National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment-Upgrade

NSTX-U

SYSTEM REQUIREMENTS DOCUMENT

Real-time Control and Protection

NSTX-U-RQMT-SRD-008-01

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Change Record

Revision	Date	Description of Change
0	7/25/18	Initial Release
1	11/19/19	Replace WBS by SBS everywhere
		Removed 5.3.1b and 5.3.2b
		Rewrite of 5.4
		Updated signatures to account for recent personnel changes
		Updated interface tables for recent design evolution

Table of Contents

References

[1] NSTX-U-RQMT-GRD-001, *NSTX-U General Requirements Document*
[2] ENG-010 *Control of Drawings*
[3] ENG-023 *Electrical Equipment Approva*l
[4] NSTX-U-RQMT-SRD-009, *Central Instrumentation and Control System Requirements Document*
[5] C-NSTX-PTP-ECS-060 *NSTX-U Control System Latency Testing*
[6] NSTX-SRD-13-163 *Digital Coil Protection System Software Requirements Document*
[7] NSTX-SRD-13-170, Rev 0 *Digital Coil Protection System Algorithm Requirements Document*

1.0 Scope

a. This document describes the following elements:

1. Real-time data stream
2. Real-time plasma control computer and software
3. Digital Coil Protection System
4. Coil electrical protection system
5. The Ip-Calculator
6. The Pulse Duration and Period Timer

b. The format of this document, including interfaces specifications, is provided in the General Requirements Document [1].

2.0 Real-time Data Stream

2.1 Functions

a. The functions of the real-time data stream are:

1. Bring analog and digital data from locations distributed throughout the NSTX-U facility to the real-time control computers.
2. Send commands from the realtime plasma control computer to NSTX-U actuators.

2.2 Materials and Design Requirements

a. The System shall be designed to conform to electrical isolation requirements as defined in the GRD [1] Section 4.2.3 Part b and Part c.

b. A combination of industry standard and in-house designs shall be used to implement the NSTX-U Real-Time Data Stream.

c. Where practical, equipment, communication protocols, and software will be utilized that is commercially available and supported by vendors or open source software communities.

d. When equipment must be designed in-house for a specific purpose, it shall conform to industry and PPPL engineering procedures defined for electronics (ENG-023 [3]) and software .

e. The use of material in the construction of this system shall conform to industry standards wherever practical following Reduction of Hazardous Substances (RoHS) directives and other industry mandates.

2.3: Configuration Requirements and Essential Features

<u>Input stream</u>

a. The real-time input stream shall be capable of analog and digital inputs. Other input types may additionally be defined as needed for specific applications.

b. The real-time input stream shall have input modules distributed as necessary throughout the NSTX-U plant, with channel counts based on current needs as well as anticipated future demands of the evolving research program[1].

[1] The data from these input modules may be concatenated into a smaller number of data streams as necessary to interface to the control computers.

c. The input data stream shall have modules or mechanisms to identify timing, i.e. timestamps or time markers.

d. The input data stream shall be provided to the primary real-time control system.

e. An identical input data stream shall be provided to a secondary real-time control system used, for development and as hot-spare, without compromising the primary control system data input.

f. Modules of the input stream located in different rooms or test cell ground classes shall have electrical ground separation.

g. Locations for input modules shall include, but not necessarily be limited to, the locations in Table 2.3-1 and Table 2.3-2.

Table 2.3-1*: Analog Input data stream channels*

Location	**Purpose**
D-Site Diagnostic DARM	Physics diagnostic data
D-Site 138’ NB Control Area	Neutral beam current, voltage, and power signals
NSTX-U Test Cell, Outer Vessel Referenced Racks	Magnetic diagnostic signals
NSTX-U Test Cell, Inner Vessel Referenced Racks	Magnetic diagnostic signals
Gas Injection Racks, North Gallery Area	Signals associated with the vessel pressure and gas injection system
Switching Power Supply (SPA) Room in FCPC 2nd Floor	SPA current and voltage, control signals
D-Site Junction Area	Coil currents, I_P Calculator Signals, Rectifier Branch Currents, Timing Signals, Other

Table 2.3-2*: Digital input data stream channels*

Location	**Purpose**
Junction Area	Coil fault flags, fault override status flags, reset flags
Gas Injection System, North Gallery Area	Valve status signals, calorimeter input status
D-Site 138’ NB Control Area	Loopback of NB control signals

Output stream

a. The real-time output stream shall be capable of analog and digital outputs. Other output types may additionally be defined as needed for specific applications.

b. The real-time output stream shall have output modules distributed as necessary throughout the NSTX-U plant, with channel counts determined as needed by the evolving demands of the research program.

c. Modules of the output stream located in different rooms or test cell ground classes shall have electrical ground separation.

d. Output channels shall be of sufficient quantity and distribution to control the actuators in Table 2.3-3.

