the 6 lower coils.

2. CPS/SPA HARDWARE AND CONTROL UPGRADES

In order to power the new I-coil set, significant changes to the existing C-coil power supplies were required. Prior to the I-coil installation the C-coil set was powered by three 5 kA current controlled Switching Power Amplifiers (SPAs). Each SPA is comprised of (36) Insulated Gate Bipolar Transistors (IGBTs) that employ a H-Bridge configuration and pulse width modulation (PWM) techniques in order to supply both positive and negative current to the I-coil and C-coil loads. The SPAs are controlled using a proportional, integral, derivative (PID) circuit that is configured in a classical current control fashion. The SPAs, in turn, require a DC input, provided by 5 kA, 350 V C-power supplies (CPS).

An immediate improvement was the realization that a single C-supply could power 2 SPAs. This is because each SPA can be considered an ideal transformer in the sense that $I_{out}V_{out} = I_{in}V_{in}$, where I and V are time averaged quantities. For an I-coil circuit powered by a SPA, $I_{in}V_{in} < 0.5\ I_{C\text{-supply}}V_{C\text{-supply}}$. A second improvement was to use two C-supplies to power two of the C-coil pairs directly (the third pair requires bipolar current). This was possible because in most configurations the C-coil current is slowly varying and unipolar. The CPS is a 6-pulse rectified power supply whose output diode bridge can be connected in series (350 V, 5 kA) or in parallel (175 V, 10 kA). Because of the difference in loads between the C-coil (260 uH and 15 m-ohms) and the SPA (94.5 mF) upgrades were made to the CPS EnerPro voltage regulator card. A typical configuration of both C-coils and I-coils is shown in Fig. 1.

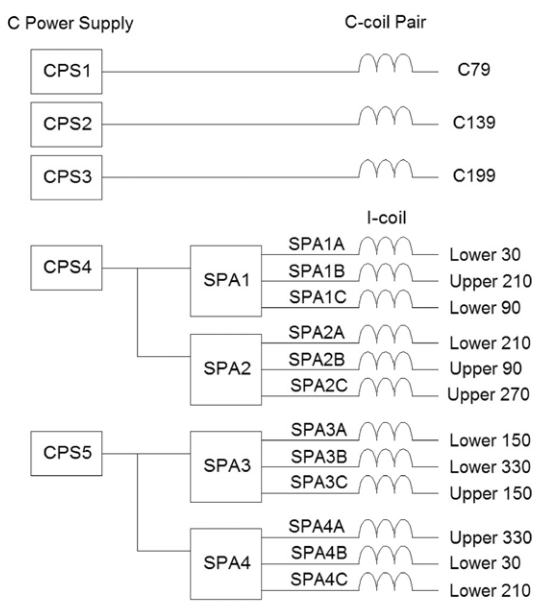

Fig. 1. Typical CPS/SPA/I-coil/C-coil connection diagram.

Significant changes were also employed on the SPA with assistance from the SPA manufacture Robicon. Because of the low inductance load of an I-coil (20 uH and 10 m-ohms, including cabling) upgrades were made to the SPA internal inductors and switching frequency. A tapped inductor (20 uH, 40 uH, 60 uH, 80 uH, and 160 uH) was added to each individual subsection of the SPAs so that stabilizing the current could be achieved. The switching frequency was doubled from the original 3.5 kHz to 7 kHz.

Finally, for experiments requiring individual current control of each I-coil, all four SPAs are operated in “triple mode”. This is possible because each SPA consists of three individually controlled subsections (labeled SPA1A… SPA4C). In triple mode, maximum current to each I-coil is limited to 1.6 kA.

With the modifications discussed above, simultaneous operation of both I- and C-coils required only one additional C-supply and one additional SPA to power the new 12 coil set.

3. VERSATILE PATCH PANEL

The successful implementation of the power supplies required a means to distribute this power to the I-coils. The requirements for different physics experiments dictated that the SPAs would be interconnected with the I-coils in many different combinations. In fact, to date more than 27 combinations have been used. The patch panel in Fig. 2 shows the SPAs in "single mode" and is one of the most common patch panels utilized at DIII–D.

