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R.E. Hatcher, et. al.

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Digital Coil Protection System for the National Spherical Torus Experiment Upgrade*

R.E. Hatcher, J. Dong, K. Erickson, R. Mozulay, P. Titus, X. Zhao, W. Davis, S. DePasquale, S. Gerhardt, C. Neumeyer, P. Sichta, G. Tchilinguirian, G. Zimmer

Princeton Plasma Physics Laboratory, Princeton, NJ, USA
Corresponding author e-mail: rhatcher@pppl.gov.

***Abstract*— An upgrade to the National Spherical Torus Experiment (NSTX) is currently in progress. The NSTX Center Stack Upgrade (NSTX-U) experimental device has an operating space that is both larger and more complex than that of the original NSTX. The mechanical integrity of some machine components can be compromised both by the instantaneous values of combinations of magnet currents and as a result of the time histories thereof. An upgrade to the existing protection systems and methodology is required to allow for both safe and effective use of the expanded operating space. A Digital Coil Protection System (DCPS) is planned as a major component of an upgraded Coil Protection System (CPS).**

Keywords—NSTX; protection; coil; magnet; torus

I. Introduction

The NSTX facility is being upgraded to allow access to new regimes of physics operation. The upgraded device (NSTX-U) will nominally double the toroidal field, plasma current and neutral beam heating power, and increase the plasma current flat-top period from 1 – 1.5 s to 5 – 8 s [1]. To achieve these and other physics goals, a new center stack (Ohmic Heating + inner Toroidal Field coils) and divertor coils are being planned in addition to the second neutral beam line. Fig. 1 is a plan view of the upgrade device. To access these new operating regimes, we require an expansion in the range and flexibility of allowable coil current combinations. The expansion in the range of allowable coil currents and pulse durations can result in increase in forces, temperatures, and stresses on the device's mechanical structures. Where possible the existing machine mechanical structures were replaced or reinforced to accommodate the expansion in operating space. However, solely upgrading the mechanical support structures is neither sufficient nor practical (complicated design, high cost and limited long-term flexibility). Individual element protection systems can sometimes result in severe operating limitations (e.g., simultaneous operation of the PF4 and PF5 coils on NSTX). The project has determined a critical set of limit values (forces, stresses, temperature, and combinations thereof) that, combined with their derivatives, define a machine "state" with respect to mechanical integrity.

The Digital Coil Protection System (DCPS) provides real-time machine integrity determination and protection using a high-speed digital computer system. The DCPS utilizes an expandable set of critical values (limit variables) that, when combined with their derivatives, define a safe operating area

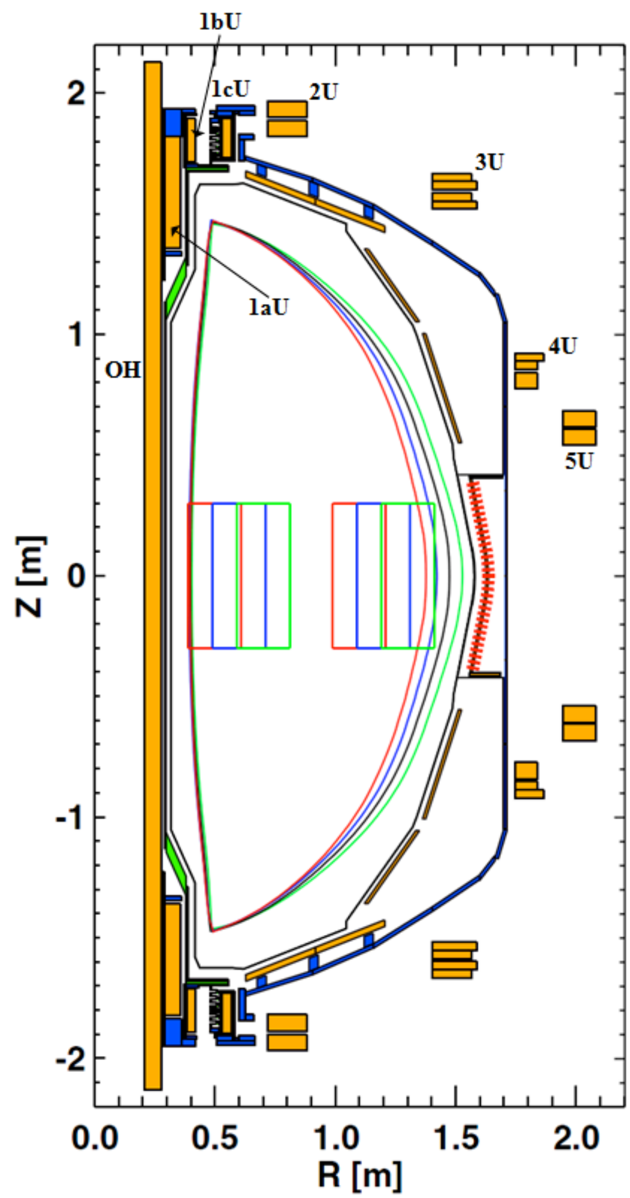

Figure 1- Plan view of the NSTX-U device with the upper coils labeled.

