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NSTX
PROTECTION AND INTERLOCK SYSTEMS FOR COIL AND POWERS SUPPLY SYSTEMS*

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***Abstract*— NSTX at Princeton Plasma Physics Laboratory (PPPL) requires sophisticated plasma positioning control system for stable plasma operation. TF magnetic coils and PF magnetic coils provide electromagnetic fields to position and shape the plasma vertically and horizontally respectively. NSTX utilizes twenty six coil power supplies to establish and initiate electromagnetic fields through the coil system for plasma control. A power protection and interlock system is utilized to detect power system faults and protect the TF coils and PF coils against excessive electromechanical forces, overheating, and over current. Upon detecting any fault condition the power system is restricted, and it is either prevented from initializing or suppressed to de-energize coil power during pulsing. Power fault status is immediately reported to the computer system.**

This paper describes the design and operation of NSTX's protection and interlocking system and possible future expansion plans.

Keywords-Coil; Detection; Fault; Overcurrent; Permissive; Power; Protection; Rectifier

I. INTRODUCTION

Nuclear fusion reaction is the process of fusing two light nuclei Deuterium (2H) and Tritium (3H) to, and the product of this reaction is the formation of a heavier nucleus Helium (4H), a neutron and a large amount of energy 17.6 MeV. The energy produced from this transformation is the fundamental of fusion power. NSTX is a start-of-the-art fusion reactor constructed and built by the Princeton Plasma Physics Laboratory (PPPL) in collaboration with the Oak Ridge National Laboratory, Columbia University, and the University of Washington at Seattle [1]. The principle of electromagnetic confinement is utilized to test the conditions needed for fusion energy production. A powerful electrical supply system is utilized to provide electricity needed for NSTX high power consumption experiments.

II. POWER SUPPLY OVERVIEW

The NSTX coil power supply system currently consists of thirty nine units of bi-sectional rectifiers. Each section is a six pulse thyristor rectifier with a parallel bypass module. Table 1 shows the electrical ratings for the rectifier [2]. The bi-section rectifier unit has one common control console, which includes the main control unit called the firing generator and the LED status monitor panel. Each section of the rectifier is equipped with a manually operated lever switch, which is selected between normal running position and bypass position. De-ionized water is supplied to the power modules for cooling. A fault detector is part of the rectifier, and it protects the coil system in four different levels. Alarm level provides warning status of the power supply with no operation interruption. Suppression level commands the power supply to de-energize the power module and also energize the bypass module. AC break level trips the breaker for the main feed to the power supply due to power module suppression failure. Ground switch level provides a path for the coil current to escape in case of bypass module failure. A Kirk key system is also implemented to insure the correct sequence of operations, and it gives the prerequisite for the activation of the power system.

Table 1. Rectifier Electrical Rating

Parameter	Value	Unit
No Load Avg. DC Voltage	1012.85	Volt
Maximum DC Current	30.0	kA
Nominal Pulse DC Current	24.0	kA
Nominal Pulse ESW	6.0	sec
Nominal Pulse Repetition Period	300.0	sec
Maximum Continuous DC Current	3.25	kA

III. COIL & POWER SUPPLY PROTECTION

Current limiting is capable of isolating a faulted circuit before the fault current has sufficient time to accelerate to its maximum value. Current limiting protection has a couple of benefits to the power system. It prevents high current and mechanical stresses created by the fault currents. The magnitude and the duration of the voltage drop caused by the fault currents are reduced. Two current limiting factors are utilized for the protection system peak or maximum current and ampere squared seconds. Maximum current is useful in determining the peak current available downstream to the coils. If the current is limited to a value less than a possible fault current value, the coil system can be protected from entering into the critical fault current level. Ampere squared seconds provides a measurement of the amount of heat energy associated with current flow.

