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NSTX POWER SUPPLY CONFIGURATION CONTROL UPGRADE

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Abstract— **The National Spherical Torus Experiment (NSTX) is in its second decade of operation at PPPL. NSTX has a total of 15 coil systems (which include the coils, their dedicated power supplies and associated auxiliary equipment) that create and control the plasma per the experimental objectives. Each coil system is individually controllable via the NSTX Power Supply Real Time Controller (PSRTC) software code written in C language. The NSTX has great flexibility in both the configuration of its coil system and in the operating envelope afforded by the connected power supplies. To ensure proper operation and to minimize the probability of lost runtime due to system faults, the project has developed a procedure that governs system configuration. The Integrated System Test Procedure (ISTP-001) documents the NSTX machine parameters, experiment configuration limits, machine protection settings and device settings.**

This paper will describe calculations for the ISTP 001 methodology and system protection settings; record keeping of the various configuration revisions and the upgrade in progress to improve readability and calculation capabilities.

Keywords- Integrated System Test Procedure, ISTP-001, National Spherical Torus Experiment, NSTX, PSRTC, Power Supply Real Time Control, mathcad excel data link

I. INTRODUCTION TO NSTX

The NSTX coil system controls and/or contains the plasma boundary within safe operational limits by creating variable magnetic fields around the vessel using large electromagnetic coils. The Toroidal Field (TF) coil, the Poloidal Field (PF) coils, and the Resistive Wall Mode (RWM) coils are electromagnetic coils used to generate varying magnetic fields to control, confine and stabilize plasma. A total of 17 such coils, namely Ohmic Heating (OH), the TF, PF1AU (upper) & L(lower), PF1B, PF2U&L, PF3U&L, PF4, PF5, RWM1, 2, 3, 4, 5, and 6 are powered and controlled, via a current feedback closed loop circuit, to run this experiment. These large electromagnetic coils aide in initiating plasma build up and shaping plasma under controlled conditions, generating plasma temperatures close to 11,000 Kelvin.

The command and control of all the coil systems is done via the NSTX Power Supply Real Time Control (PSRTC) software. The control software was originally written in FORTRAN and later converted to C. The PSRTC uses data from configuration files or an MDSPlus database for system parameters and machine protection settings to ensure safe and error free operations. The PSRTC governs flow of information (permissive signals, alpha requests, etc.) to the NSTX rectifiers. PSRTC also ensures that only those coil systems which are required to run a particular plasma shot are active. The protection scheme of the NSTX machine is an integral part of the entire experimental setup ensuring the correct operation and protection of the machine as well as protection of each run shot. The Integrated System Test Procedure (ISTP-001) document contains all the information regarding the software and hardware protection scheme parameters and has testing guidelines to check the same.

A. *NSTX PROTECTION SCHEME*

NSTX has primarily three levels of coil current protection each level acting as back up to its predecessor. Fig.1 shows the block diagram of this three level protection scheme.

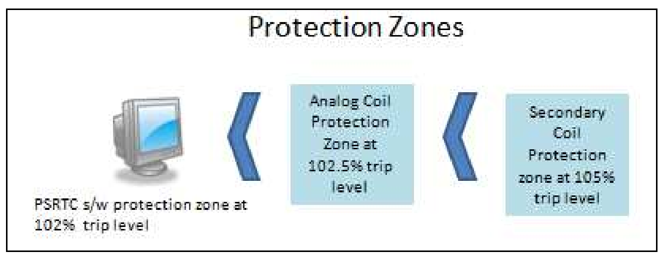

Fig. 1 Graded three protection levels

The secondary coil protection is available only to OH, PF2, PF3, and TF coil systems via the RIS (named after its manufacturer *Rochester Instrument Systems*). NSTX is also equipped with protection against excessive coil temperatures, current and voltage rate limits, weld stresses, axial forces between coils, and faults in the Hardwired Control System. Outside this protection window are protective devices for the power supplies and their components.

B. *NSTX POWER SUPPLIES*

NSTX uses *Transrex* rectifier modules, originally used for the Tokomak Fusion Test Reactor (TFTR). There are a total of 39 modular 12-pulse phase controlled thyristor rectifiers. Each PS consists of two 6-pulse Power Supply Sections (PSS) which are electrically isolated from each other but

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subject to the same Firing Generator (FG). The PSSs are powered by 3 winding transformer with a rating of 13.8kV/ 750 V with Δ/Y secondary windings, providing a natural phase shift of 30° between the two sections. Each PSS has a full rated bypass module designed to carry the full load current when the rectifiers are suppressed and bypassed thereby protecting the last two operating thyristors against decaying currents. The nominal pulse current rating of each PSS and its associated bypass module is 24 kA for 6 seconds every 300 seconds; and is rated to output maximum average DC output voltage of 1012.85 kVdc (= 750 V* 2.34/√3 ~ 1 kV). These power supplies (PSs) power the TF, OH and all the PF coils.