Table 2.3-3: *Actuators controlled by the output data stream*

Actuator	**Actuator Location**	**# of channels**
FCPC Rectifiers	1st Floor, Field Coil Power Conversion Building, both TF and PF wings	Sufficient to control the voltage output of all FCPC TRANSREX Rectifiers (firing angle and digital input data such as convert and block bypass)
Switching Power Amplifiers	2nd Floor FCPC SPA Room	Sufficient to control the current output of six SPA sub-units (Reference voltage digital input data)
Neutral Beams	D-Site 138' Level	Sufficient to control the on-off status of six neutral beam sources
Gas Injection System	GIS Racks in North Gallery north door	Sufficient to control all gas injectors
Granule Injector	GIS Racks outside NTC north door	Sufficient to control the impeller speed and dropper on/off status.

2.4 Baseline Performance and Operational Requirements

a. The input datastream shall deliver a full set of input data to each client system at a minimum of 5 kHz.

b. The output datastream shall deliver a full data set of commands to actuators at a minimum of 5 kHz.

2.5 Upgrade Performance and Operational Requirements

a. Expansion of the input and output streams to additional locations within the PPPL infrastructure may be required.

b. Provision of additional I/O channels or types at existing or future locations may be required.

c. Input or output streams of varying sample rates may be required.

2.6 Interfaces

Table 2.6-1*: Interfaces for the realtime data stream (SBS 1.7.3.6.1)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.3.1.2	Vacuum Gauges and Residual Gas Analyzers	Electrical Signal	Breakout panel of SAD	Vacuum pressure measurements provided to the real-time data stream	CWD
1.3.4.5	Valve Driver and Interface Systems	Electrical Signal	Output cable of realtime digital output module	All gas injection system control information is delivered by digital output modules from the realtime data stream; gas system signals are often archived by the stream	CWD
1.5.2.1	TF Power Systems Converters	Fiber Optic	At fiber optic interface to the firing generator	Reference firing angles are provided to the TF rectifiers from the Realtime Data Stream	CWD
1.5.2.2	OH Power Systems Converters	Fiber Optic	At fiber optic interface to the firing generator	Reference firing angles are provided to the OH rectifiers from the Realtime Data Stream	CWD
1.5.2.3	PF Power Systems Converters	Fiber Optic	At fiber optic interface to the firing generator	Reference firing angles are provided to the PF rectifiers from the Realtime Data Stream	CWD
1.5.2.4.2	SPAs Inverters	Fiber Optic	At SPA reference input connector	Reference currents, in the form of an analog voltage, are provided by the Realtime Data Stream	CWD
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	At penetration	Fibers go through penetrations	N/A
1.8.1.1.2	NTC Cable Trays	Structural	At tray	Fibers reside in cable trays	N/A
1.4.1.5.1	Toroidal CHERS	Electrical Signal	Acquisition Devices in Darm Crate	Plasma rotation measurements in realtime are provided from the subset of fast CHERS spectrometers and computers	CWD
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	Output of Integrators (Cat4,3 Crates)	Magnetics measurements for realtime control	CWD
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	Gas Control Crate	Granule Injector Control Signals	CWD
1.7.3.6.8	Ip Calculator System	Electrical Signal	At breakout panel of the SAD	The IP calculator output is given to the FPDP stream for real-time control	CWD
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for the FPDP data stream at various locations	N/A
1.4.1.2.2	Mirnov and Flux Loop System	Electrical Signal	At realtime digitizer input	Some signals from flux loops are directly digitized by the realtime stream w/o any intermediate integrator (there is likely a passive voltage divider in these cases).	Spreadsheet
1.5.2.4.1	SPA DC Link	Fiber Optic	At fiber optic interface to the firing generator	Reference firing angles are provided to the OH and PF rectifiers from the Realtime Data Stream	CWD
1.7.3.6.5	DCPS Hardware Interface, Expansion Chassis & WDTs	Electrical Signal	At SAD	Currents are provided to the FPDP stream through the expansion chassis	CWD
1.7.3.6.2	Control Real Time	Fiber Optic	At fiber	The real-time computer collects	CWD

	Linux Computers		connecting to computer	data from the real-time data stream, and sends commands out on the stream	
1.7.3.6.9	Shorted Turn Protection System	Fiber Optic	At card in back of computer	Voltages, currents, and timing information are provided to the Shorted Turn System realtime computer via the FPDP stream	CWD
1.7.3.6.9	Shorted Turn Protection System	Electrical Signal	At SAD	Shorted Turn Protection Interconnection system provides voltage data to the FPDP data stream	CWD

3.0 Realtime Plasma Control Computer and Software

3.1 Functions

The functions of the real-time plasma control hardware and software are:

a. Receive data from the real-time input data stream.

b. Format the input data stream for consumption by algorithms.

c. Deterministically execute a heterogeneous collection of algorithms

d. Generate output commands based on execution of algorithms or from a preprogrammed source

e. Provide output commands to the output data stream.

3.2 Materials and Design Requirements

a. The system shall use reliable, enterprise-class hardware components.

b. The operating environment[2] shall provide deterministic, real-time behaviour.

3.3: Configuration Requirements and Essential Features

a. The system shall have a mechanism for calibrating all input data. This may include
    a. Decoding the digitizer data to its respective voltage range,
    b. Conversion from electrical units to physics/engineering units (A, V, etc.)
    c. Baseline subtraction, including a sloped baseline to account for integrator drift for magnetic sensors.

[2] The Operating Environment (OE) includes the Operating System (OS) and all supporting technologies, such as the BIOS, other firmware, drivers, user space tools, system configurations, etc.

b. The system shall have a graphical user interface allowing the operator to configure the software and provide reference values, gain settings, and other input data.

c. The system shall be capable of executing heterogeneous algorithms based on the realtime input data, operator inputs, and other configuration settings.

d. The system shall produce output commands for all configured output modules.

e. The system shall allow algorithms to deterministically exchange data.

f. The system shall allow the choice of which algorithm to execute from pre-defined groups on a per-cycle basis.

g. The system shall have the capability to switch which algorithm controls a given actuator or provides a given piece of data to a subsequent algorithm, based on either pre-determined changes in the algorithm sequence or as a result of detected events.

h. The system shall be capable of using multiple cores for algorithm execution.

i. The system shall be capable of restoring entire or partial pulse configurations from archive for inspection and running future pulses.

j. The system shall allow optional configuration settings to be automatically skipped when restoring from archive.

k. The system shall archive all input data in both raw and calibrated form.

l. The system shall archive all attempted output commands.

m. In the event of a full hardware failure, the system shall be recoverable in less than 4 hours.

n. The system shall restrict configuring designated algorithms to an administratively controlled list of authorized users.

o. Without assuming the role of other protection systems, the plasma control system shall enforce limits on operator inputs.

p. The system shall record all changes in pulse configuration with timestamp and user identity.

3.4 Baseline Performance and Operational Requirements

a. The system shall operate with a maximum 0.2 msec periodic. Some more complex numerical algorithms may require multiple cycles to complete execution.

b. The control system latency, including the input/output stream, as measured through the vertical control loop shall, be less than 800µs.

c. The system shall have capabilities for the simultaneous operation of the following control algorithms:
    a. Generation of firing angle and reference current commands for FCPC rectifiers and Switching Power Amplifiers (SPAs), based on input voltage and current requests.

    b. Real-time solution of the Grad-Shafranov equation, constrained by input data

    c. Plasma boundary shape control in limited and diverted configuration, based on either magnetic sensor data alone or the equilibrium output from the Grad-Shafranov solver

    d. Gas valve control, including pulse width modulation on piezo valves, based on either feed-forward control or feedback from real-time measurements

    e. Neutral beam status control, based on either feed-forward commands or profile control algorithms

    f. Analysis of 3D perturbations from magnetic sensors, and development of SPA current requests based on feedback operations on those perturbations.

    g. Lithium granule injector (LGI) status control, based on either feed-forward or feedback commands.

d. Additional algorithms shall be expected, and this list shall be used for conceptual guidance only.

e. The system shall be designed such that it satisfies the FMEA design criteria in the GRD [1]. System failures shall be reduced to being an "Extremely unlikely Event" as defined in Table 4.2.1.1-1

3.5 Upgraded Performance and Operational Requirements

a. The system shall be designed with the continued addition of algorithms anticipated. This may involve upgraded or additional hardware to support the required computation rate.

3.6 Interfaces

Table 3.6-1: *Interfaces for the Realtime Plasma Control Computer (SBS 1.7.3.6.2)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.7.3.6.1	FPDP Data Stream	Fiber Optic	At fiber connecting to computer	The real-time computer collects data from the real-time data stream, and sends commands out on the	CWD

				stream	
0.1.1.3	PPPL Network Infrastructure	Ethernet	At connectors on computer	Computers have network access for various HMI, data acquisition, and data transfer functions	N/A
1.7.3.6.3	Real Time Control Software (PCS, FPDP)	Software	N/A	Realtime software runs on the realtime computer	N/A

***Table 3.6-1**: Interfaces for the Realtime Plasma Control Software (SBS 1.7.3.6.3)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.7.3.6.2	Control Real Time Linux Computers	Software	N/A	Realtime software runs on the realtime computer	N/A
1.6.2.2	Data Archiving Systems	Software	Network Interface	Archived data, including data that is used for shot restores, is archived in the MDS+ database	MDS+ API

4: Digital Coil Protection System

4.1 Functions

The functions of the digital coil protection system (DCPS) are:

a. Prevent an overheating or over-current condition on the coils.

b. Prevent temperature difference between OH coil and TF where TF is hotter than OH.

c. Prevent excessive forces, stresses, and moments on coils and their mounting structures as well as combinations of the former.

d. Prevent current from flowing during the time between pulses, defined by the time between two timing events 'End Of Pulse' (EOP) and 'Start Of Pulse' (SOP) provided by the Timing Synchronization System [4].

4.2 Materials and Design Requirements

The protection from mechanical stresses is provided by algorithms executing within the DCPS. The systems shall:

a. The System shall be designed to conform to electrical isolation requirements as defined in the GRD [1] Section 4.2.3 Part b and Part c.

b. A combination of industry standard and in-house designs shall be used to implement the DCPS.

c. Where practical, equipment, communication protocols, and software will be utilized that is commercially available and supported by vendors or open source software communities.

d. When equipment must be designed in-house for a specific purpose, it shall conform to industry and PPPL engineering procedures defined for electronics (ENG-023 [3]) and software.

e. The use of material in construction of this system shall conform to industry standards wherever practical following Reduction of Hazardous Substances (RoHS) directives and other industry mandates.

f. Be built using standard engineering practices for real-time systems

4.3: Configuration Requirements and Essential Features

4.3.1: Robustness

a. Two separate DCPS instances shall be installed and operated without allowing for degraded operation.

b. Hardware systems associated with DCPS shall detect duty-cycle failures[3].

4.3.2: Input Data

a. The system shall have as input data redundant measurements of the following currents:
   i. TF coil
   ii. OH coil
   iii. All PF coils
   iv. Plasma.

b. The system shall adjudicate between the redundant measurements using a fail-safe, worst-case method.

c. The system shall convert the input data stream to the physics and engineering representation required by the algorithms.

4.3.3: System Timing

a. The system shall operate in tandem with the existing facility clock.

b. The system shall define two discrete states of active protection aligned with the facility clock:
   i. During a pulse

[3] Duty-cycle failures here refer to events where the system stops operating unexpectedly.

ii. Between pulses

4.3.4: Algorithms

a. The system shall perform deterministic, real-time calculations of algorithms necessary to protect the coils and their supports from mechanical and thermal failure outside their design limits meeting the requirements defined in [6] and [7].

b. The system shall ensure that the coils are protected both between pulses and during pulses.
   i. There shall be no current allowed in any coil between pulses.
   ii. The system shall execute predefined protection algorithms during a pulse.

4.3.5: Algorithm Configuration, Limit Values, and Faults

a. Algorithms shall be configurable offline
   i. Configuration shall include both the internal parameters of an algorithm along with the limits against which it is evaluated
   ii. Configurations shall be secured from accidental or intentional tampering.
   iii. Configurations shall be validated and verified before use.
   iv. The user shall be able to add and modify algorithms through configuration changes to adapt to changing operational scenarios.

b. There shall be a single fault response for any declared fault resulting in, at a minimum, the following:
   i. Prevention of further plasma operations
   ii. Deenergizing of all coils
c. The system shall assert a fault within 1.0 ms following detection of any of the following conditions:
   i. Duty-cycle failure
   ii. Redundant input mismatch
   iii. Any algorithm exceeding its configured limit

d. Faults shall be fail-safe.

e. Faults shall require an operator action to clear.

4.3.6: Archiving

a. The system shall archive at a minimum all calculation results, fault outputs, and necessary internal state.

b. Data archives shall be immutable once created.

4.3.7: Modes of Operation

a. The online protection mechanisms shall be fail-safe.

b. The system shall allow fail-safe reconfiguration without compromising protection.

c. The system shall support offline testing using pulse archives or custom waveforms as input.

4.4 Baseline Performance and Operational Requirements

a. The system shall enforce the protections defined in section 4.3 with limit values tailored to a maximum latency of 1ms.

b. The system shall be designed such that it satisfies the FMEA design criteria in the GRD [1]. System failures shall be reduced to being an "Extremely unlikely Event" as defined in Table 4.2.1.1-1

4.5 Upgrade Performance and Operational Requirements

a. There are no planned upgrades to the DCPS.

4.6 Interfaces

Table 4.6-1: *Interfaces for the DCPS Autotesters (SBS 1.7.3.6.4)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.7.3.6.5	DCPS Hardware Interface, Expansion Chassis & WDTs	Electrical Signal	Where cables from computer plug into hardware interface	The autotester connects to the hardware interface, where it can then be directed throughout the DCPS system pending the selection of key cards.	CWD
1.6.2.2	Data Archiving Systems	Software	At ethernet port	Data from the DCPS Autotester is directly archived in MDS+	MDS+ API
0.1.1.3	PPPL Network Infrastructure	Ethernet	At connectors on computer	Computers have network access for various HMI, data acquisition, and data transfer functions	N/A
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	power for the DCPS autotesters	N/A

Table 4.6-2: *Interfaces for the DCPS Hardware Interface, Expansion Chassis & WDTs (SBS 1.7.3.6.5)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.5.3.2	OH Convertor DC Systems	Electrical Signal	At input to HSC	The signal from the OH current transducers in FCPC are provided DCPS hardware, which subsequently directs them to the Halmar signal	CWD

				conditioners	
1.5.3.3	PF Convertor DC Systems	Electrical Signal	At input to HSC	The signal from the PF current transducers in FCPC are provided DCPS hardware, which subsequently directs them to the Halmar signal conditioners	CWD
1.6.1.1	Control I/O systems	Electrical Signal	Electrical Connection	Control I/O system used to provide DCPS I/O functionality from Plant Control and Monitoring (EPICS) via the Hardware Interface	CWD
1.5.4.1	Hardwired Control System & PLC	Electrical Signal		Output: Level-1 Fault Indication	CWD
1.3.2.4	Water System PLC	Electrical Signal	Digitizer (SAD) in JA	Inputs: Status of water PLC	CWD
1.5.4.3	DCCT Signal Conditioners	Electrical Signal	Cross Connects in JA	HSCs are used in an integral fashion with the DCPS hardware system. HSC inputs are routed through the hardware system. HSC outputs are routed to the FPDP link and DCPS through the hardware system	CWD
1.7.3.6.8	Ip Calculator System	Electrical Signal	Connectors on front of the level 1 expansion chassis	Fault from the IP shall pass through the DCPS Level 1 expansion chassis	CWD
1.7.3.5.1	PDP Timer	Fiber Optic	Output of PDP	PDP sends status signals to DCPS	CWD
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for the DCPS hardware	N/A
1.7.3.6.4	DCPS Autotesters	Electrical Signal	Where cables from computer plug into hardware interface	The autotester connects to the hardware interface, where it can then be directed throughout the DCPS system pending the selection of key cards.	CWD
1.7.3.6.7	DCPS Realtime Linux Computers	Electrical Signal	At connectors on computer	Input signals to the computer are routed through the hardware system	CWD
1.6.1.1	Control I/O systems	Electrical Signal	Digitizer (SAD) in JA	Pulse Timing of the Digitizer (SAD) in JA	CWD
1.6.1.3	Timing and Synchronization System	Electrical Signal	At digital input to DCPS	Sampling clock for digitizers at digital input to DCPS	CWD
1.7.3.6.9	Shorted Turn Protection System	Electrical Signal	At panel on hardware interface	STP L1 faults transferred to HCS via the DCPS interface	CWD
1.7.3.6.1	FPDP Data Stream	Electrical Signal	At SAD	Currents are provided to the FPDP stream through the expansion chassis	CWD

Table 4.6-1*: Interfaces for the DCPS Software (SBS 1.7.3.6.6)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.7.3.3	Digital Coil Protection System (DCPS) Algorithms	N/A	N/A	Algorithms run within the context of the DCPS software	N/A
1.6.2.2	Data Archiving	Software	At ethernet	DCPS Software Outputs:	MDS+ API

	Systems		port	Archived data, including data that is used for shot restores, is archived in the MDS+ database	
1.7.3.6.7	DCPS Realtime Linux Computers	N/A	N/A	DCPS software runs on the DCPS computers	N/A

***Table 4.6-1**: Interfaces for the DCPS Realtime Computers (SBS 1.7.3.6.7)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for the DCPS realtime computer	N/A
1.7.3.6.6	DCPS Software	N/A	N/A	DCPS software runs on the DCPS computers	N/A
1.7.3.6.5	DCPS Hardware Interface, Expansion Chassis & WDTs	Electrical Signal	At connectors on computer	Input signals to the computer are routed through the hardware system	CWD
0.1.1.3	PPPL Network Infrastructure	Ethernet	At connectors on computer	DCPS realtime computer has a connection to PPPL network for various access	N/A

5: Shorted Turn Protection System

5.1 Functions

a. The shorted turn protection system is designed to detect internal coil turn-to-turn and layer-to-layer faults, as well as arcs across coil terminals and bus leads.

5.2 Materials and Design Requirements

a. The system shall have galvanic isolation from any coil or power supply terminals.

b. A fail-safe design philosophy shall be utilized for all components of the system.

5.3: Configuration Requirements and Essential Features

5.3.1: Input Data

a. The system shall have as input data redundant measurements of the following measurements[4]:
    i. TF coil current and voltage
    ii. OH coil current and voltage
    iii. All PF coils current and voltage
    iv. Plasma current

b. This requirement is removed.

c. The system shall adjudicate between the redundant measurements using a fail-safe, worst-case method.

d. The system shall convert the input data stream to the physics and engineering representation required by the algorithms.

e. The system shall have access to the plasma current data, from the plasma current Rogowski after compensation for vessel and linked-coil pickup.

f. The system shall take all configuration data from secure external input mechanisms. This may include:
    - Circuit parameters
    - Fault thresholds

5.3.2: Faults

[4] Coil voltage information, if needed, may be included from suitably isolated voltage transducers. Alternatively, voltage values may be taken from rectifier command data, if this information can be shown to provide sufficient sensitivity.

a. There shall be a single fault response signal for any declared fault. The declared fault shall result in, at a minimum, the following:
    i. Prevention of further plasma operations
    ii. Deenergizing of all coils

b. This requirement is removed.

c. This requirement is shifted.

d. Faults shall be fail-safe. Any fault in the system itself shall result in the assertion of the fault response.

5.3.3: System Timing

a. The system shall operate in tandem with the existing facility clock.
b. The system shall define at minimum two discrete states of active protection aligned with the facility clock:
    i. During a pulse, i.e. in the time from the Start-Of-Pulse (SOP) event to the End-Of-Pulse (EOP) event,
    ii. Between pulses, i.e. in the time from the EOP event to the SOP event.

5.3.4: Archiving

a. The system shall archive all input data, calculations, as well as its level-1 fault outputs.

5.4 Baseline Performance and Operational Requirements

a. The system shall be designed to detect low impedance electrical faults in the NSTX-U coil systems with minimum sensitivity sufficient to detect :
    i. terminal arcs on any NSTX-U coil system,
    ii. layer-to-layer faults on any PF coil system, or the OH coil system,
    iii. arcs between individual flags on the TF coils,
    iv. faults within individual TF outer legs,
    v. arcs between individual water feeds on the OH coil.

b. The system shall assert a fault within 1.0 ms following occurence of any of the following conditions:
    i. A coil fault / arc
    ii. Duty-cycle failure
    iii. Redundant input mismatch

c. The system shall have a nominal response time of 1.0 msec from the occurrence of the fault state to the reception of the fault signal at the HCS.

d. The system shall be designed such that it satisfies the FMECA design criteria in the GRD [1].

5.5 Upgrade Performance and Operational Requirements

a. Protection of the RWM coils may be included into the protection scheme at a later time.

5.6 Interfaces

***Table 5.6-1**: Interfaces for the Shorted Turn Protection System (SBS 1.7.3.6.9)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.6.1.1	Control I/O systems	Electrical signal	Network Interface	The data from the Shorted Turn Protection system are archived in MDS+ following the discharge	CWD
1.6.2.2	Data Archiving Systems	Software	At ethernet port	Data is archived to MDS+ by the shorted turn system	MDS+ API
1.5.3.1	TF Convertor DC Systems	TBD	TBD	Line and ground switch positions for the TF provided to the shorted turn protection system	TBD
1.5.3.2	OH Convertor DC Systems	TBD	TBD	Line and ground switch positions for the OH provided to the shorted turn protection system	TBD
1.5.3.3	PF Convertor DC Systems	TBD	TBD	Line and ground switch positions for the PF provided to the shorted turn protection system	TBD
1.5.3	Rectifier DC Systems	Electrical Signal	At output of signal conditioner	Power systems send Coil Voltages to	CWD
1.7.3.6.5	DCPS Hardware Interface, Expansion Chassis & WDTs	Electrical Signal	At panel on hardware interface	STP L1 faults transferred to HCS via the DCPS interface	CWD
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for shorted turn protection system	N/A
1.5.3.1.9	TF Voltage Measurements	Electrical Signal	At termination panel in the JA	Signals from voltage measurements in SDS cabinets are brought to Junction Area where they are interfaced to the Shorted Turn Protection Interconnections	CWD
1.5.3.2.9	OH Voltage Measurements	Electrical Signal	At termination panel in the JA	Signals from voltage measurements in SDS cabinets are brought to Junction Area where they are interfaced to the Shorted Turn Protection Interconnections	CWD
1.5.3.3.9	PF Voltage Measurements	Electrical Signal	At termination panel in the JA	Signals from voltage measurements in SDS cabinets are brought to Junction Area where they are interfaced to the Shorted Turn Protection Interconnections	CWD
1.7.3.6.1	FPDP Data	Fiber Optic	At card in back	Voltages, currents, and timing	CWD