A. Abbreviations

ACP = Analog Coil Protection
CHI = Coaxial Helicity Injection
EPICS = Experimental Physics and Industrial Control System

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FPDP = Front Panel Data Port
MDSPlus = Model Data System Plus
OH = Ohmic Heating
PDP = Pulse Duration Protection
PF = Poloidal Field
RIS = Rochester Instrument System
RWM = Resistive Wall Mode
SOP = Start of Pulse
SPA = Switching Power Amplifier
TF = Toroidal Field
TFTR = Tokamak Fusion Test Reactor
VME = Versa Module Eurocard

B. Rectifier Fault Detection Systems

Rectifier fault detection system can be viewed as two major sections. One section is responsible for the internal fault detection, and the other one monitors the external faults from other fault detection control areas. Rectifier internal fault detection can be functionally categorized into three ways to fulfill total protection for the power supplies and the coils. Equipment level protection prevents the rectifiers from any overcurrent, incorrect voltage, and over temperature. Each rectifier section utilizes thirty six AC current transducers to provide AC phase overcurrent protection. When any of the AC current transducer reads a value higher than the preset trip level, the system undergoes a fault mode and suppresses the rectifier. For redundancy, each section of the rectifier uses an overall section overcurrent to monitor the overall current reading not to exceed a certain trip level. In order to ensure the phasing quality of the twelve pulse rectifier, each transformer is equipped with an over time check so that the coil has a consistent power supply. There are multiple DC voltage levels required for the rectifier to operate, and these local power supplies are being closely monitored for any low voltage reading. Upon high current supplied to the coil system, the thyristor temperature of each rectifier can be heated to a very high temperature. The thyristor temperature is monitored and simulated at all time. The logic level protection is embedded in each of the rectifier protection system. Upon receiving a fault condition, the bypass module of the rectifier should immediately receive commands following suppressing the firing signal. If a bypass module fails to receive a command signal, rectifier operation is prohibited. The permissive level protection provides the initial and running conditions for the rectifiers. With prerequisite equipments in ready-to-run and not fault conditions, the rectifier also checks for the level of the cooling water system before the power supply can be activated for operation.

C. RIS Protection System

The original TFTR fault detection monitor system is modified and utilized to provide the backbone of the NSTX coil protection system. This system only covers five of the coil systems OH, PF2L, PF3U, PF3L, and TF. The current transformers provide crucial current information which is manipulated and compared with several fault detection control presets. If any of these faults is detected, each power supply system immediately acknowledges the fault and terminates its operation. Figure 1 shows a flow control diagram for the RIS protection system. An overcurrent fault is triggered by comparing constantly monitored current signal with the current limit preset. Any current value over the preset passes the fault signal to each power supply through the hardwired control system. Thermal monitoring is also conducted to ensure the current does not generate excessive thermal stress to the coil system. When the I^2t value is higher comparing to the preset, the power supplies suppress and activate bypass circuits. The protection system was later enhanced to have second current information for each coil. The additional current signal channel not only provides redundancy feature but also a secondary comparison with the first channel of coil current.

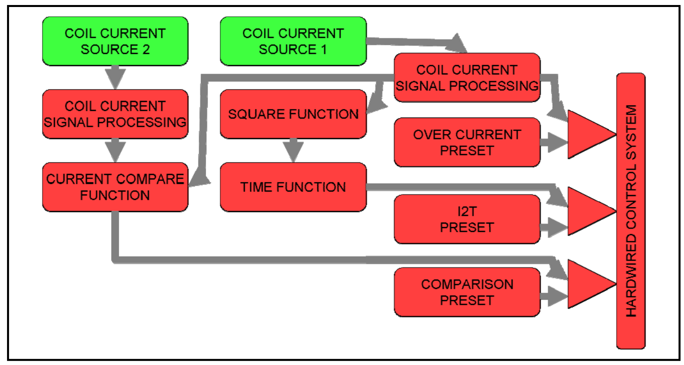

Figure 1. RIS protection control flow diagram

D. Analog Coil Protection System

The analog coil protection system was later designed and implemented to upgrade the original coil protection system to be more efficient and reliable. Over the past decade, more physics diagnostics are needed to prove and understand plasma physics. Consequently more equipment is added to the existing power supply set up. In order to provide a very robust testing environment, all coils are equipped with overcurrent protection. The additional coils to receive this protection include PF1AU, PF1AL, PF1B, PF2U, PF4, PF5, CHI, and SPA. A minimum current level is used to start a current allowed window. When any current is detected within the current not allowed window or the current inhibit window, a fault condition is generated. Figure 2 shows a flow control diagram for analog coil protection system.

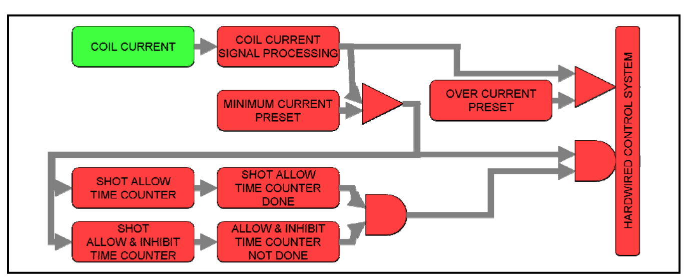

Figure 2. Analog coil protection control flow diagram

E. Ground Fault Protection System

NSTX coil system has tremendous amount current going through when pulsing for experiment and it is important to protect and isolate the coils from any unintentional grounding. The current design of the ground fault detection applies to all coils. Figure 3 shows the basic logic flow of how the ground fault is detected and implemented. Multiple coil ground current signals are connected to the protection system in parallel. The protection system detects the sum of all the ground current in real time. If any coil introduces current through the ground loop, the ground current resistor reacts to an instantaneous current flow and provides a fault condition to inhibit any active power operation. In series to the instantaneous coil ground current detections system, the inverse time over current relay is a standard DC electromagnetic relay and has been functioning reliably in parallel with the instantaneous ground fault protection. Typically the relay is set to trip at 5 ma of ground fault. [3]

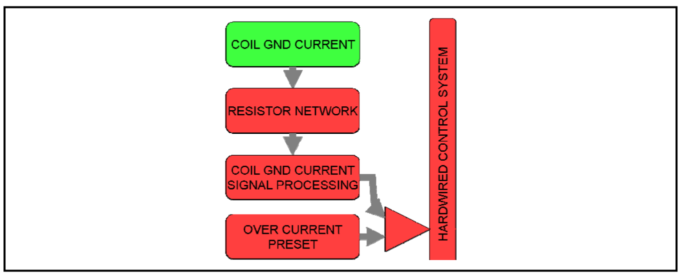

Figure 3. Ground fault protection control flow diagram

F. Pulse Duration Protection System

On top of real-time analog current fault detection, an enhanced pulse duration permissive control was also added to the coil and power supply protection system. Since each plasma pulse is relatively short and allows the power supplies to carry tremendous amount of power into the coil system, a pulsing window is implemented to allow plasma pulsing command the proper time. As the synchronized SOP is generated, plasma shot control cycle is divided into three sequential sections allowing, inhibiting, and waiting. During the allow window only one shot request can be commanded. Figure 4 shows the control flow diagram of the pulse duration protection system.

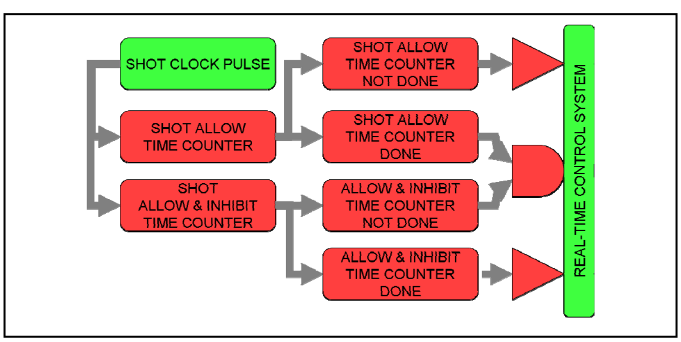

Figure 4. Ground fault protection control flow diagram

IV. PROTECTION CONTROL CONFIGURATIONS

Fault detection systems are built and constructed based on VME chassis. FDPD serves as the standard protocol for transmitting and receiving the fault signals. Since the NSTX test cell is located in a stand alone area, fiber optic lines provide the link between the fault detection systems and the EPICS user interface.

The power protection system is implemented and operated on several hardware platforms. If any fault condition exists, the fault signal enters into the hardwired control system, which can be either serial or parallel. Since the hardwired control system can be easily interfaced to any control platform, a serial or a parallel fault signal energizes the fault state in the real-time control system. The real-time control consists of four dual core AMD Opteron 880 2.4GHz processors and its front panel data port, and the FPDP bus is a 32 bit parallel synchronous bus providing data transfer at rates up to 160 MB/s with 40MGhz clock. With its high processing speed, the hardwired fault signal can be detected and processed to prevent any unwanted power or coil system damage.

As a serial or parallel fault signal enters into the real-time control system, it also enters into the CAMAC control platform input module. The EPICS-enabled computers provide monitoring nodes (Figure 5) to the CAMAC control platform through fiber optic serial link. The up-to-date fault status can be available to the users at an update rate of every two seconds. Historical data is also stored in the MDSPlus database, and it allows previous data to be used for trouble-shooting and analysis (Figure 6).

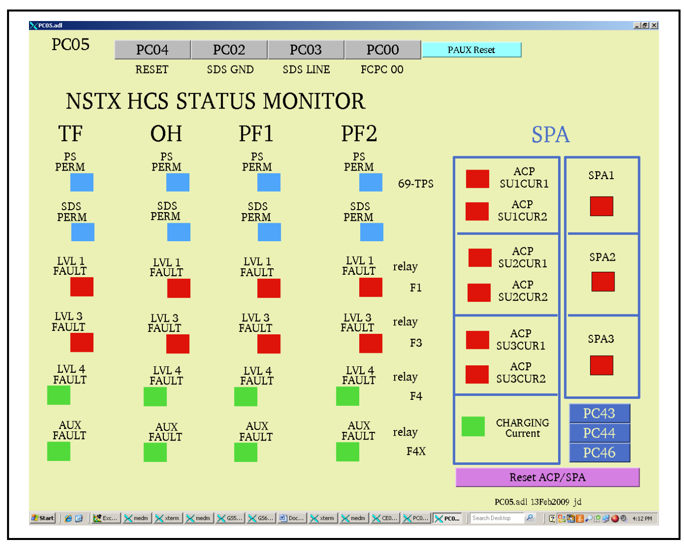

Figure 5. EPICS status monitoring page

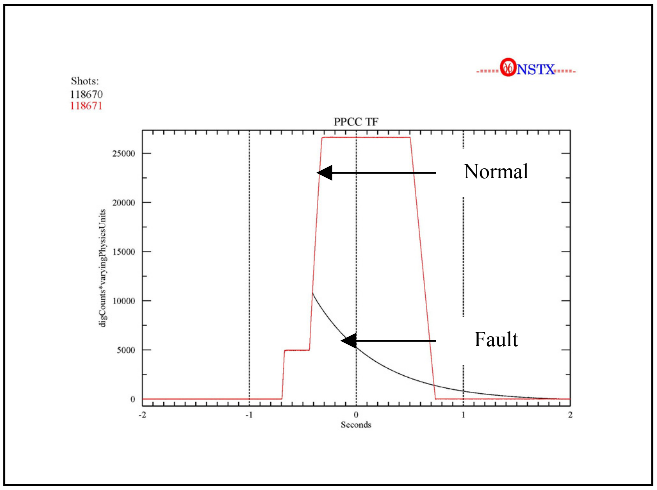

Figure 6. TF coil current normal vs. fault

V. FUTURE EXPANSIONS

The existing NSTX power protection system has evolved for decades, and many new control technologies have been introduced in the market. New technologies can provide benefits to the future improvements. Presently the current fault system is controlled by a electro-mechanical relay network which is complicated, hard to modify, prone to failures, and is a large design and maintenance resource burden. Modular microprocessor-based logic control has several advantages over the traditional electro-mechanical system. Much of the hard-wired mechanical relays and their wiring can be eliminated. Flexible control logic can be performed by the logic controller. The unauthorized access can be restricted to the control logic. All modular controllers can be communicated on a network. The control process can be monitored and interfaced through a human machine interface or other computer systems. The modular programmable logic controller can upgrade the existing hardwired system providing increased functionalities and flexibilities while decreasing operations and maintenance efforts.

