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Abstract—**This The National Spherical Torus Experiment (NSTX) has been designed and installed in the existing facilities at Princeton Plasma Physic Laboratory (PPPL). Most of the hardware, plant facilities, auxiliary sub-systems, and power systems originally used for the Tokamak Fusion Test Reactor (TFTR) have been used with suitable modifications to reflect NSTX needs. At present, the NSTX power system is feeding thirteen (13) circuits from the Power converters. An upgrade of the NSTX center stack is proposed. This entails a much higher Toroidal Field Current from 71.2kA to 129.8kA, and requires major configuration changes including doubling the number of parallel strings of rectifiers along with associated power loop changes. Also, three additional coils will be installed in the machine. The control and protection of the rectifiers have to be replaced to reflect state of the art features to enhance the performance. This paper describes the details of the proposed Power system for NSTX upgrade.**

INTRODUCTION

The Magnet Coil power supply system located in the D-Site of PPPL, was originally installed for TFTR. These DC systems were reconfigured and modified to supply the NSTX coil systems currently in operation. The AC power to the facility remains unchanged. The NSTX center stack is planned to be upgraded to expand the operational space of the device to establish the physics basis of the next ST device.

The main power supply systems for NSTX upgrade are for the Toroidal Field (TF), Poloidal Fields (PF) with twelve individual circuits), the Ohmic Heating Solenoid (OH) coil circuit, the Coaxial Helicity Injection (CHI) system, and the Resistive Wall Mode Coils (RWM). Table 1 gives the details of the NSTX coil system circuits for the upgrade mode. All the DC power loops are kept floating.

The Coaxial Helicity Injection (CHI) system is retained. For CHI operation, the vacuum vessel is divided into two electrically separate parts. These act as the two electrodes for the CHI. Thus the vessel sections are also required to float during CHI operation.

This paper describes the salient aspects of the power systems upgrade.

DC POWER SYSTEM DESCRIPTION

Thyristor Power Supplies at D-Site in PPPL

PPPL has 39 modular power supplies originally procured for TFTR (Figure 1) with conversion and bypass modules. A power supply has two sections, each of which provides an equivalent rating of 1 kV, 24 kA – 5.5 seconds equivalent square wave (ESW) every 300 seconds. Each power supply is fed by one three winding transformer with a polygon primary and delta/wye secondary. The polygon is arranged to produce + 7.5° or -7.5° phase shift depending on the phase sequence of the 13.8 kV input to the polygon. The DC outputs from the D-Site thyristor rectifiers are fed to the coils as per Table 1.

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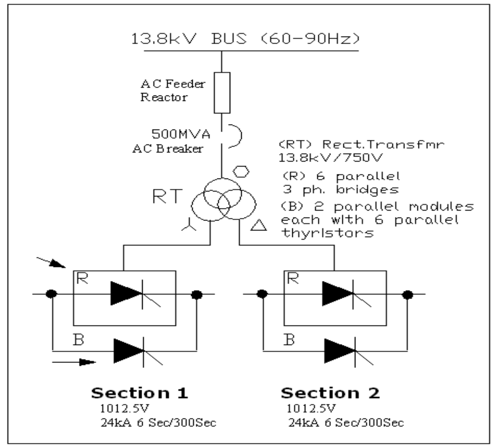