The RWM coils are powered by Switching Power Amplifiers (SPAs). These are four quadrant inverters which can switch a DC source capacitor bank on the terminals of the RWM coils using pulse width modulation (PWM). The DC source capacitor bank is charged by a separate Transrex power supply module. Currently there are three SPA sub-units, each rated 1 kV/3.333 kA for 6 seconds every 300 seconds. There are three new sub-units included for the next run period which will give us a dedicated SPA unit for each RWM coil. Each of the above mentioned coil systems is powered by a dedicated PS system comprising of PS(s) in series (NS) and parallel (NP), depending on its current and voltage requirements. The PS ratings for all the coil systems and their current carrying capabilities are listed in Table 1.

Table 1 NSTX Coil System ratings

COIL SYSTEM	Circuit Type	NS	NP	Imax Coil Design (kA)	V (kV) [Vrated* NS]
TF	Unipolar, 2-wire	1	4	71.2	1
OH	Bipolar, 2-wire	6	2	24	6
PF1AU	Unipolar, 3-wire	1	1	24	1
PF1AL	Unipolar, 3-wire	1	1	24	1
PF1B	Unipolar, 2-wire	1	1	20	1
PF2U	Unipolar, 3-wire	1	1	20	1
PF2L	Unipolar, 3-wire	1	1	20	1
PF3U	Bipolar, 3-wire	2	1	20	2
PF3L	Bipolar, 3-wire	2	1	20	2
PF4	Unipolar, 2-wire	1	1	20	1
PF5	Unipolar, 2-wire	3	1	20	3
RWM(1-6)				3.333	1

II. COIL SYSTEMS

Fig.1 shows the elevation view of the NSTX machine showing the location of the electromagnetic coils. The inner TF and OH coils form the center stack of the machine.

i. The OH coil is responsible for initiating and ohmically heating the plasma.
ii. The TF coil can produce a magnetic field of 0.6 T at 0.854 m.
iii. The PF coils are mounted circumferentially around the vessel and are numbered with respect to their location relative to the center stack from top to bottom. The PF4 and PF5 coils are located in close proximity to one another which results in large axial forces between them. NSTX has software and hardware protections against excess stress in the affected weld.
iv. The six RWM coils are each powered and controlled by SPA sub-units which are themselves powered by a rectifier power supply.

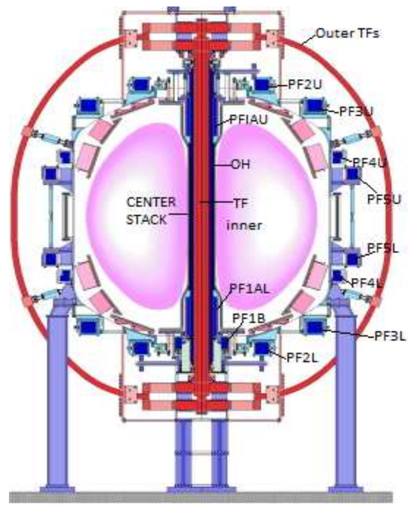

Fig. 2 NSTX elevation view

III. ISTP-001 PROCEDURE

The ISTP-001 procedure is a configuration control mechanism to protect the machine and ensure correct setting of the protection schemes and operational setup. The procedure includes an optional set of test shots to be run as required. These procedural shots are typically performed at the start of a run period or when a major change to the machine hardware or control software is done to enable various physics experiments. The changes, during the run period, that require issuing a new ISTP-001 document and engineering test shots to be carried out are:

i. Coil polarity link changes
ii. Configuration changes like coil current levels, coil supply voltage, reversal in coil current direction, NS value, etc.
iii. Software, ACP and RIS setting change as a result of changes stated in item ii
iv. Secondary protection trip settings that act as a backup to the ACP trip settings changes.

The ISTP-001 also documents protection settings of equipments (feeder breaker, PS transformer, feeder cable, rectifier sections and bypass modules) that are tested by a separate procedure but use this document as a reference.