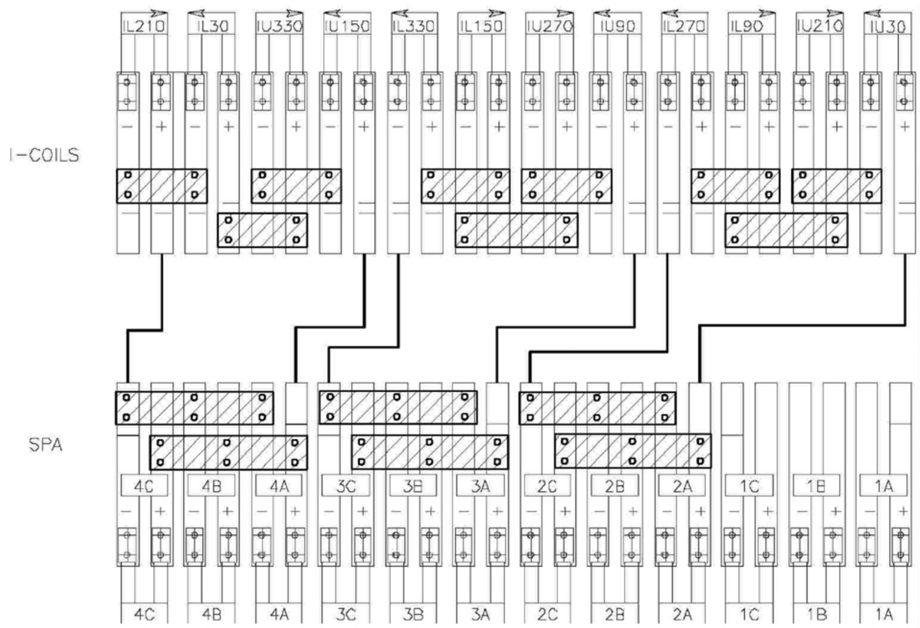

Fig. 2. Two hundred forty (240) degree quartet I-coil configuration.

4. INSTRUMENTATION AND DATA ACQUISITION UPGRADE

In order to control and monitor the new I-coil set, a new data acquisition system (DAQ) was employed that included: high bandwidth isolation amplifiers, installation of (12) closed loop current transducers, and the installation of a compact PCI (cPCI) data acquisition system (DTAQ). On a typical shot the system acquires: (36) SPA signals, (15) CPS signals, and (12) I-coil currents.

The high bandwidth isolation amplifiers were designed to: eliminate ground loops, provide 5 kV isolation, and resolve the 7 kHz switching frequency of the SPAs. To eliminate ground loops in the system each isolation amplifier has an onboard DC/DC converter installed which in turn provides 5 kV isolation between the differential inputs and outputs of the isolation amplifier. A Burr-Brown ISO102B isolation amplifier was used to provide 5 kV isolation between the inputs and outputs. The ISO102B has a small signal cutoff frequency of 50 kHz so resolving the 7 kHz voltage and current signals is well within its specification.

The data acquisition computer supports three 32-channel digitizer cards with a 1 GHz Pentium CPU running LINUX. Data is transferred after each shot via an Ethernet TCP/IP connection. This data is included with all other DIII–D shot data. The digitizers support up to 250 k samples/s operation and each has 128 MB memory on the digitizer card [3].

5. LOW INDUCTANCE CABLING

Another important physics design requirement was to design the I-coil system utilizing low inductance low resistance cabling while reducing external magnetic fields in the case of operating the SPAs up to 300 Hz. The cabling was designed to withstand 7 kA current pulses for 10 sec with a minimum of a 10 minute cooldown time. The cables that run from the CPS/SPA power supply room to the I-coil patch panel are 2/0 quadrapole cables. The power cables that run from the I-coil patch panel to the I-coil leads are 373 MCM quads. The use of quadrapole configuration greatly reduced the cable inductance.

6. CONCLUSION

To date several interesting physics experiments have been conducted showing the versatility and effectiveness of this new power supply system. Future upgrades to the I-coil power supply system may include the use of audio amplifiers to generate AC waveforms with frequencies up to 8 kHz and current to 800 A.

7. REFERENCES

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8. ACKNOWLEDGMENTS

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