*This work support by U.S. DOE Contract No. DE-AC02-09CH1146 for the machine. A simple algorithm amenable to automatic computation approximates each limit variable [4]. At each instant in time, the DCPS will protect the integrity of the NSTX-U mechanical structure by

- Determining if the calculated value of any limit variable exceeds its limit value.
- Determining if transient behavior subsequent to a power supply fault would result in any limit variable exceeding its limit value.
- Determining if (given power supply response, present trajectory, etc.) any limit variable will exceed its limit value before the next calculation time.
- Providing a means whereby candidate scenarios can be simulated to assess their suitability for operations.

Utilizing a fast, programmable digital system for the DCPS offers some advantages over the alternatives:

- Easy reconfiguration and expansion
- Protection is achieved with high precision
- Low maintenance
- Ability to monitor and interlock intersecting / competing objectives with high accuracy
- Predictive capabilities afforded by the ability to simulate
- Possible interaction with other control processes for fault avoidance (future)

The DCPS is a configurable, real-time protection system for a modern magnetic fusion facility.

II. NSTX Coil Protection System

NSTX utilized multiple independent protection elements that, when considered as a group, defined the coil protection system (CPS) [2]. Fig. 2 is a block diagram of the NSTX

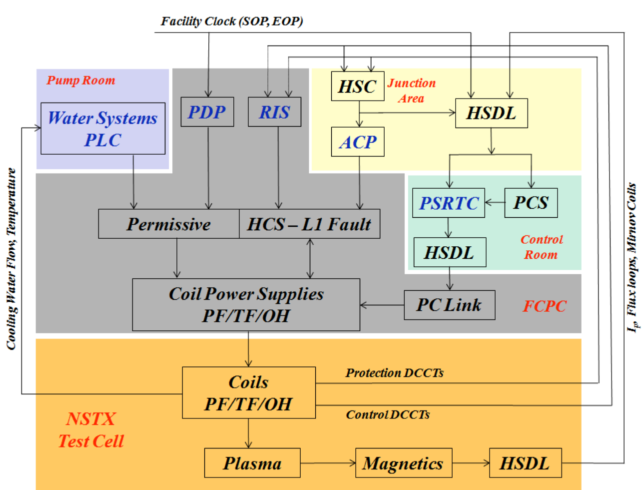

Figure 2 – NSTX block diagram with CPS protection elements highlighted in blue.

experiment components with the coil protection system components highlighted in blue.

The protection system elements are: the water systems PLC, the pulse duration and period timer (PDP), the Rochester Instruments System (RIS), the analog coil protection system (ACP), and the power supply real-time controller (PSRTC). Each of these elements performs a protection function which is, for the most part, independent of the others. In addition, each system, in general, provides protection on a coil-coil basis. The protections offered by each system are as follows:

- Water Systems PLC – cooling flow and temperature interlock
- PDP – adjustable interlocking of pulse duration and duty cycle
- RIS – instantaneous over current, single time constant (τ) i^2t simulator, DCCT imbalance
- ACP – instantaneous over current, i2t simulator, current over time, ΔI comparator, open cable fault
- PSRTC – over current, i^2t, ΔI comparator, command sanity checks, dwell time current, axial (z-directed) forces, TF joint friction and loading, coil moments

An additional small digital computer protection system (not shown) was added towards the end of NSTX operations that allowed for expanded combined operation of the PF4 and PF5 coils (EFIS45). In a sense, the EFIS45 interlock was a first small, simple example of a digital coil protection system.

III. NSTX-U Coil Protection System

The upgrade to the CPS for NSTX-U is shown in Fig. 3. Some components have been deleted (RIS, ACP, EFIS45), some upgraded (WS-PLC, PDP), and one added (DCPS).