	Stream		of computer	information are provided to the Shorted Turn System realtime computer via the FPDP stream	
1.7.3.6.1	FPDP Data Stream	Electrical Signal	At SAD	Shorted Turn Protection Interconnection system provides voltage data to the FPDP data stream	CWD

6: I_p Calculator

6.1 Functions

The I_p Calculator is designed to complete two functions:

a. Provide calibrated and compensated[5] plasma current signals for use by various other systems.

b. Provide permissive signals to other systems based on the plasma current level and the various other signals.

6.2 Materials and Design Requirements

a) The System shall be designed to conform to electrical isolation requirements as defined in the GRD [1] Section 4.2.3 Part b and Part c.

b) A combination of industry standard and in-house designs shall be used to implement the NSTX-U Plant Control I/O system.

c) Where practical, equipment and software shall be utilized that is commercially available and supported by vendors.

d) When equipment must be designed in-house for a specific purpose, it shall conform to industry and PPPL conventions for electrical, electronic, and software engineering.

e) The use of material in construction of this system shall conform to industry standards wherever practical following Reduction of Hazardous Substances (RoHS) directives and other industry mandates.

f) Redundancy shall be used for increased reliability.

6.3: Configuration Requirements and Essential Features

a. The system shall process the signals from two plasma current (I_p) Rogowski coils.

b. The system shall compensate the signal by subtracting all linked currents from the Rogowski, as captured by the following equation:

$$I_P = I_{rog} - I_{VV} - N_{1bU} I_{1bU} - N_{1bL} I_{1bL} - N_{1cU} I_{1cU} - N_{1cL} I_{1cL}$$

I_P : Plasma current
I_{rog} : Current measured by the Rogowski
I_{VV} : Toroidal Vacuum vessel current
$I_{1bU}, I_{1bL}, I_{1cU}, I_{1cL}$: Currents in the coils PF-1bU, PF-1bL, PF-1cU, PF-1cL

[5] Here, calibrated refers to the conversion from output volts to current. Compensation refers to the removal of signal components so as to isolate the plasma current signal.

$N_{1bU}, N_{1bL}, N_{1cU}, N_{1cL}$: Number of turns in the coils PF-1bU, PF-1bL, PF-1cU, PF-1cL

c. There are 2 equations calculated, Ip High Gain and Ip Low Gain. The unique term in each equation is Irog High Gain and Irog Low Gain. The scale factors for the outputs are: Ip High Gain: 100 kA/V and Ip Low Gain: 1000 kA/V

d. The vacuum vessel current shall be derived from a weighted sum of loop voltages, i.e. $I_{VV} = \Sigma\alpha_i V_{loop.i}$. Eight flux loops on the CS assembly and 16 flux loops on the vacuum vessel, passive plates, and outboard divertors shall be used in this summation. The weights shall be α_i shall be determined by project physics.

e. The system shall produce permissive signals to other systems by comparing the calculated plasma current against thresholds, where the thresholds shall be independently adjustable.

f. Internal failures of the system shall produce a system fault that prevents plasma operation.

g. External pulse timing information shall be provided by the facility clock.

6.4 Baseline Performance and Operational Requirements

a. The system shall produce a low-gain and high-gain output for each Rogowski, with full-scale outputs of 10,000 kA for the low-gain and and 1000 kA for the high-gain output[6] .

6.5 Upgrade Performance and Operational Requirements

There are no proposed upgrades to the system.

6.6 Interfaces

***Table 6.6-1**: Interfaces for the I_p Calculator (SBS 1.7.3.6.8)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.7.3.6.1	FPDP Data Stream	Electrical Signal	At breakout panel of the SAD	The IP calculator output is given to the FPDP stream for real-time control	CWD
1.7.3.6.5	DCPS Hardware Interface, Expansion Chassis & WDTs	Electrical Signal	Connectors on front of the level 1 expansion chassis	Fault from the IP shall pass through the DCPS Level 1 expansion chassis	CWD
1.6.1.3	Timing and Synchronization System	Electrical Signal	At connector on Ip Calculator Chassis	Pulse events (Start, T0, End) At connector on Ip Calculator Chassis	CWD
1.6.1.1	Control I/O systems	Electrical Signal	At input to Ip Calculator chassis	Data from Ip Calculator is digitized for archival in MDS+	CWD
1.2.4.7	Neutral Beam Control Systems	Fiber Optic	At output of IP Calculator Permissive	NB Permissive is removed, with delay, when plasma current drops beneath threshold	CWD

[6] The high gain setting provides better resolution for lower current values.