Figure 1
Typical Power Supply with two sections
R: Rectifier; B: Bypass

Circuit	Type	Volts (kV)[3]	Series/ Parallel PSS	Volts (kV)	ESW Current (kA) [4]	ESW time (sec)
TF	I	1	1/8	1	129.8	7.08
OH	III	+/-8	6/2	6	+/-24	1.47
PF1a Upper	IV	+/-1	1/2	1	18	5.5
PF1a Lower	IV	+/-1	1/2	1	18	5.5
PF1b Upper[1]		1	1/1	1	13	2.1
PF1b Lower	I	1	1/1	1	13	2.1
PF1c Upper[1]		1	1/1	1	16	4.34
PF1c Lower[1]		1	1/1	1	16	4.34
PF2 Upper	II	2	2/1	2	15	5.5
PF2 Lower	II	2	2/1	2	15	5.5
PF3 Upper	IV	+/-2	2/2	2	16	5.5
PF3 Lower	IV	+/-2	2/2	2	16	5.5
PF4	I	2	2/1	2	16	5.5
PF5	I	3	3/2	3	34	5.5
CHI	I	2	2	2	24	0.8
RWM1,2,3[2]	I	+/-1	1	1	3.33	.5
RWM4,5,6[2]	I	+/-1	1	1	3.33	.5

(1) Power supplies will be provided during second stage
(2) Switching Power Amplifiers are used for these circuits
(3) Available Volts
(4) Peak current in circuit is same as ESW current.

Table 1
NSTX Circuit Types and Ratings (Upgraded system)

Coil circuits

The circuits are shown in the Table 1. Type I are two wire unidirectional; Type II are three wire unidirectional; Type III

are two wire bidirectional and, Type IV are three wire bidirectional circuits.
By adopting a three-wire circuit, savings were accomplished by reducing the number of power cables installed to the machine. A DC current limiting reactor is provided for each branch of the power supply to reduce the short circuit current, to insure better sharing of the load when parallel branches are used and /or limit the circulating current. The major change for the upgrade is for the TF circuit.

Toroidal Field (TF) Power Loop

The NSTX TF coil (Figure 2) is a Type I circuit. For the upgrade the TF Current has to be increased from 71.17 kA for 1.3 seconds every 300 seconds to 129.8kA pulsed current of 7.2 seconds duration every 2400 seconds. This requires that the number of branches be increased from four to eight parallel power supplies. Also the design has also to be such that the period between the pulses can be reduced from 2400 seconds to 1200 seconds.
Each parallel will have two 1 kV Transrex power supply sections in series. One of the sections will be kept on electrical bypass thus effectively acting as a diode. This prevents the other parallel supplies from feeding into a fault across the terminals of one parallel. The existing four Safety Disconnect Switches (SDS) of the TF with additional parallel supplies will be used. Thus two parallels will feed via each switch. Note that the switches can handle two strings of power supply for the upgrade mode. Limited space makes it very difficult to install additional switches in the first floor. Also the existing TF Ground Switch will be used without any changes.

The existing four TF DC Current Limiting Reactors (CLR) and the existing four OH CLRs – a total of eight CLRs will be used for the TF system with one CLR in each parallel path. All these reactors will be installed in the TF Wing.

Because of space constraints inside the Field Coil Power Conversion (FCPC) building, it is necessary to remove some of the equipment in the aisle. In the new design of the PF1a coils no ripple reduction reactors are needed. Thus these will be removed from the TF aisle. Also the new design of the Fault Detector eliminates some of the instrumentation racks releasing the space in the center aisle.

Power Cabling:

Extensive power cabling changes will be made within the FCPC. Existing power loop for the TF circuit inside the FCPC building, use unshielded 5kV, 750 kcmil cables. During the reconfiguration, part of the existing cables of nearly 5000 feet will be reconnected and reused. About 14000 feet of the 750 kcmil cabling will be removed. Nearly 7000 feet of new 1000kcmil 5kV shielded power cables will be installed for the additional four parallels and connections to CLRs. Since the space in FCPC is a premium, with proper design this can be accommodated. Limited space makes it extremely difficult to install buses instead of cables.

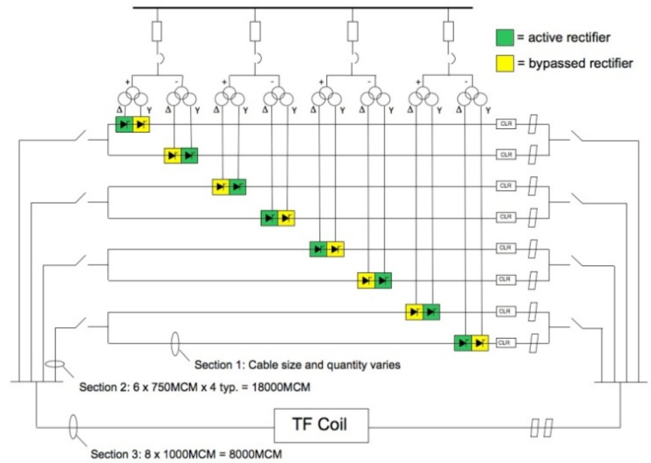


Figure 2
TF Power Supply circuit (Type I)

Additional power cables are required for the TF power loop from the Transition Area (TA) to the NSTX Test Cell. At present we have 5 /1/c-1000 kcmil power cables in each leg of the TF. Based on thermal analysis this is required to be increased to 8 1/c-1000 kcmil cables to handle the current when operated with a period of 2400 seconds between pulses. Keeping the future plans in view, a total of 6-1/c- 1000mcm cables will be released from other circuits in the run from the TA to NSTX Test Cell. These will be connected in the TF loop with three additional cables in each leg of the TF loop. Also modifications will be made in the Power Cable Termination Structure (PCTS) inside the NSTX Test Cell to accept additional power cables in the TF as well as to handle fault currents.

Hardwire Controls:

The controls for the TF and OH circuits will be changed to a Programmable Logic Controller (PLC), replacing the electro-mechanical relays used at present.
The existing system consists of two central Control Boards – one each for TF & OH. The ten Transrex power supplies lined up for each system are currently provided with hardwired controls housed locally for each supply. These will be replaced with one central PLC located near the Control Boards. Local Input/Output (I/O) modules located in each power supply will interface with the CPU of the PLC. Siemens PLC controller S319 is selected based on its high performance functionality, control robustness, capability, and its I/O count. Since the 300 series features a modular design, it allows decentralized system structure, and it is easy and cost effective for future expansion. The system is designed to be SIL3 safety system for all critical controls. The central control unit and its associated control units in each power supply are interconnected by fiber optic links in a ring structure.

Rectifier Control
A new digital Firing Generator (FG) will be designed and installed. This will receive commands over a fiber optic

communication link for the thyristor phase control delay angle "α" and to generate firing pulses at the appropriate phase of the incoming AC voltage. In addition the FG receives block commands for the bridge and bypass thyristors and issues control signals accordingly. Necessary functions include synchronization with the variable frequency (50-90Hz) incoming AC voltage as well as implementation of an inversion limit such that the margin angle "δ" is maintained above a preset value. Note that while the existing system manages only a single set of commands and applies them equally to the two sections, the new system shall manage two sets of commands, one for each section. The phase angle command "α" is computed and generated by the Power Supply Real Time Controller (PSRTC) based on the required current. The PSRTC is programmed such that the required coil current gets established.

Rectifier Protection

The existing Fault Detector (FD) in each Power Supply will be replaced with state of the art design thus enhancing the speed and reliability. All the protective functions will be retained. The new fault detector will consist of two independent sections, one for each rectifier section and a common communications section. The new unit will use all existing cables and connectors for existing signals, but can add new connectors for new signals, such as Ethernet communications. New signals can also be added to unused pins on the existing connectors. The new unit can use the existing DC voltages for power as long as it draws no more current from these lines than the existing unit uses. Optionally 110VAC can be supplied to the new fault detector for new internal power supplies.

Instrumentation:

Two DCCTs in each of the eight branches will be installed within FCPC. One of these sets of DCCTs are for control purposes to establish current balance in the branches. The second set will be used for protection. There are eight existing DCCTs in the TF loop. Additional eight DCCTS (+/-25kA) will be procured and installed.
In order to measure the total TF current, two fiber optic DCCTs with a range +/- 160kA, will be purchased and installed in the Transition Area. These two DCCTs will also be used to control and protect the TF Coil.