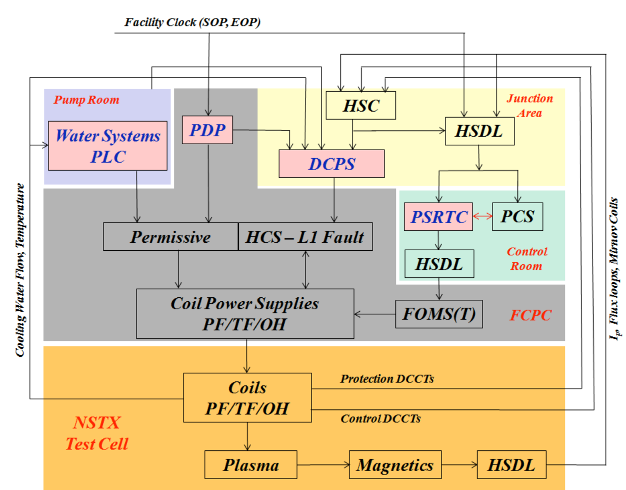

Figure 3 – NSTX-U block diagram with upgraded/new CPS protection devices highlighted (blue) and shaded (pink).

In Fig. 3, the DCPS takes the place of the RIS and ACP in the CPS. The other elements of the CPS will be upgraded as follows:

- Water Systems PLC – upgraded (new) PLC with expanded monitoring of all coil coolant flows and output temperatures
- PDP timer – upgraded (new) to accommodate longer duration and dwell times, increased flexibility in setting and accuracy
- PSRTC – simple coil protection algorithms replaced with a "drop-in" version of the DCPS algorithms with reduced limit value settings

IV. NSTX-U DCPS

As mentioned above, the DCPS functionally replaces the ACP and the RIS in the CPS. The goal of the DCPS is to provide effective protection to the NSTX-U mechanical structure while enabling access to a complicated operating space. The central idea of the DCPS is to describe limits prescribed on the physical structures with simple analytic expressions suitable for digital computation. The algorithms, primarily based on coil currents, are used to describe a physical quantity (e.g., a force, current, or moment) that must be kept within an allowable range or below a maximum value. Utilizing an algorithmic approach allows for a much more complex description of protection boundaries than can be described using simple single coil limits as were used in NSTX. Fig. 4 illustrates how when just considering two coils (PF4 and PF5) the operating space can be reduced [5].

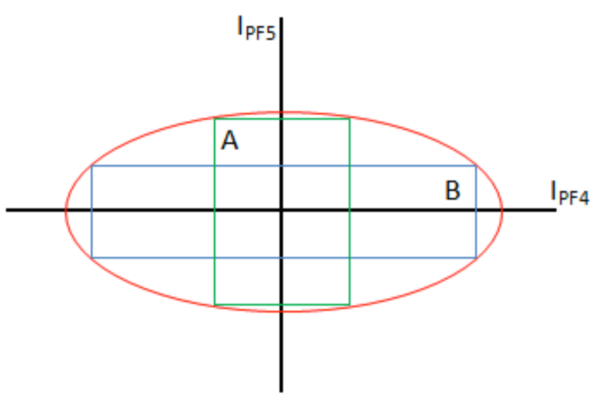

Figure 4 - An example of allowable regions of combined operation for two coils as determined from analysis of mechanical structures (red) or single coil limits (blue and green).

In the figure, the red line defines a boundary of combined operation for the two coils. From structural mechanical considerations, any combination of currents inside the red boundary is allowed. If we have a system that can only implement protection using single coil limits, the reduced operating regions (A) or (B) result depending on which coil we give preference to having the higher current limit. In contrast, protection based on an algorithm that determines where a given combination of currents lies within boundary can access the entire operation space. Therein lies the power of the DCPS approach. Note that in reality the situation is much more complex. In the NSTX-U there are interactions between all of the coils, the interactions are sometimes asymmetric, there are multiple competing limit variables, and there are many other elements, other than coils, that require protection. The resulting operation space has high dimensionality and complex shape.

The DCPS is a fast digital computer system capable of executing many protection algorithms in software (at present more than 100 are planned) on a time-scale consistent with the combined coil – power supply system response (≤ O(ms)). For the remainder of this paper, we will describe the different components that comprise the DCPS and the progress to date on the project.

A. DCPS Software

The DCPS software will repeatedly execute the set of protection algorithms during the plasma discharge window to provide protection to the mechanical structures of the NSTX-U device [3]. When the computed output value (or predicted next-time-step value) of any algorithm exceeds its limit value, a fault is generated. A fault issued by the DCPS software causes the NSTX power supplies to move to their faulted state so that the coil currents experience an uncontrolled L/R decay to zero. Limit values are adjusted to address mutual coupling between the coils that might increase some coil currents during a fault shutdown. Similarly inductively driven over-currents during a disruption are estimated and added to current levels when determing the limiting variables. There will also be "between pulses" algorithms that ensure that the machine is similarly protected (e.g., zero coil current checks, system self checks, coolant temperature interlock check, etc.). For the NSTX-U copies of the DCPS software will run on both the DCPS computer and in the PSRTC. Selecting a software solution allows great long-term flexibility and extensibility of the DCPS system. The software is at the core of DCPS operation.

