Real Time Control System for the National Spherical Torus Experiment (NSTX)

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Abstract

The NSTX [1] is a national facility for the study of plasma confinement, heating, and current drive in a low aspect ratio, spherical torus (ST) configuration. The ST configuration is an alternate magnetic confinement concept which is characterized by high β (ratio plasma pressure to magnetic field pressure) and low toroidal field compared to conventional tokamaks, and could provide a pathway to the realization of a practical fusion power source.

The NSTX depends on a real time, high speed, synchronous, and deterministic control system acting on a system of thyristor rectifier power supplies to 1) establish the initial magnetic field configuration; 2) initiate plasma within the vacuum vessel; 3) inductively drive plasma current; and 4) control plasma position and shape. For the initial "day 0" 1st plasma operations (Feb. 1999), the system was limited to closed loop proportional-integral current control of the power supplies based on preprogrammed reference waveforms. For the next "day 1" phase of operations beginning mid-summer 1999 the loop will be closed on plasma current and position. The ultimate "day 2" system is envisioned to include real time reconstruction of the plasma internal current distribution so that control can be exercised over internal plasma parameters such as current and pressure profile.

This paper addresses the day 1 system, with emphasis on the magnet power supply control. Companion papers address plasma control [2,3].

I. INTRODUCTION

A cross section of the NSTX device is shown in Figure 1. Parameters and ratings are summarized in Table 1. A hydrogen (deuterium) plasma is contained in an axi-symmetric toroidal vacuum chamber surrounded by water cooled copper magnets which carry current in the toroidal and poloidal directions to produce poloidal field (PF) and toroidal field (TF), respectively. The plasma current I_p flows in the toroidal direction. The net magnetic field is predominant in the toroidal direction but with a helical twist due to the poloidal field from the PF coils and plasma. Plasma particles tend to follow the magnetic field lines and are thereby confined. The vertical component of the magnetic field in the z direction (B_z) exerts radial $J \times B$ force on the plasma particles and the radial component B_r a horizontal force. The plasma cross sectional shape and current profile result from an equilibrium force balance between the $J \times B$ forces arising from the applied fields and the plasma current, along with its kinetic gas pressure.

Table 1
NSTX Parameters and Ratings

Major Radius (R_0)	85.4	cm
Aspect Ratio (R/a)	1.25	-
Plasma Current	1.0	MA
Toroidal Field @ R_0 (max.)	6.0	kG
Plasma Ramp Time	0.2 - 0.4	sec
Plasma Flat Top (max.)	5.0	sec
Repetition Period (min.)	300.0	sec

Figure 1: Cross Section View of the NSTX Device

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During a pulse the typical sequence of events is as follows:

- Central Ohmic Heating (OH) solenoid coil is precharged
- TF is applied
- Fuel gas is injected
- OH coil current is rapidly decreased, such that toroidal loop voltage is generated to ionize the fuel gas
- Plasma current is driven by induction by OH coil
- PF coils are used to control plasma shape and position

A conceptual block diagram of the system is given in Figure 2. Typically, upon initiation of a pulse the Power Supply Real Time Controller (PSRTC) performs closed loop current control to precharge the OH coil, initiate the TF coil current, and pre-bias other PF coils as required. Then, at the start of a pre-programmed time window, the Plasma Real Time Controller [1,2] initiates the plasma and controls plasma current, position, shape, etc. via voltage requests to the PSRTC. Upon termination of the plasma current the PSRTC extinguishes the current in all coil systems according to pre-programmed current derivatives.

Figure 2: Conceptual Block Diagram of Control System

II. POWER SUPPLIES & CIRCUITS TO BE CONTROLLED

A. Power Supplies

The PPPL "Power Supplies" (PS), consist of thirty nine (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 subject to the same "Firing Generator" (FG). Each PSS is

equipped with a full rated bypass module which can carry the load current when the rectifiers are suppressed. Each PSS is rated to produce a maximum average DC output voltage of 1012.85VDC ($\approx 1\text{kV}$), no load, with 13.8kV AC input voltage applied to the converter transformer primary. Nominal pulse current rating of each PSS is 24kA-6sec/300sec. The FG of each PS controls, in effect, the voltage produced by its two PSS by phase controlling the thyristor firing pulses in accordance with a Control Word received as an input from the PSRTC. The Control Word is an 11 bit digital command.

B. Circuits

Circuit types to be controlled are as depicted in Figure 3, where the boxed thyristor symbol represents one or more PSS connected in series/parallel combination. The lines connecting the circles represent removable bus links.

Figure 3: NSTX Circuit Configurations

- Type I is a "Unipolar", "2-Wire" circuit. Current flows in one direction through one load coil group.
- Type II is a "Unipolar", "3-Wire" circuit. Current flows in one direction through two load coil groups; the magnitude of the current may be different in the two "twin" load coil groups.
- Type III is a "Bipolar", "2-Wire" circuit. Current flows in either direction through one load coil group.
- Type IV is a "Bipolar", "3-Wire" circuit. Current flows in either direction through two load coil groups; the magnitude and polarity of the current may be different in the two "twin" load coil groups.

A listing of the NSTX circuits along with type, number of DC poles, and number of PSS is given in Table 2.