Ohmic Heating Coil Power Loop

The NSTX OH coil (Figure 3) requires a 6 kV (reversible) supply with a rating of +/- 24 kA for 1.47 seconds every 2400 seconds. Two strings are connected in anti-parallel configuration and is the type III circuit of Table 1. Based on analysis of the circuit the CLR in each branch will be changed from the existing 544uH reactors to one milli-henry reactors. This limits the circulating currents to acceptable levels prior to trip on a fault. Figure 3 shows the one line of the circuit.

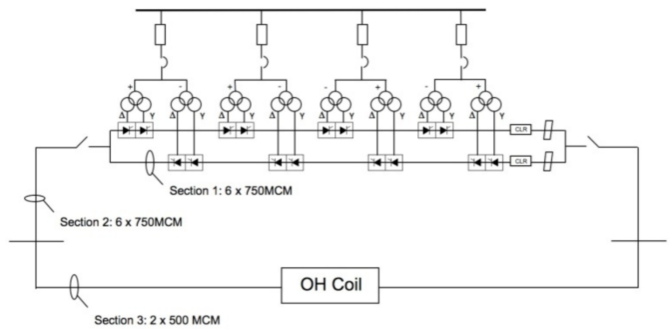
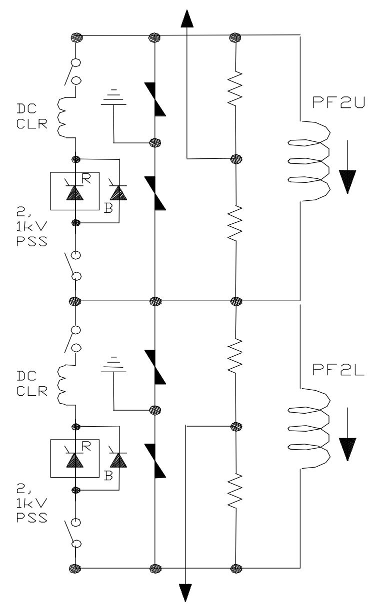


Figure 3
OH Power supply circuit (Type III)

Poloidal Field Power Loops

The existing PF system consists of 9 circuits, with each circuit connected to its own power supply system. These circuits will be retained. During the second stage of the upgrade the additional three circuits (PF1bU, PF1cU & PF1cL) will be powered as shown in Table 1. Note that the PF1a, PF2 and PF3 coil systems have been provided with individual feed to the Upper and Lower coils, with a three wire feed system to reduce the number of leads from 4 to 3, for a cost effective installation. The PF2 is a Type 2 circuit as shown in Figure 4.



To Ground detection ckt.
Figure 4
Unidirectional three-wire configuration for PF2
(Type II ckt)

The PF1 and PF3 Upper and Lower coils circuits are bidirectional with rectifiers connected in anti-parallel. These are three wire configuration for the coil system. The circuit is same as Figure 4 except that anti-parallel power supplies are provided for four-quadrant operation.

NSTX has also a Coaxial Helical Injection circuit (CHI). The CHI is pulsed from a capacitor bank. The FCPC power supply is used only for conditioning purposes and needs a maximum of 10kA. The FCPC feed is a Type I circuit.

Resistive Wall Mode Coils (RWM) Power Feed

NSTX has six RWM coils which are installed around the machine in the mid-plane. These coils need fast and accurate controls. In the original design a Switching Power Amplifier (SPA) with three sub-units was procured, installed and commissioned along with other power loop components. Two RWM Coils were connected in series and fed from one SPA sub-unit. Operational requirements dictated that each of the RWM coils be separately fed and controlled. Hence an additional SPA with three sub-units has been procured and installed. The two sections of the existing TFTR HF thyristor rectifier is used as DC input to the Switching Power Amplifiers. The controls for the RWM were integrated into the overall computer control of the DC Power systems for NSTX.