A finite state machine model both describes and governs operation of the DCPS software. The state diagram for the DCPS software state machine is shown in Fig. 5. The software has ten (10) allowable states with support for four (4) modes of operation. Access to the various software modes and states are limited by assigned user privileges. Users will interface to the DCPS software through a custom Graphical User Interface (GUI) that enforces operational restrictions as defined by the user assigned privileges. We anticipate that users will also be able to run simulations on standalone versions of the DCPS software on remote engineering workstations or personal computers.

System configuration data security will be maintained by implementing a "secret" MDSPlus data server accessible only from the DCPS computer by trusted processes (or locally at the console by the root user). The DCPS output data will be archived and accessible via the usual mechanisms. Commonality of data storage with other NSTX-U physics and engineering data is a plus.

The DCPS software will take advantage of modern software engineering tools and programming languages (UML design and C++11) and utilize modular code design. The use of

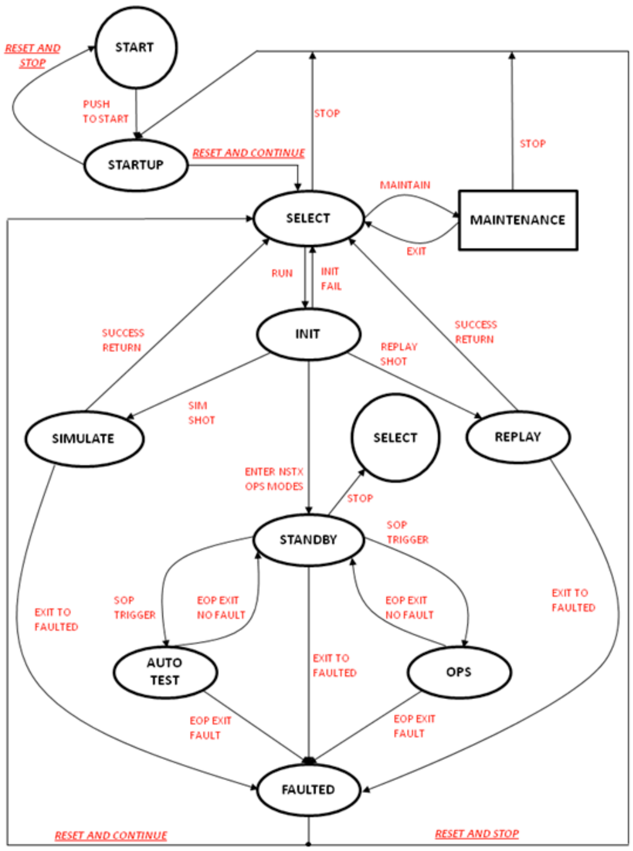

Figure 5 – DCPS software state diagram.

these tools should alleviate some of the coordination issues inherent in managing a large software project, such as the DCPS software, when multiple programmers are involved.

The goal is for the software to complete each algorithm calculation cycle within 200 µs (with a hard limit of ≤ 500 µs). The operating system (RedHawk Linux) guarantees a process dispatch latency of less than 15 µs (observed times are 1 – 5 µs).

B. DCPS Hardware and Computer System

The DCPS hardware and computer system components are located in the FCPC junction area. This hardware replaces the "retired" ACP and RIS protection systems. Fig. 6 shows an interconnection block diagram for the hardware components. Short descriptions for the main hardware components follow:

- DCPS computer – Super Micro H8DG6-F, dual 16-core AMD Opteron processors, 64 GB 1600 MHz ECC RAM, 6 PCIe slots, on-board RAID, configured and tested for real-time application by Concurrent Comp. Corp.
- Analog Input Cards - General Standards 16AI64SSC, 64/32-channel, 1 MB FIFO data buffer, software selectable input voltage range (±10 V, ±5 V, ±2.5 V, 0 – 5/10 V), 200 kS/s per channel
- Acquisition Timing - Concurrent Comp. Corp. real-time clock and interrupt module (RCIM) 20 MHz, 8-32-bit real-time clocks with 1 µs resolution, 12 external output interrupts, PCI interface, multi-RCIM synchronization via fiber optic input
- Digital I/O - Adlink 7296, 96/48-channel input/output configurable (banks of 24), TTL/DTL compatible
- Halmar Signal Conditioner (HSC) – multi-channel signal conditioning (buffer/amplifier, filtering) for the coil current signals
- DCPS interface – interface chassis that facilitates switching the inputs to the DCPS computer between the experiment data and the Auto Tester
- RTU1,2 – reconfigurable timing units used to provide timing events to the DCPS computer and Auto Tester
- Junction Area Interface (Dashboard) – interface between the DCPS hardware components and the outside world (fault lines, RTUs, external system interlocks)
- Auto-Tester computer – PC (Intel) based automated test facility for the DCPS using National Instruments analog and digital I/O cards running LabView™ software

Most of the DCPS hardware components are purchased and are currently on-site. System commissioning and pre-operational testing will take place later this calendar year (2013) with integrated system testing to follow (Jan 2014).