1.2.1	High Harmonic Fast Wave (HHFW)	Electrical Signal	At output of IP Calculator Permissive	HHFW Permissive is removed, with delay, when plasma current drops beneath threshold	CWD
1.8.1.1.5	NTC Penetrations	Wall/Floor Penetration	At penetration	Fibers go through penetrations	N/A
1.8.1.1.2	NTC Cable Trays	Structural	At tray	Fibers reside in cable trays	N/A
1.4.1.2.5	Digitizers and Integrators	Electrical Signal	At input to fiber optic transmitter in NTC	Plasma current signal brought from integrator output to the FO transmitter	CWD
1.4.1.2.2	Mirnov and Flux Loop System	Electrical Signal	At input to the electronics chassis in the NTC	Poloidal flux loops are used to generate estimates of the current flowing in the vessel under loop voltage.	CWD
1.5.4.3	DCCT Signal Conditioners	Electrical Signal	At input to Ip Calculator chassis	Data from HSCs is input to the Ip Calculator, and some data from the Ip calculator is distributed via the HSCs	CWD
1.5.1.2	D-Site Auxiliary Power	Electrical Power	wall plug	Power for the Ip Calculator	N/A
1.4.1.2.1	Plasma Current Rogowski System	Electrical Signal	Through integrators	Integrated signal from plasma current Rogowski coil provided to Ip Calculator system	Schematic

7: Pulse Duration and Period Timer

7.1 Functions

a. The function of the Pulse Duration and Period Timer (PDP) is to enforce:

- A maximum duration for which the FCPC power supplies can be enabled, and
- A minimum duration between pulses

7.2 Materials and Design Requirements

a. The System shall be designed to conform to electrical isolation requirements as defined in the GRD [1] Section 4.2.3 Part b and Part c.

b. A combination of industry standard and in-house designs shall be used to implement the Pulse Duration Timer.

c. Where practical, equipment and software shall be utilized that is commercially available and supported by vendors.

d. When equipment must be designed in-house for a specific purpose, it shall conform to industry and PPPL conventions for electrical, electronic, and software engineering.

e. The use of material in construction of this system shall conform to industry standards wherever practical following Reduction of Hazardous Substances (RoHS) directives and other industry mandates.

7.3: Configuration Requirements and Essential Features

a. The two durations t_{period} and t_{allow} shall be user configurable in the range from 0 seconds to 1999 seconds for t_{period} and in the range from 0.0 seconds to 99.9 seconds for t_{allow} .

b. There are two (2) PDP timers: One for the OH system and one for the PF/TF system. The PF/TF timer connects to legacy solid state relays which in turn generate permissive signals to the HCS system. The OH PDP timer connects to a PLC system which in turn generates a permissive to the HCS system.

7.4 Baseline Performance and Operational Requirements

a. The PDP timer shall have three states: WAIT, ALLOW and INHIBIT

b. The PDP timer shall update the asserted state every 0.1 ms.

c. The ALLOW state shall be true for a duration t_{allow} following a pulse ('trigger pulse") from the facility clock, indicating the start of a shot

d. The INHIBIT state shall be true, starting at time t_{allow} after the trigger pulse, for a duration t_{period}-t_{allow}.

e. The WAIT state shall be true after the end of INHIBIT and before the reception of the next trigger
pulse

f. The FCPC permissives shall only be enabled with ALLOW and not(INHIBIT) and not(WAIT).

g. Trigger pulses shall be ignored during ALLOW and INHIBIT.

7.5 Upgrade Performance and Operational Requirements

a. There are no upgrade requirements

7.6 Interfaces

Table 7.6-1: *Interfaces for the PDP Timer (SBS 1.7.3.5.1)*

Interfacing SBS	Interfacing System	Nature of Interface	Interface Boundary	Interface Description	Required Interface Documentation
1.6.1.3	Timing and Synchronization System	Electrical Signal	Input of PDP	PDP Timer receives trigger pulse	CWD
1.7.3.6.5	DCPS Hardware Interface, Expansion Chassis & WDTs	Fiber Optic	Output of PDP	PDP sends status signals to DCPS	CWD
1.5.4.1	Hardwired Control System & PLC	Electrical Signal	Output of PDP	PDP sends permissive signals for OH, PF and TF	CWD
1.5.4.1	Hardwired Control System & PLC	Electrical Signal	Output of PDP	PDP sends status signals to the HCS	CWD
1.5.1.2	D-Site Auxiliary Power	Electrical Power	Wall plug	Power for PDP Timer	N/A