Analysis of Power System using PSCAD

The TF & OH power loops were simulated and analyzed using the PSCAD program. In the case of TF circuit eight parallels were incorporated with each power supply with its own PI current controller. The control algorithm was written to control the converter firing angle "α" such that the current in each branch is 1/8 of the total TF coil current. The simulation showed that the short circuit current at different points in the power loop, coil temperature rise and I^2*t values, agreed with calculations.
In the case of OH the simulation was used to establish the optimum value of the CLR in each branch.

Coil & Supporting Structure Protection

A new digital coil protection (DCP) calculator will be installed. Protection will be accorded against instantaneous over-current and $\int i^2(t)dt$ limit in each coil circuit, simulation of heating and cooling of each coil using coil current as input and protection against over-temperature, simulation of various design-limiting quantities based on algorithms using the coil currents as input, and protection against design limits of the coil and machine support structure. The hardware involves a suitable micro-processor and associated components. The DCP will issue a trip command to suppress and bypass the rectifiers if any of the set operating limits are exceeded.

Ground Fault Protection

All circuits are kept floating. This precludes any damage due to ground fault current in the event of a single ground fault. The basic ground detection scheme is same for all types of circuits.
Figure 5 shows the typical ground detection scheme. The resistances R1 & R2 (of equal value in all circuits except CHI) are connected across the load. The junction of R1 & R2 is connected to ground via the ground fault relays and a permanent resistor. 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.
The inverse time over-current relay 51G is a standard DC electromagnetic relay and has been functioning very reliably. Typically the relay is set to trip at 5 ma of ground current. Instantaneous over-current relays 50G were designed and installed in all circuits. These are typically set at 100 ma. One set of commercial current transducers were also installed. The relay 50GP detects current in the positive direction and the relay 50GN detects in the negative direction.
A unique method of interconnecting similar independent electrical power loops was devised (Figure 5), via a high resistance network for ground detection for each group. Some of the coil circuits are grouped. TF, OH and CHI circuits are provided with dedicated ground fault relays. The rest of the six circuits have been grouped and are served by one relay circuit. Ground fault in each group will be detected and power supply tripped.

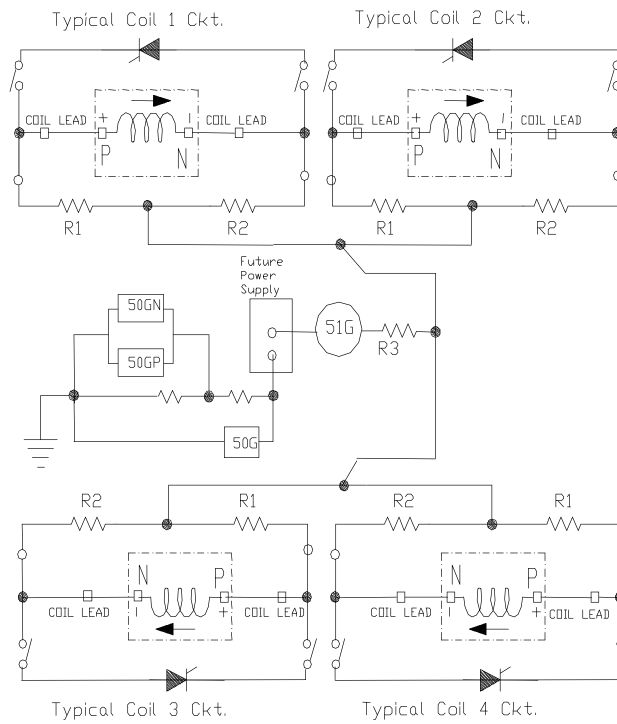


Figure 5
Ground Fault Detection – combining circuits

Conclusions

The electrical power system design meets the requirements established in the General Design Requirements stipulated for NSTX Upgrade. Space constraints were taken into account when designing the system. The power system was designed and analyzed using PSCAD program. Control and protection was enhanced using state of the art design.
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The preferred spelling of the word “acknowledgment” in America We want to record our appreciation to Dr. O. Nayak and A. Thant of Nayak Corporation, Princeton NJ, for analyzing the circuits using the PSCAD program, and providing their recommendations.

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