Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Enhancing operational safety: The NSTX-U Shorted Turn Protection (STP) system

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ARTICLE INFO

Keywords:
Real-time protection
State-space model
Kalman filter
Fault detection

ABSTRACT

The NSTX-U Shorted Turn Protection (STP) system is a vital safety feature designed to protect the tokamak's coils during operations. It employs a Kalman filter-based algorithm to monitor coil currents and detect faults in real-time. If an anomaly is detected, the system swiftly terminates the tokamak pulse to prevent damage. Developed with Matlab and Simulink, the STP system has been validated through real-time simulations, ensuring its effectiveness for the upcoming upgrades of the NSTX-U facility. This article presents the theory for implementation of the STP algorithm and the results from simulation and real-time implementation.

1. The NSTX-U model

The NSTX-U is an spherical tokamak located at the Princeton Plasma Physics Laboratory (PPPL) in New Jersey, USA. Fig. 1 shows a schematic of the reactor stressing the presence and location of the poloidal field (PF) coils, its main characteristics are a Toroidal field of 1 [T], major radius R = 0.93 [m], minor radius a = 0.68 [m] and plasma current Ip≈1 [MA] [1]. The objectives of NSTX-U research are to reinforce the advantages of spherical tokamaks while addressing the challenges [2].

The TokSys modeling and simulation environment is a MatLab and Simulink based tool used on fusion devices for constructing both axisymmetric and nonaxisymmetric MHD control models. TokSys facilitates the design and testing of control systems by integrating project-specific data on geometries, materials, and system descriptions into a standard format for calculations. These calculations include resistances, inductances, and Green functions, which map conductor currents to magnetic fields [3].

A TokSys model of NSTX-U was used to represent the PF coils and the passive elements of the vacuum vessel as a state-space model [4] where the inputs of the system are the voltages on the PF coils and the states are the currents on the PF coils and the passive elements. The plasma current (I_p) and its derivative ($\dot{I}_p$) are key elements of the model used in this work. ($\dot{I}_p$) is included in the input vector. This influences the state vector, through the system B matrix; this accounts for the interaction of the plasma with the coil currents. The mutual inductance between the plasma and the PF coils, was obtained from a simplified model based on Principal Component Analysis (PCA) [5]. This approach compresses a large database of mutual inductance matrices (built from approximately 1000 NSTX-U plasma shots) into a small set of principal components and their time-dependent coefficients. This reduced-order model captures the essential coupling dynamics while keeping the system computationally efficient.

2. The Shorted Turn Protection (STP) algorithm

The STP system was created as a real-time protection and health diagnosis system for impedance changes on PF coils through an implementation of a real-time model-based algorithm non-dependant on a plasma equilibrium reconstruction. Detection of shorted turns allows for the prevention of collateral damage to other parts of the tokamak.

In real practical systems that have been modeled as state-space, it may occur that the state vector, which is vital for performing the feedback control of the methods just presented, is not fully measurable; when this occurs, it is necessary to retrieve the state vector x(t) from the system output y(t) and it can be obtained through an state estimator or Kalman filter to estimate non-measurable state variables [6].

A Kalman filter estimates the state vector based on the measurements of the input and output system signals. The input of the filter is the model output y(t) and the control input u(t) vectors. Similarly with the construction of a state-space controller, the filter uses an observer gain weighting matrix to the correction term that involves the difference between the measured output $y(t)$ and the estimated output $x_{est}(t)$, where $x_{est}(t)$ are the estimated states [7].

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https://doi.org/10.1016/j.fusengdes.2024.114784
Received 3 October 2024; Received in revised form 17 December 2024; Accepted 20 December 2024

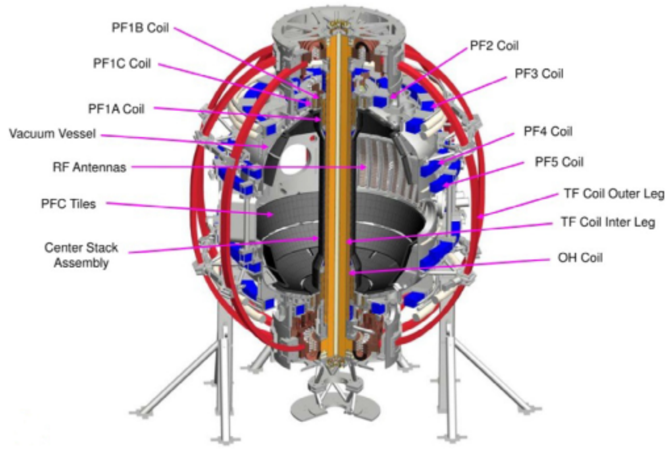

Fig. 1. NSTX-U vessel and poloidal field coils configuration.