The DCPS computer will run a custom Linux operating system provided by Concurrent, RedHawk, optimized for real-time applications. The operating system software package includes a customized kernel and drivers (source code included) and a suite of debugging and code optimization tools. Long-term maintenance is also available at a reasonable cost.

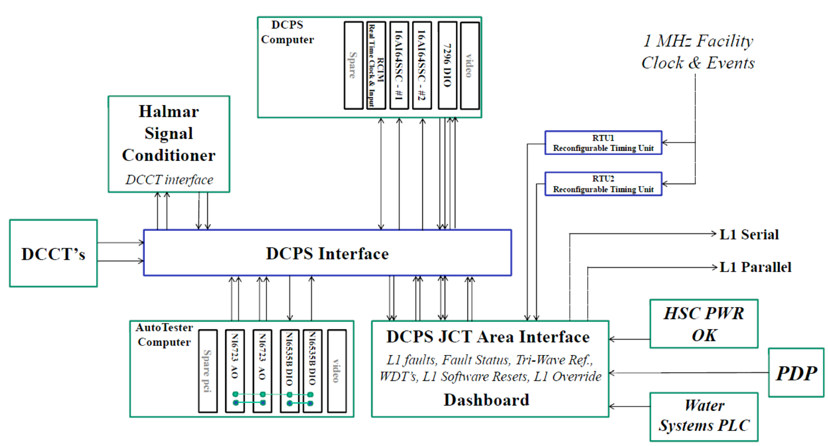

Figure 6 – DCPS hardware interconnection diagram.

C. DCPS Algorithm Development

Algorithms are the backbone of the DCPS. There are more than 100 algorithms planned for the initial implementation of the DCPS. Each algorithm approximates the value of a mechanical quantity (axial force, moment, etc.) for some structural element (bracket, coil support, bolt, etc.) of the NSTX-U device that may be exceeded during operations. The algorithms were derived from detailed design and analysis and were statically qualified against 96 normal operating scenarios that span the available physics parameter space. At present:

- The project is performing a check of the engineering basis for all the algorithms, and
- Time dependent scenario qualification simulations or the algorithms are being developed.

Algorithm interface and coding in DCPS is simplified by the introduction of algorithm classes (4 are currently planned) in the DCPS software. Every algorithm will be "cast" into one of the standard class forms. Algorithm execution is optimized by the use of parallel processing of dedicated pipelines (queues). The algorithm pipelines can be adjusted via the DCPS software in Maintenance mode.

D. DCPS Auto-Tester

The DCPS Auto-Tester is a standalone computer that can be used to drive the system in automated end-to-end tests. The Auto-Tester interfaces to the DCPS at the front-end (ahead of the HSC) and will provide all the necessary I/O signals for DCPS operation. The Auto-Tester contains two analog output cards (2 - NI PCI-6723, 13-bit, 32 channels (45 kS/s), ±10 V, 5 ma current drive) and two digital I/O cards (2 - NI PCI-6535B, 32 channels, 10 MHz, TTL compatible) that provide input signals to the DCPS computer. This configuration allows the Auto-Tester to drive both versions of the DCPS software. The RTUs can be configured to allow isolated testing of the DCPS or testing of the DCPS as part of larger facility wide tests.

The Auto-Tester software, including a GUI, is written in LabVIEW. The software will support custom waveform generation and modification via the GUI or may be driven with archived data from actual NSTX-U plasma discharge cycles. Test results are archived making the system suitable for use in system regression testing.

E. Summary

An upgrade to the coil protection system for NSTX-U is required to allow routine operation within a complex operating space. The DCPS replaces older analog systems that have been retired (the ACP and RIS) in the new CPS. The DCPS will be the first instance of an integrated programmable protection system deployed on an MFE device. The experience gained in operating the DCPS should prove useful for application in new devices (ITER, QUASAR, etc.). Most of the hardware is in house with software development ongoing and integrated systems testing planned for early 2014.

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2245
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov