Princeton Plasma Physics Laboratory

PPPL-5164

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July 2015

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

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***Abstract*— The National Spherical Torus Experiment (NSTX) is undergoing a significant upgrade. The upgrade increases the toroidal field and pulse length, adds three new diverter coils and a second neutral beam injection (NBI) system. The magnet coil power supply systems for the NSTX have been redesigned with many modifications to reflect NSTX upgrade needs. The NSTX power supply system includes three major parts. The first part is the DC power supplies for the magnet coils. The second is the power supply real time control system. The third is the coil and power supply protection system. In this paper, a brief overview of the power system upgrade is presented.**

Keywords*— national spherical torus experiment upgrade (NSTX-U); power supply real time control system (PSRTC); Digital coil protection system (DCPS)

I. Introduction

The objective of the National Spherical Torus Experiment Upgrade (NSTX-U) is to expand the NSTX operational space [1]. NSTX-U doubles the toroidal field, plasma current, and NBI heating power. The plasma flat top time is also increased from 0.5 s to 5 s. All the magnet coil power supplies need to be reconfigured and modified to fit the NSTX-U needs. The NSTX-U power supply system includes three major parts.

The first part is the DC power supplies which supply the current for the toroidal field (TF) coils, the poloidal field (PF) coils, the ohmic heating (OH) coil and the resistive wall mode (RWM) coils. Changes to the basic configuration of the TF, PF and OH coil power supply systems will be described.

The second part is the power supply real time control (PSRTC) system. The scope of the upgrade includes a new stand-alone digitizer version 2 (SAD2) , a new digital signal processor (DSP) based firing generator (FG), a new power supply communication link and a new real time control computer which runs the new PSRTC software.

The third part is the power supply protection system which is used to prevent the coils and the power supplies from the damage under fault conditions. It includes a new digital coil protection system (DCPS), a new PLC based hardwire control system (HCS), a new pulse duration permissive (PDP) timer, a power supply fault detector (FD), and a ground fault detector in each coil circuit.

II. AC power, Magnet Coil and DC Power System

A. AC Power System

The existing AC power system at D-site is used for NSTX-U without any changes [2]. The local utility company (PSE&G) delivers the power to the PPPL site using a 138 kV transmission line. Two transformers XST-1 and XST-2 are used to step down the voltage from 138 kV to 13.8 kV. The AC power system is divided into two major sub-elements, the experimental system and the auxiliary system. The experimental system includes all the magnet coil loads, heating and current drive system. The auxiliary system consists of the vacuum pumping system, the gas delivery system, the cooling water system, etc.

The AC power system is shown in Fig. 1. XST-1 feeds the power to the S1 bus. It delivers the power to the two motors and generator exciters. Each generator is rated 475 MVA, 13.8 kV and 60-90 Hz. Only one generator is needed for the NSTX-U operation. The generator output is connected to the coil system through the variable frequency buses SV1 and SV2.

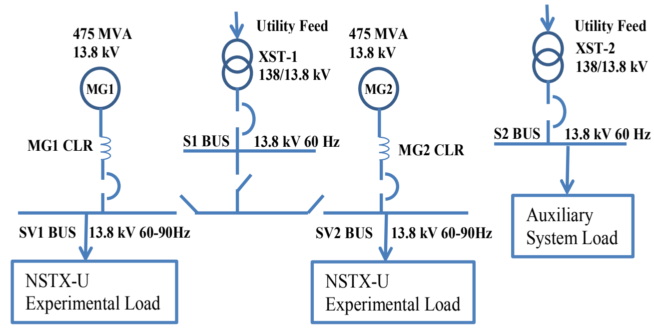


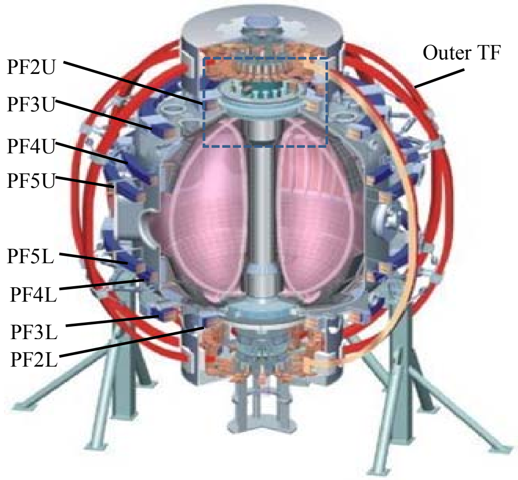
Fig. 1. AC power system

B. Magnet Coils System

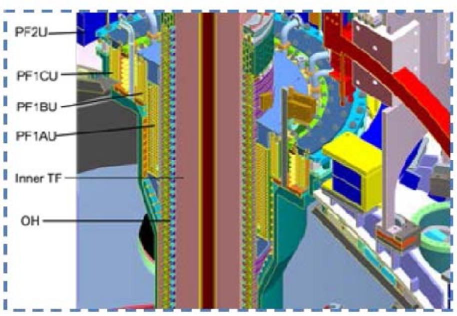
The magnet coils used on the NSTX-U machine are shown in Fig. 2. The inner TF and OH coils are in the center stack of the machine.

- The function of the TF coil system is to provide the toroidal magnet field for the NSTX-U plasma confinement.
- The function of the OH coil is for the plasma initiation and heating the plasma.
- The function of the PF coil system is to control the plasma position and shape, including vertical and radial position stability control. PF1BU/1CU/1CL are new coils for NSTX-U. All the other coils are existing coils in the NSTX.
- The RWM coils are used to generate non-axisymmetric magnet fields for a variety of purposes that enhance plasma stability.

This work is supported by the U.S. DOE Contract No. DE-AC02-09CH11466 .



(a) NSTX-U elevation view



(b) Cross section view on the center stack top

Fig. 2. Magnet coils location on NSTX-U

C. DC Power System

NSTX-U uses thyristor rectifier power supplies, originally supplied by Transrex in the 1980's for the TFTR project, to supply the DC current to the magnet coils. Each power supply consists of two 6-pulse independent sections which are electrically isolated from each other. They are independently controlled by the new FG.

Input power is supplied to each power supply by a three-winding transformer with a rating of 13.8kV/750V. The transformer has a polygon primary and Δ/Y secondary windings. The polygon is arranged to produce +7.5º or -7.5º phase shifts [3]. Each power supply section has a rating of 1kV, 24kA - 6 seconds equivalent square wave (ESW) every 300 seconds. It also has a bypass module designed to carry the full load current when the rectifiers are suppressed and bypassed.

Fig.3 shows one section of a Transrex power supply. The power sections are comprised of six power modules and two bypass modules. Each power module is a 6-pulse rectifier rated at 1 kV and 4 kA DC. Six power modules are paralleled in each rectifier section which provides 24kA rating. There are two bypass modules in parallel in each section. The sections are designated "A" and "B". A mechanical disconnect/bypass switch (Pringle switch) allows each section to be selected on- or off-line. The FG receives the firing angle command from the real time control computer and generates the proper sequence of 6 pulses to the master gate drivers (MGD). The MGD then generates the trigger pulse for the thyristors. The FD is used to detect local over- current and over-time faults. It also provides the interface to the parallel fault system and a new HCS. An HCS Defeater is to remove the power supply from the HCS interlock system when it is taken off-line.

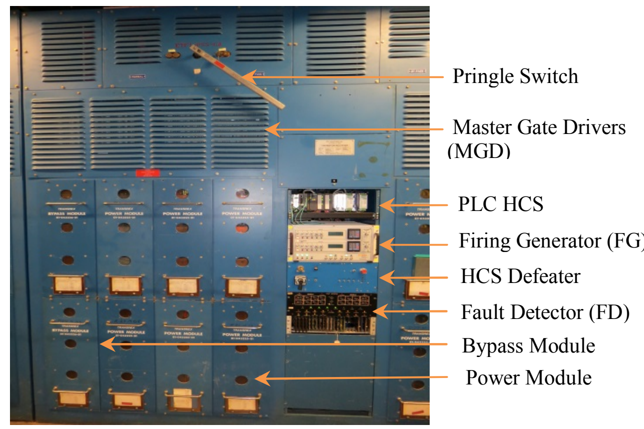


Fig. 3. Transrex thyristor power supply section A

1) TF Coil Power Supply System

The upgrade increases the TF ESW current from 71 kA for 1.1 seconds to 130 kA for 7.04 seconds. The number of parallel branches of the TF power supply system increases from four to eight. Each parallel branch has two 1 kV Transrex power supply sections in series. One section is kept on an electrical bypass condition acting as a diode. The other section is set up as a normal 1 kV power supply. If a short circuit fault occurs in one power supply branch, this scheme prevents the back-feed of the seven remaining branches into the faulted branch. A current limiting reactor (CLR) is used in each parallel branch for the current balancing.

The TF power supply system schematic is shown in Fig. 4. The typical current waveform for the TF coil during the Integrated System Test Procedure (ISTP) is shown in Fig. 5.

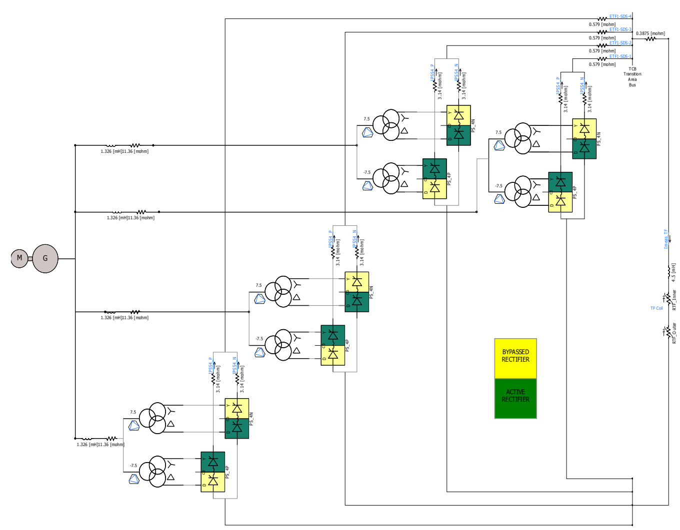


Fig. 4. NSTX-U TF power supply system schematic

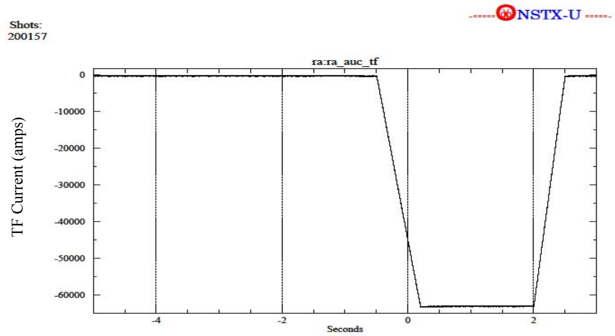


Fig. 5. Typical NSTX-U TF coil current waveform during ISTP.

2) *OH Coil Power Supply System*

The NSTX-U OH coil requires a 6 kV bipolar (4-quadrant) power supply with an EWS rating of +/- 24 kA for 1.47 seconds. Two branches of power supplies are connected in anti-parallel. The CLR in each branch will be changed from the existing 544 μH reactors to 1 mH reactors to limit the circulating currents to acceptable levels under fault conditions. Fig. 6 shows the OH power supply system schematic. Fig. 7 shows the current waveform for the OH coil during the ISTP.

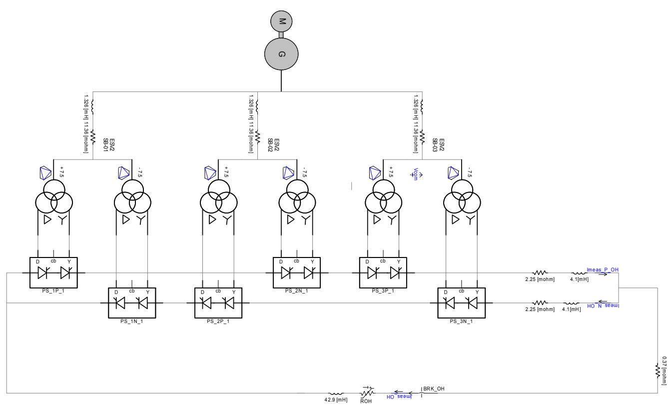


Fig. 6. NSTX-U OH power supply system schematic

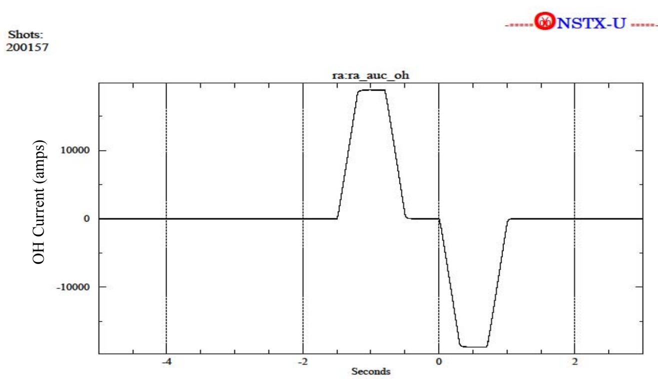


Fig. 7. Typical NSTX-U OH coil current during ISTP.

3) *PF Coil Power Supply System*

The PF coil system has 12 circuits. The PF1bU, PF1CU and PF1CL are new coils for the NSTX-U. The PF1 and PF3 upper and lower coils circuit are bipolar power supplies. A typical PF3U coil current waveform during the ISTP is given in Fig. 8.

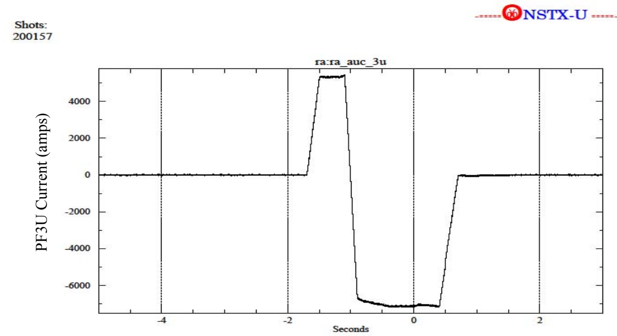
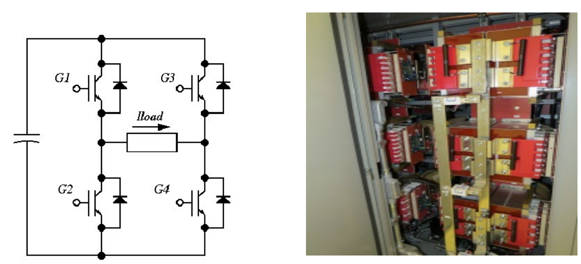


Fig. 8. Typical NSTX-U PF3U coil current during ISTP.

4) *RWM Coil Power Supply System*

The six RWM coils require fast and accurate current control to stabilize the plasma. The switching power amplifier (SPA) technology is selected as the power source. The SPA consists of three independently controlled sub-units. Each SPA sub-unit consists of an H-bridge PWM inverter capable of 4-quadrant operation. The rating for each sub-unit is 1kV/3.333 kA for 6 second every 300 second. The thyristor rectifiers are used to charge the capacitor bank which is the energy source for the SPA. Fig. 9 shows the SPA power supply.



(A) SPA Schematic (B) SPA IGBT Bridge

Fig. 9. SPA power supply for RWM coil

Each of the above coil system is powered by several individual rectifier power supplies either in series or in parallel depending on the voltage and current requirements for the coil. The power supply type and rating for each coil on NSTX-U are listed in Table I.

TABLE I. NSTX-U COIL POWER SUPPLY TYPES AND RATINGS

Circuit (Coil)	Type	Series/ Parallel	Voltage (kV)	Currents (kA)	ESW Time (Sec)
TF	Unipolar	1/8	1	130	7.04
OH	Bipolar	6/1	6	+24/-24	1.47
PF1AU PF1AL	Unipolar	2/1	2	19	5.5
PF1BU PF1BL	Unipolar	2/1	2	13	2.1
PF1CU PF1CL	Bipolar	2/1	2	-8/+16	4.3
PF2U PF2L	Unipolar	2/1	2	15	5.5
PF3U PF3L	Bipolar	2/1	2	-16/+12	5.5
PF4	Unipolar	2/1	2	16	5.5
PF5	Unipolar	3/1	3	34	5.5
RWM1-6	Bipolar	1/1	1	+/-3.33	6

III. Power Supply Real Time Control System

The PSRTC system for NSTX-U has a series of system upgrades. The PSRTC runs on a computer with 64-bit real-time Linux operating system. The software was developed using the General Atomics Plasma Control System (GA PCS) code generator for code portability and maintainability [4].

A real time computer with 64 2.8 GHz cores is used for the NSTX-U plasma control system (PCS), including the PSRTC. It has 64 GB memory and several PCI Express cards. It also has two 4-port fiber optic SL240 Serial FPDP (SFPDP) cards used for communication.

The PSRTC software is incorporated into the existing PCS framework. The PSRTC requires configuration data from an MDSPlus data tree for each power supplies. For each shot, the PSRTC also archives a set of shot data in the MDSplus trees. It has the graphical user interface (GUI) shown in Fig. 10. The control reference timing waveforms for each power supply can be defined in the PSRTC GUI using piecewise-linear method.

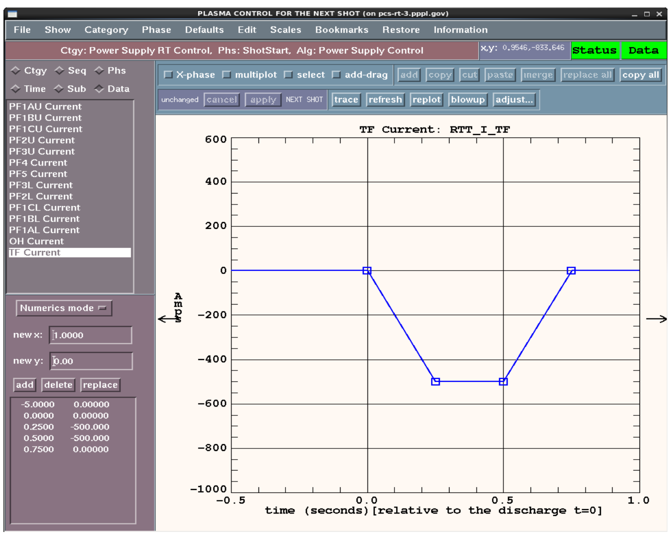


Fig. 10. Graphical user interface for PSRTC.

Compare to the NSTX legacy software [5], there are some new features added in the new PSRTC software:

- Legacy PSRTC standalone software combined all control functions and various protection functions. The new PSRTC software handles only control functions. The DCPS handles all protection functions as described later in this paper.
- The new PSRTC software uses different control functions for the thyristor power supplies and the SPA.
- A new version of the overcurrent clamp function is included in the voltage and physics control mode.

The PSRTC control block diagram is shown in Fig. 11. The PCS and PSRTC software are in the same real time computer and they can communicate easily for more advanced control or protection shutdowns.

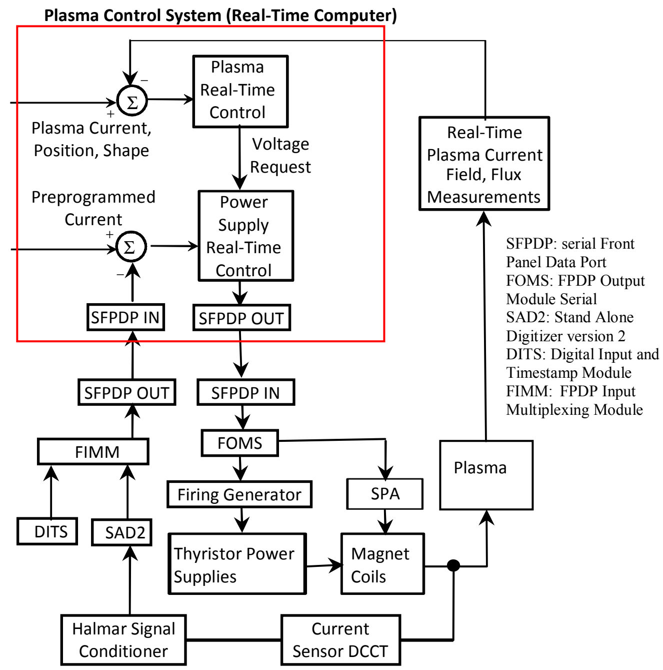


Fig. 11. PSRTC control block diagram

The instantaneous currents in each coil are measured by the zero-flux type Direct Current Coil Transducers (DCCT) manufactured by Halmar Electronics (now DynAmp). All of these signals are fed to a "Halmar Signal Conditioner" (HSC) which buffers, filters, and sends out the signals to the Stand Alone Digitizer version 2 (SAD2). SAD2 converts all the analog signals to 14 bit digital data and packages two channels of data into the FPDP words. These FPDP stream and the 48 bit time-stamp information from the Digital Input and Timestamp Module (DITS) are buffered and combined in the FPDP Input Multiplexing Module (FIMM). FIMM combines multiple FPDP streams by concatenation and forward data to the Curtiss-Wright SL100 card. The multi-channel SL100 SFPDP boards send the data to the real time computer through the 1km fiber optic cable.

The output control command from the PSRTC is also in FPDP word format including the firing angle, the convert bit and the bypass bit. An SL100 card is also used here for the long distance fiber optic data transfer. The new FPDP Output Module Serial (FOMS) transmitter is used to buffer and routing the control data to different FOMS receiver which is built in the Firing Generator (FG). Base on the received information, the new FG generates the 6 firing pulses to control the thyristor power supply. For the SPA, another FOMS receiver is used to change the digital current command to analog voltage to control the RWM coil currents.

In this paper, two important topics are described in detail. One is the PSRTC control operation mode and the other is the PSRTC control hardware upgrade.

A. PSRTC Control Operation Mode

The PSRTC computer uses the firing angle, the convert and the bypass command to control the thyristor power supplies. The firing angle is related to the voltage output of the power supply. The voltage command are derived either from the closed loop proportional-integral (PI) current control based on reference current waveform or from a direct voltage request. There are three typical control operation modes in PSRTC [5]:

1) Close Loop Current Control Mode

A proportional-integral (PI) controller is used for the closed loop current control for the NSTX-U coils. The control reference timing waveforms for each power supply can be defined in the PSRTC GUI using piecewise-linear method. To avoid integral windup, the integral gain is only applied when the error between the real load current and reference current falls below 5% of the reference. This mode is used for the dummy load and the Integrated System Test Procedure (ISTP) test for the magnet coils on the NSTX-U.

2) Voltage Control Mode

The voltage request is from the preprogrammed reference voltage waveform. This is an open-loop voltage control. This mode is typically used for the open circuit test for the power supply without any coil current.

3) Physics Control Mode and Current Clamp

The voltage request is coming from the PCS. The coil current control is based on the physics requirement for the plasma control. When the load current limit is reached, the voltage request is limited by a current clamping feature.

The SPA has its internal regulators to control the output current. It only needs the target current signal and do not use feedback control that is implemented in PSRTC. The target SPA current in the PSRTC is simply bounded below 3.33 kA and passed through to the FOMS.

B. PSRTC Control Hardware Upgrade

There are many PSRTC control hardware upgrade. In this paper, only three key components the SAD2, the FOMS and the new FG are described in detail.

1) Stand Alone Digitizer Version 2 (SAD2)

The new SAD2 is developed for the real time coil current data acquisition. It uses ADS8548 14bit eight-channel analog-to-digital converters (ADC). It has 32 differential analog input channels, maximum 50 kHz sample rate. All these channels can be sampled simultaneously through an external sample clock.

Xilinx XC95288 CPLD is used to implement the SAD2 logic function. When received the trigger signal, it generates the ADC chip select, convert and read pulse. It also controls the transceiver when to send the stored ADC data to the FPDP bus. The sampled data is packaged such that each FPDP word contains two channels data. After sending out the FPDP data, it generates the next out signal to let the next SAD2 to gain control of the FPDP bus.

The SAD2 can be setup to replace the existing Merlin digitizers used for NSTX. The SAD2 can also be daisy chained to expand the analog input channels. Fig. 12 shows the circuit boards of the SAD2.

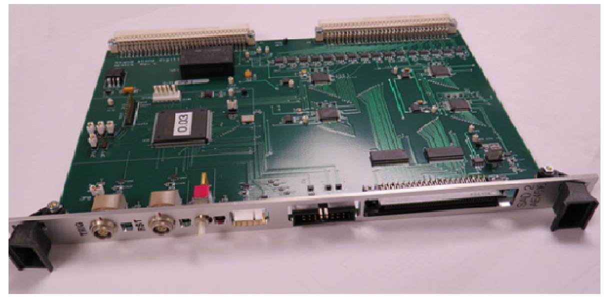


Fig. 12. Stand Alone Digitizer version 2 (SAD2) circuit board

2) FOMS Transmitter and Receiver

The FOMS transmitter shown in Fig. 13 is a VME-format board that is used to receive 32-bit FPDP word from the real time computer. It works like a router and reads the Group, Module and Power address information in the FPDP word to determine its ultimate power supply destination. It sends the 12 bits of the firing angle data, four control bits to the assigned shift registers for the destination power supply. The shift register use the Manchester encoding to send them out through the optical fiber to the FOMS receiver embedded in the FG.

Fig. 13. FOMS Transmitter Board

There are two versions of the FOMS receiver board. One is the digital version which receives the 16-bits digital command word and send directly to the digital signal processor inside the FG as shown in Fig. 14. The second is the analog version which converts the digital command to an analog signal to control the SPA.

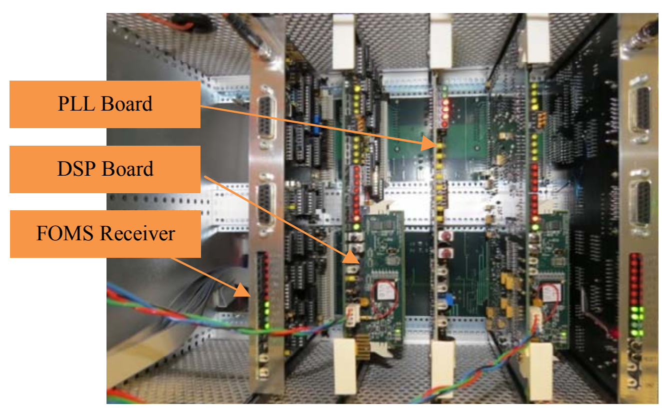


Fig. 14. FOMS receiver in the Firing Generator.

3) *New Firing Generator (FG)*

The new FG is designed based on the TI TMS320F28335 DSP. It receives the firing angle command from the PSRTC real time computer and generates the six firing pulses for the thyristors at the appropriate phase angle of the incoming AC voltage. Since the thyristor power supplies are operated at the variable frequency (50-90 Hz), the phase lock loop (PLL) circuit is used for the synchronization. One advantage of the PLL is that its operation is free from waveform distortions and transients.

The PLL board shown in Fig.14 receives the phase A, B, C voltage signal and generates the continuous digital pulse train which runs at 3600*f Hz (f is the input AC voltage frequency). The digital pulse train is used as a counter clock and each clock is 0.1 degree. The DSP uses this clock to control the timing for the six thyristor firing pulse. Fig, 15 shows the front panel of the new FG. The display shows the voltage, the current, the line frequency and the firing angle information.

Fig. 15. Firing Generator front panel

IV. Coil and Power Supply Protection

There are two separate protection systems in NSTX-U. The first is the coil protection system. NSTX-U replaced the old analog coil protection system (an assemblage of various analog-based sensors) with the new DCPS. The new DCPS will protect the coils and their mechanical supports when the magnetic Lorentz forces, the mechanical stresses or the temperature exceed the operating envelope due to control misoperations. Hardware and software designs of the DCPS are presented in [6] and [7].

The second is the power supply protection system. This system prevents the rectifiers from any overcurrent, incorrect voltage, and over temperature fault. The Fault Detector (FD) is the key component for this system which will be discussed in detail.

The Hardwired Control System (HCS) is the central protection control system which is used to coordinate the two protection system. It is implemented to invoke the Level 1 (suppress and bypass power supplies) and Level 3 (close mechanical bypass/grounding switches) faults of the rectifier power supply system. Each of the Level 1 & Level 3 Fault initiations has two redundant systems. One is designated as "Series" system L1S & L3S, and the other is "Parallel" system L1P & L3P. The HCS has been redesigned using Siemens PLC S7-300 for the NSTX-U.

A. *DCPS Hardware System*

DCPS has a large amount of concurrent processing and rapid responses in less than 200 µs. This requires the computer hardware capable of parallelizing many protection algorithm instances and responding within a tight tolerance. The Concurrent Linux based iHawk AMD-based multiprocessor computer was selected.

The NSTX-U DCPS comprises the Fusion Computation Center (FCC) DCPS and the Junction Area (JA) DCPS. The FCC DCPS share the real time computer with the PCS. The JA DCPS use a stand-alone real time computer. Combined with the FD, it has three levels of coil current protection. The instant trip settings from low to high are the FCC DCPS, the JA DCPS and the FD. Each level acts as the back up to its predecessor. Under a fault condition, JA DCPS uses the HCS Level 1 fault to shut down the power supply. FCC DCPS can directly send the command through the PSRTC control computer to shut down the power supply.

The DCPS block diagram is shown in Fig. 16.

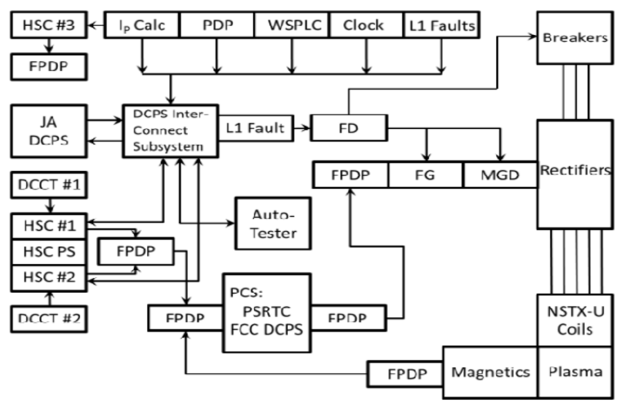


Fig. 16. DCPS Block Diagram

DCPS receives three kinds of input signal.

1. 5 kHz clock signal and other discrete clock events o trigger different types of operation for DCPS.
2. Several digital signals on a digital I/O card to handle resetting and overriding an OH TF, PF1, PF2 coil fault.
3. Several analog instantaneous current signals in the NSTX-U coils. There are two channels for each coil current, duplicated for redundancy.

DCPS has several digital outputs.

1. The four coils (OH TF, PF1, PF2) fault signal are used to differentiate between faults detected in different sets of coils.
2. A heart beat signal which alternates between a high and low state each time a 200 µs cycle is complete.
3. A watchdog timer signal is generated and sent out to the DCPS interconnection subsystem to monitor the health of the computer or the software.
4. Multiple system status bits each provide a dedicated line to signal what state the system is in,

The DCPS interconnection subsystem provides the copper and fiber optic connectivity for several NSTX-U control, data acquisition, protection and testing systems. The features and functionality includes:

- Connect all analog inputs and digital inputs and outputs for the JA DCPS real time computer.
- Centralize fault latching and routing from multiple systems to the FD.
- Hardware user interface shown in Fig. 17 provides the status and configuration indicators, operator manual control and configuration inputs.
- Quick, repeatable and interlocked reconfiguration of interconnections for Auto Tester interfacing to the JA DCPS.

Fig. 17. DCPS Interconnection Subsystem Hardware User Interface

B. *DCPS Software Algorithms*

The new DCPS protection scheme considers the different coil currents combination for the force and stress calculation. The DCPS has five types of software algorithms for the coil protection.

1) Over-Current Trip

When the magnitude of the current in the coil circuit is over the limit specified as an input parameter, DCPS will trip.

2) Action Integral Trip

Action integrals, $\int I^2(t)dt$, is used to estimate the coil temperature rise due to Joule heating. If the calculation result is over the limit which will lead to the coil over temperature, DCPS will trip.

3) Forces and Moments (torques)

The integrated force on a coil is a multivariable quadratic function of the coil currents. This algorithm will calculate the radial, vertical magnetic Lorentz forces and torque on the coil and will trip if the value is over a certain limit.

4) Derived Limit Variables Type I

For material operating within elastic ranges, stresses are linear with spatial distribution of force and temperature loadings. This algorithm can be used to calculate the particular mechanical stress at a certain location in the coil support structure.

5) Derived Limit Variables Type II

This algorithm is a square root of the sum of squares of all Type I limit variables. This is reserved for the future use.

C. *Hardwired Control System (HCS)*

For NSTX-U, the HCS has been redesigned using the Siemens PLC [8]. The HCS block diagram is shown in Fig. 18.

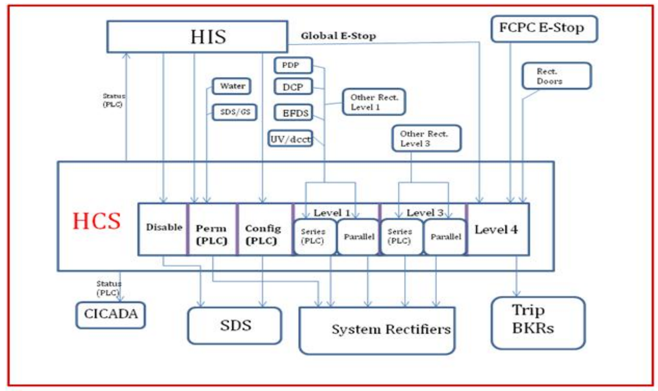


Fig. 18. HCS function block diagram

The PLC used for the power supply is shown in Fig. 19. The function of the PLC includes:

- The PLC accepts the interlock commands from the Hardwired Interlocked System (HIS) from the main control room. The CONFIGURE command is used to permit the line and ground switch to be configured. The ARM command is used to give the permissive signal to allow the power supplies to be controlled by the real time computer. The Enable/Disable command is used to suppress the rectifiers, open the line switches and close the ground switches.
- Process the fault trip signals from DCPS, FD, PDP timer, etc. and invoke Level 1 (series) Fault in all the associated power supplies.
- Display the status on the device for the trouble shooting and send the status back to the HIS.

Fig. 19. PLC used in the Tranrex power supply

D. *Fault Detector (FD)*

The FD is a key component for the rectifier power supplies. It monitors the over current fault in each thyristor leg inside the power module using the AC current transformer (ACCT). The current in the Bypass Module is also monitored through DCCTs in each of the 6 thyristor legs in each bypass module. The total current in each section of the power supply is monitored by the FD. The trip level can be adjusted based on the coil current protection requirement.

Whenever the input variable frequency voltage is below limit or the three input voltage phases are unbalanced, the FD will trip and issue a Level 1 fault.

There is also an overtime protection inside the FD used for the coil protection. When the rectifier has been producing DC current for a time longer than the preset operating time of the coil, the FD will trip.

E. Pulse Duration Period (PDP) Timer

The FD overtime protection is not functional when the coil current below 3 kA. To prevent the coil from overheat due to long time small current, the Pulse Duration Period (PDP) timer is added to the coil protection system. To cover longer pulse length and repetition period, the new PDP timer has been designed and implemented for NSTX-U.

There are two time settings for the PDP timer. One is the "Allow Time" which is from 1 to 20 seconds adjustable in 0.1 second step. The other is the "Period Time" which is from 1 to 40 minutes adjustable in 1 second step. The PDP timer is triggered by the NSTX-U standard clock events Start of Pulse (SOP). During the allow time, the PDP timer send out the permissive signal to the HCS, DCPS, and all the power supply control system until the "allow time" is expired. The PDP will not re-trigger until the "period time is expired. The plasma shot control cycle is divided by the "PDP" timer into three sequential sections: allowing, inhibiting, and waiting. The PDP timer circuit board is shown in Fig. 20.

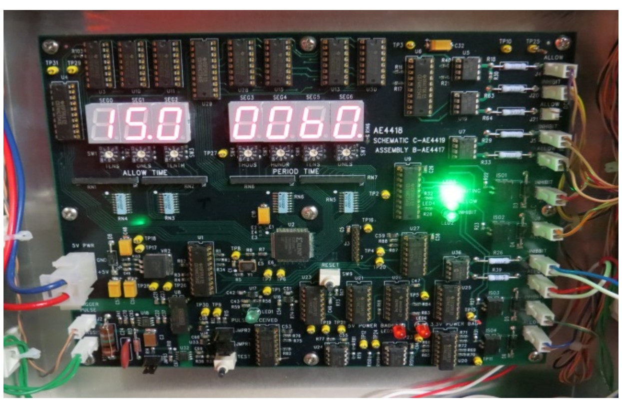


Fig. 20. PDP timer circuit board

F. Ground Fault Protection System

All the coils in the NSTX are kept floating at high voltage 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 [9].

The ground fault detection circuit is shown in Fig. 21. The resistances R1 & R2 are connected across the load. The junction of R1 & R2 is connected to ground via the ground fault relays and a permanent resistor R3. The values of R1, R2 & R3 were chosen depending on the operating voltage of the circuit. Typically the values are such that no more than 800 ma of current can flow through the circuit in case of a bolted ground fault.

Two relays are used to detect the ground current. One relay is the inverse time over-current relay 51 G which is set to trip at 5 mA. The other is the instantaneous over-current relay 50G is used which is typically set at 100 mA.

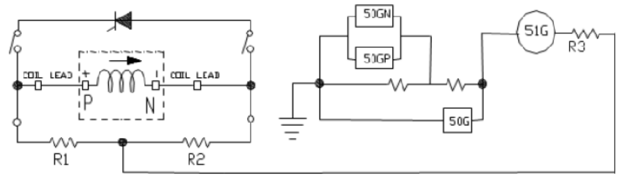


Fig. 21. Ground fault detection circuit.

V. CONCLUSIONS

The legacy analog FG was in use for 35 years and needed to be redesigned and modernized for the NSTX-U. The new DSP-based FG is designed and implemented with excellent performance and reliability. The legacy PSRTC was developed in 1998 using an old computer platform that had become obsolete and needed a thorough revision. The new PSRTC runs on a real time computer with 64-bit Linux operating system. The old analog coil protection system was replaced with the new DCPS. The DCPS introduces protection features that consider combinations of coil currents, rather than individual coil currents, thereby allowing full exploitation of the operating envelope provided by NSTX-U. The old HCS system used electromechanical relays for the protection. A new PLC based HCS system is designed and implemented to facilitate easy monitoring and trouble shooting for the power supplies.

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