Table 2
NSTX Circuit Types, Poles, and PSS

Circuit	Type	DC Poles	Series/Parallel PSS
TF	I	2	1/4
OH	III	2	6/2
PF1a Upper	II	3	2/1
PF1a Lower			2/1
PF1b	I	2	2/1
PF2 Upper	II	3	2/1
PF2 Lower			2/1
PF3 Upper	IV	3	2/1
PF3 Lower			2/1
PF4/5	I	2	2/1
CHI	I	2	2/2
Spare		2	2
Total	12 ckt	21 pole	42 PSS

The voltage applied to, or the current produced in, each of the circuits must be explicitly controlled. Therefore, eleven (11) separate sub-circuit control loops are required in case all of the bus links are in place, plus one spare, for a total of twelve (12). However, it is noted that if the bus links are not installed in the Type II and Type IV circuits, then they reduce to Type I and Type III, respectively, and the number of explicit control loops is correspondingly reduced. When the bus links are not in place two halves of the former Type II or Type IV circuits are treated in all respects by the PSRTC as single Type I or Type III circuits, respectively. Currents in twenty one (21) poles are measured and monitored.

III. POWER SUPPLY REAL TIME CONTROLLER

A. Power Supply Control Function

The Power Supply Control Function is depicted in Figure 4. The same basic function is applied to all of the circuits. The output of the control function consists of the firing angle (α) and convert bit commands which are delivered to the PS in the form of the PS Control Words. Since the firing angle is related to the voltage, these commands are, essentially, voltage commands. The voltage commands are derived either from closed loop proportional - integral (PI) current control against a programmable reference, or from a direct voltage request. The direct voltage request is obtained from either a programmable reference, or a signal supplied in real time by the PRTC. When in the voltage control mode, a current clamp feature is applied if the current approaches a programmable limit. Additional features include rate limiting, and control of antiparallel rectifiers, including the required α limiting.

Following is a description of these features, with reference to Figure 4.

1) Closed Loop Current Control

The load current I_{load} is subtracted from a programmable reference $I_{reference}$. The difference is the error I_{error} . I_{error} is multiplied by proportional gain G_p , and is integrated and multiplied by integral gain G_i . The sum of these two terms is the voltage requested by current control $V_{current}$. The integrator includes an "anti-wind-up" reset feature which is a function of time; one reset time shall be allowed per circuit.

2) Voltage Control & Current Clamp

The source of the command $V_{command}$ can be either the programmable reference $V_{reference}$ or a real time signal provided by the PRTC V_{PRTC} . The time window during which V_{PRTC} is enabled shall correspond to the PCW. Voltage control is subject to an override by a current clamping feature which comes into play when limits are reached. The clamping is based on PI control which generates a voltage adjustment term V_{clamp} whenever the load current I_{load} passes outside the range between the positive and negative clamp settings $I_{clamp} > 0$ and $I_{clamp} < 0$. When the current returns to the allowable range the clamp integrator is reset. The net voltage request based on voltage control $V_{voltage}$ is the result of the addition of $V_{command}$ and V_{clamp} .

3) Voltage to Alpha Conversion

The selection of the source of the voltage request V_0 from either voltage control $V_{voltage}$ or current control $V_{current}$ is a function of time. V_1 is the per unit version of V_0 based on $V_1 = V_0 / V_{max}$, where V_{max} is the maximum no-load voltage available for the circuit in question. V_{max} is based on the programmable number of series PSS (NS), and the primary side AC rms line-to-line source voltage E (nominally 13.8kV at D-site). V_2 is a rate and magnitude limited version of V_1 , where the rate limit is programmable for each circuit and the magnitude limit is -1 to 1 per unit. The rate limit is only applied when the antiparallel mode is in effect (see next section). α_0 is the firing angle request, and α_1 is the final firing angle command after limiting. If antiparallel operation is not in effect, then the allowable range of α_1 is 0 to α_{max} , where α_{max} is the maximum permissible delay angle. It is calculated based on the load current per PSS, equal to I_{load}/NP where NP is the number of parallel PSS branches in the circuit being controlled, the AC source frequency ω , the commutating inductance L_c , and the AC source voltage E , along with a programmable inversion margin angle γ . If antiparallel operation is in effect, then the minimum permissible delay angle α_{min} is set equal to $180 - \alpha_{max}$, so that the allowable range of alpha is therefore $\alpha_{min} \leq \alpha_1 \leq \alpha_{max}$ in the antiparallel mode.

- Themis host computer (Sparc 10 running Sun OS)
 - ethernet connectivity
 - user interface
 - data management
 - software development
- Skybolt I Shamrock real time computer
 - four parallel Intel 80860 processors
 - 64MB shared memory
 - DMA port
- Precision Filters data acquisition system
 - two 32 channel analog input modules
 - 10kHz
 - DMA to Skybolt
- Power Conversion (PC) Link driver
 - interface to serial command link which distributes commands to 39 distributed PS at PPPL facility

The PSRTC occupies one of the four parallel i860 processors; the other three are available to the PRTC. The control system update rate is 1kHz (once per millisecond). Typical execution time of the PSRTC algorithms with all circuits running is less than 800 μ S.

The PSRTC utilizes 47 of the 64 DAS channels available. The remainder are reserved for the PRTC Ip, flux loop, and B probe signal inputs. These signals are transmitted from the transducers located in the NSTX test cell to the location of the control computer rack via analog fiber optic links.

F. Future Plans

A graphical user interface is under development to provide capability for editing the text files used to input the control and waveform data.

An upgrade to a new computer system [3] is planned for late 1999 (a.k.a. "day 2"). This will include:

- Upgraded Themis host computer
- Upgraded Sky computer
- Distributed data acquisition system based on multiple VME crates strung together using fiber optic links and Front Panel Data Port (FPDP) direct access to the real time processor.

The new computer system is not required in principle for the PSRTC but will instead facilitate an advance in the PRTC development, including more than a doubling of the number of inputs.

IV. REFERENCES

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