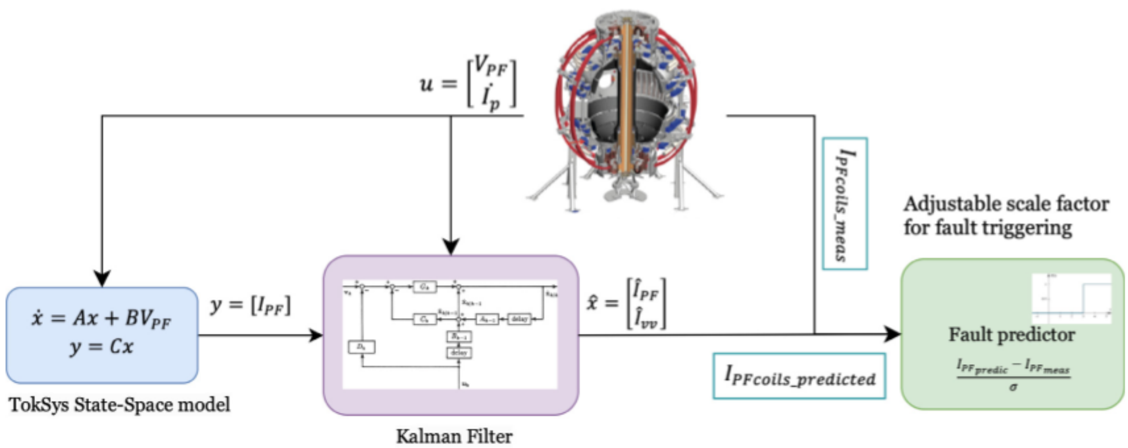

Fig. 2. Block diagram of the STP algorithm architecture, illustrating key components such as data acquisition, Kalman filtering, current prediction, and fault detection processes.

The STP algorithm utilizes a digitized Kalman Filter to predict currents in the poloidal field (PF) coils I_{PF}, which are part of the state vector $x(t)$. The predicted currents are then compared to the measured values, and any discrepancy between them indicates a potential change in the impedance of the PF coils, signaling a fault. The Kalman Filter was tuned through several simulations. Different scenarios are run and the gains Q and R are adjusted to obtain the desired behavior. The tuning objectives are: to detect a shortcircuit in any of the coils, as fast as possible and with sufficient detection margin. Also, the Kalman Filter should not trigger false positives, when a shortcircuit is not present.

The error signal, used to detect a change in the plant's impedance, is calculated as: $\frac{I_{predicted}-I_{measured}}{\sigma}$, where σ is the standard deviation derived from the error covariance matrix of the system. The standard deviation σ provides a statistical measure of the uncertainty in the Kalman filter's estimate [8]. When the error signal is small (below 1.5), it is likely due to measurement noise; however, if it exceeds 1.5, this indicates a discrepancy in the plant, suggesting a potential fault or change in the system impedance. The surpass of the error threshold level will signify that the system fault signal changes from 0 to 1. Fig. 2 shows the block diagram of the STP algorithm, highlighting its key components and workflow.

3. Implementation and auto-generated code

The implementation of algorithms using MATLAB-Simulink's [9] code generator for real-time purposes in fusion devices has been successfully developed in recent years. Control algorithms are programmed as block diagrams in MATLAB-Simulink, offering a powerful environment for modeling and control design. C++ code is then automatically generated from the Simulink block diagrams and compiled using Simulink Embedded Coder [10].

The STP algorithm is implemented and simulated using MATLAB-Simulink. It consists of blocks that handle the PF coils' voltage and current signals, which are then fed into a Kalman Filter based on the state-space vacuum model of NSTX-U. Another block computes the difference between the measured and predicted currents on the PF coils to detect faults in the system. The auto-generated C++ code for the STP is migrated to a dedicated server where it executes in real-time during the tokamak discharge, synchronized with the PCS. Upon fault detection, a signal is triggered, and the energy in the coils is gradually reduced to zero.

Since NSTX-U is currently undergoing upgrades and is not operational, historic NSTX-U MDSplus shots were used to feed the system with realistic plasma and coil signals to test the functionality of the STP algorithm. MDSplus is a data management system widely used in fusion research, designed to handle large amounts of experimental data and facilitate access to real-time data for diagnostics, control systems, and post-processing [11].