IV. ISTP-001 SPREADSHEET

The present ISTP-001 document is an Excel spreadsheet dedicated to protection of the machine. It consists of 15 worksheets, maintained by the NSTX PS Engineer, and contains data and calculations of system parameters, protection settings, operational limits, etc. When a change in system configuration is required to accommodate a new experimental setup, an ISTP-001 document showing these changes is issued. Description of the worksheets in their order of occurrence is as follows:

1. ***Revision History*** – This page lists in chronological order the revisions issued every time ISTP-001 was released with brief description of the associated changes.
2. ***Op_Envelope*** – The Operation Envelope page summarizes the parameters to set up the protection system of the NSTX machine equipments for operations and control. There is a parameter validation check on this page which prints an 'OK' for acceptable values and 'X' otherwise. Fig. 2 shows the plot of the permissible current window.

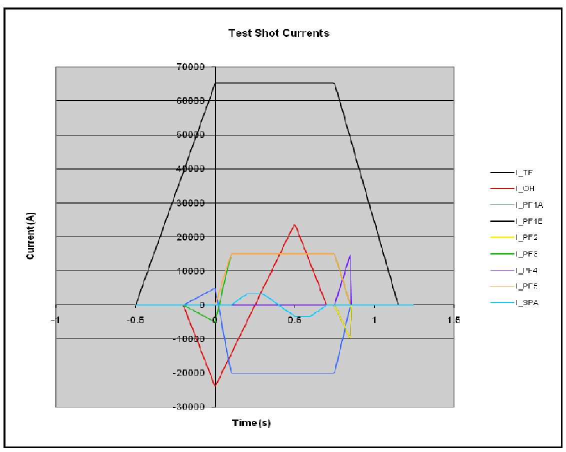

Fig. 3 ISTP-001 permissible current waveforms window

3. ***PSRTC*** – Lists the software protection settings contained in the configuration data files or MDSPlus database. The protection parameters tabulated on this page are: OC settings, I^2T limits, Maximum Axial Force limits and TF Joint Data. The NS, NP, and Coil connection polarity sign are the non protection values also listed here.
4. ***Protection*** – Tabulates the ACP (primary) and secondary hardware protection settings.
5. ***Field Coil Power Conversion (FCPC)*** – The page contains protection settings pertaining to rectifier protection scheme.
6. ***AC_POWER*** – This page contains the Time Delayed and Instantaneous relay (50/51) protection settings for the power supply components.
7. ***TEST_SHOT*** – This page calculates a safe operational window of the machine. The combined field test shot current waveforms (Fig. 2) are used to determine the inductive voltage buildup, I^2T values, the power usage profile (Fig. 3) to predict the Motor Generator set loading, OH Hoop Stress loads (Fig.5), Axial Forces, and TF Joint data (Fig.6). The limits calculated here are reflected on the Operations Envelope page.

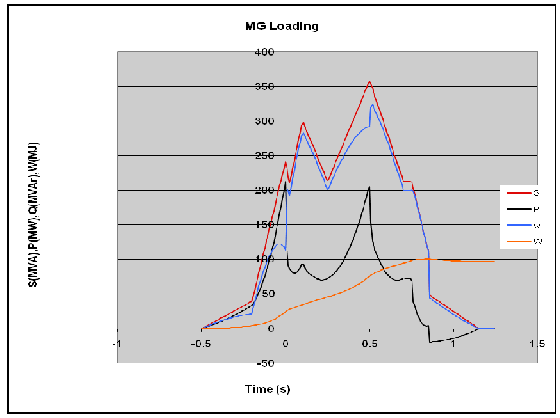

Fig. 3 Power drawn during each test shot

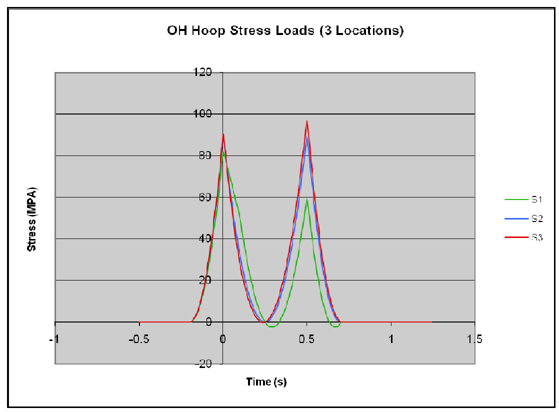

Fig. 5 OH stress loads during a 100% current level test shot

8. ***TF*** – Calculates design limits of the coil, maximum current carrying capacity, heating, temperatures, power losses, cooling requirements, stress factors, thermal constants, pressure, and thermal modeling.

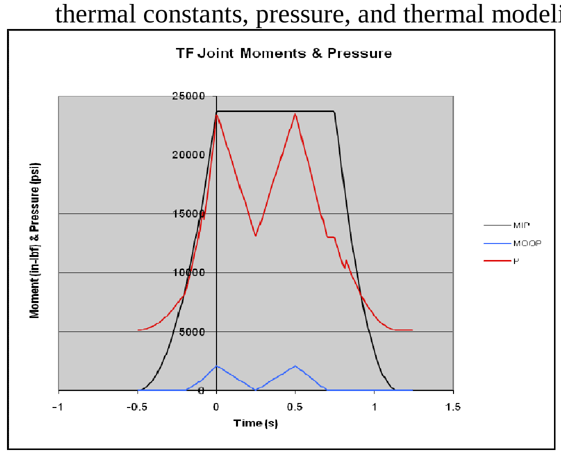

Fig. 6 TF Joint Data plot

9. ***COMM_SHOT* –** Lists out the minimum and maximum current limits for each coil in either directions and the number of commissioning shots per coil system as per ISTP requirements.
10. ***PF_OH* –** This page calculates design limits for the PF, OH, RWM and PF Absorber (PFAB) coils. Other calculations on this page: initial & final temperatures of the coils, I^2T, power losses, heat sink parameters, required water-cooling rate, thermal modeling and stress factors.
11. ***ACDS* –** The feeder breaker trip settings calculated.
12. ***CABLE*** – The physical parameters and Irms ratings of all the cables in the NSTX system are listed on this page.
13. ***TRANSREX*** – This page lists out the rectifier operation parameters and its protection settings.
14. ***EE*** – contains the coil system inductance matrix and array of each coil system's total loop resistance. Using this matrix and resistance value the net voltage drop (resistive and inductive) across each coil is calculated.
15. ***ME*** – contains the axial force coefficients matrix, stress coefficients; TF Mid-inner plane coefficient and outer plane coefficient for lifted off and not lifted off plane conditions, TF Flag Box force coefficients, the TF flag loads calculations, OH loading stress coefficients and loading stress calculations.

V. ISTP-001 UPGRADE WORK

Mathcad worksheets have been created to replicate the functionality of the ISTP-001 spreadsheet. Using the Mathcad tool a link between the existing Excel spreadsheet and a new Mathcad worksheet is achieved. The purpose of this upgrade is to ease editing the ISTP-001 document and facilitate understanding. The Mathcad worksheet acts as the primary calculation platform where shot configuration requirements are plugged-in and the results will cascade through an array of formulas outputting the calculated settings to the Excel spreadsheet. A NSTX reference parameter formula sheet has been created which acts as a "bible" containing all system parameters, reference settings, design parameters, machine parameters, and dimensions. Here the experimental setup parameters are to be plugged in. The 15 worksheets in the current ISTP-001 spreadsheet have been converted to Mathcad formula sheets and are linked to this parameter reference file. Thus any change made in the reference file is a universal change propagating to all the linked worksheets. The upgrade combines the flexibility of carrying out mathematical calculations in Mathcad with the comprehensive data representation in Excel to improve the entire ISTP-001 record keeping process. The formula sheets created in Mathcad include explanations of the calculations, the assumptions made, and results for the system protection level setting calculations and more.

A. Tools used for data import and export

The Worksheet Import tool in Mathcad has been used to make *unidirectional* data link between excel and mathcad active. The term unidirectional means that data flow is from Mathcad to Excel. When a change in system hardware/software is requested the mathcad worksheet input parameters will be changed and the output will then be exported to excel spreadsheet where reading the results in tabular format is easier.

B. Advantagesof using Mathcad for calculations

- Mathcad is a very powerful tool for carrying out optimized engineering calculations methodically with full units support enabling testing before finalizing for design.
- Mathcad can perform more complicated and sophisticated calculations with greater accuracy.
- The layout is comparable to a hand calculation worksheet, thus making it easy to read, edit, and review compared to the long cell referenced formula arrays in Excel.
- Mathcad provides much better mathematical modeling capabilities to output more accurate results; this is helpful in predicting the static, dynamic and transient responses of a system.
- The unidirectional data link established between Excel and Mathcad combines best of both the worlds to build a procedural document which is more efficient and sophisticated.
- The flexibility to include comments/notes in between calculation steps, while building a model or methodical array of formulae, aides in creating a detailed, self explanatory and informative worksheet.

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