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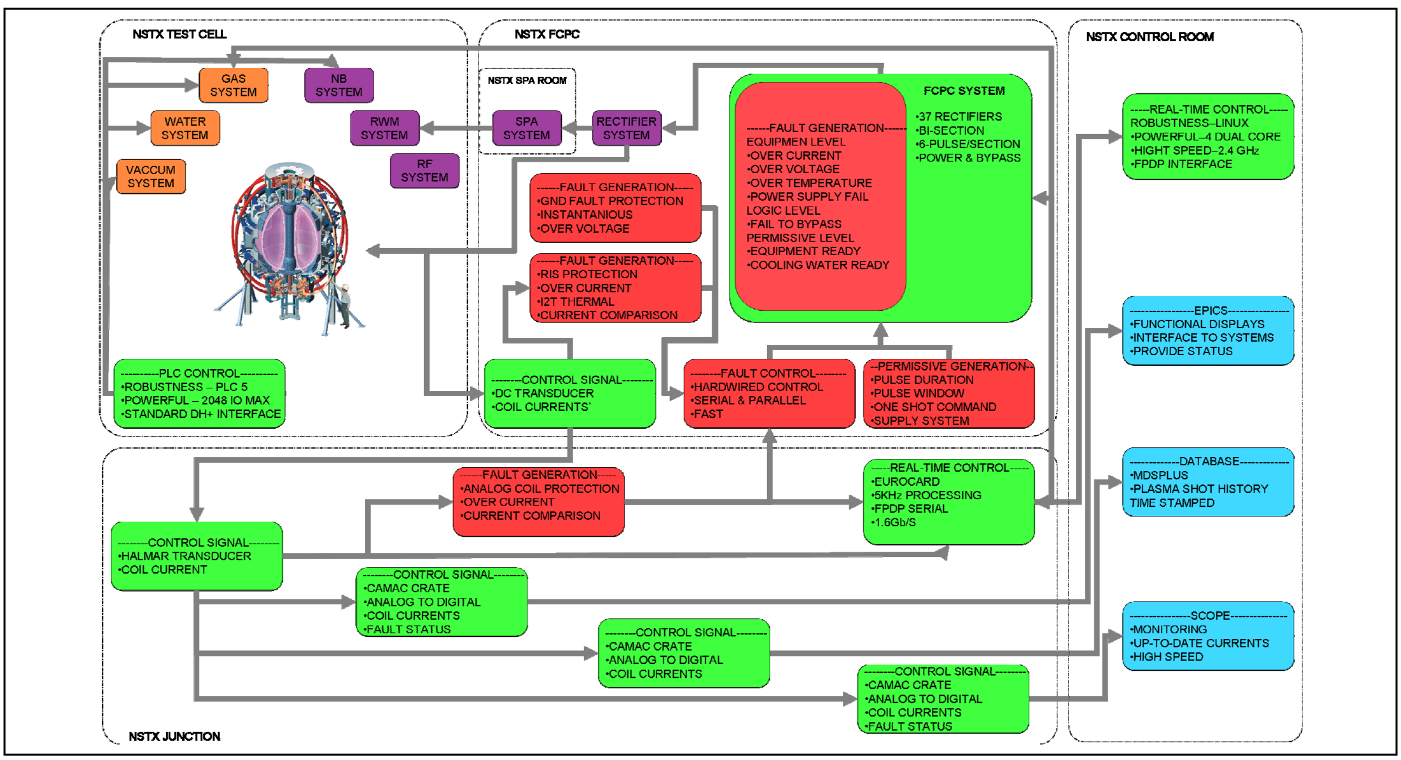

Figure 7. NSTX coil and power protection overview

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