4. STP shorted plant simulation

The STP algorithm's exported C code has been tested using experimental 2016 NSTX-U data from discharges with a plasma current of 1 [MA]. The code is supplied with MDSplus stored signals to evaluate its ability to predict faults. A certain number of coils are selected to

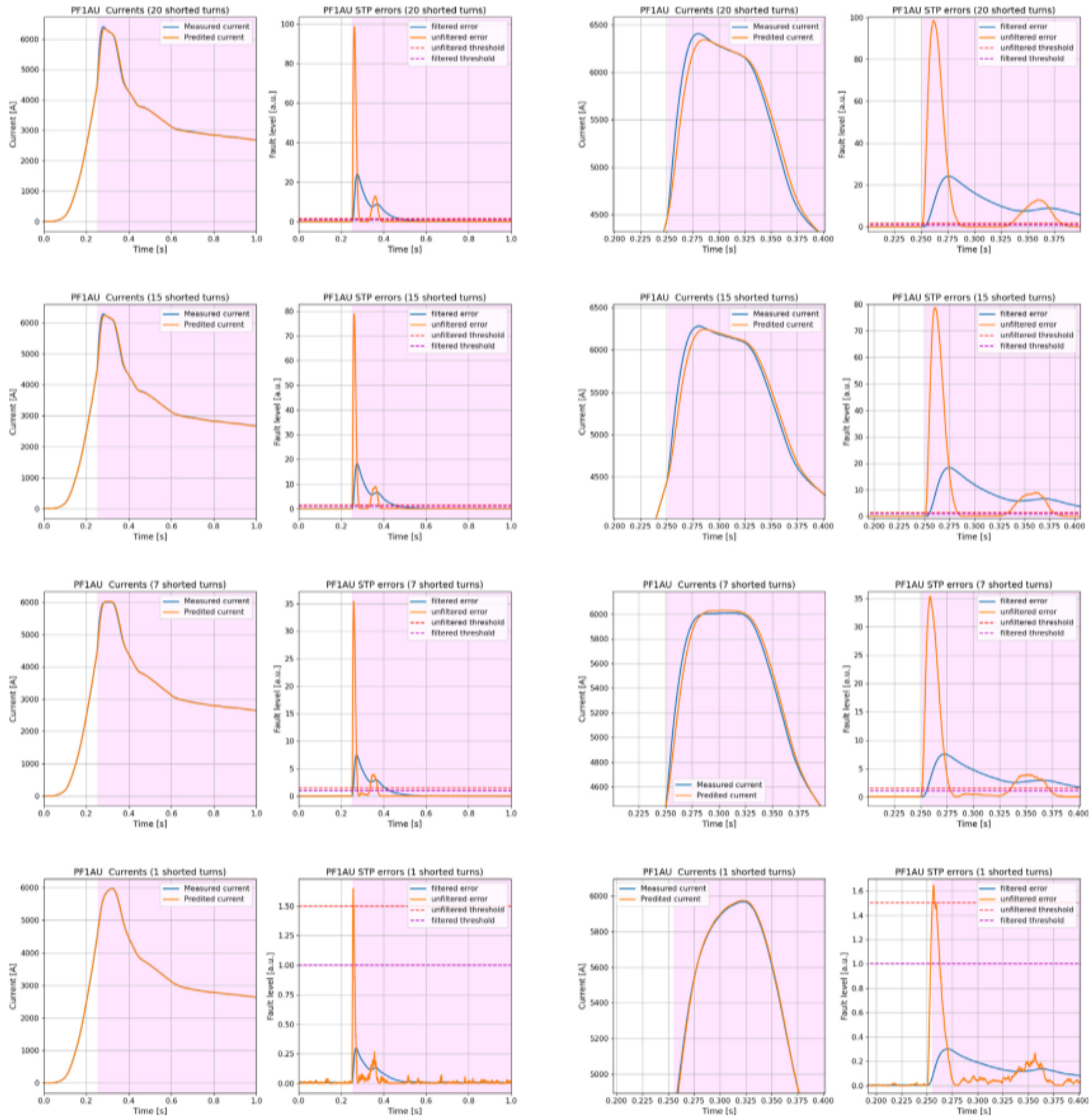

Fig. 3. Simulation results of the STP faulted plant simulation for 20, 15, 7 and 1 shorted turns at 0.25 [s] in a discharge with Ip≈1 [MA]. The zoomed-in view on the right highlights currents and errors, making it easier to observe the differences between measured and predicted currents after the fault occurs. The pink background indicates when the fault was detected by the STP algorithm.

have one or more shorted turns, which is artificially introduced into the MDSplus signals. Python scripts are used to test the auto-generated code in a simulation. In Fig. 3, the results for the simulation of 20, 15, 7, and 1 shorted turns at 0.25 [s] in the PF1AU coil are shown, the STP algorithm successfully triggers a fault in all cases. The examples presented in this work focus solely on the PF1AU coil, as it was a critical element during NSTX-U operation and was selected for demonstration purposes.

5. Real-time implementation and results

The NSTX-U infrastructure has the capability to feed real-time input streams with both real and artificial data to test algorithms. This functionality allows the STP system to operate without distinguishing between actual and simulated data. The testing system, known as the Autotester, consists of PCI cards and a LabVIEW interface that generates input signals, including coil voltages, currents, and plasma current.

The Autotester imports historical shots from MDSplus and transmits these signals via the real-time data input stream. This stream is connected through optical fiber to both the PCS and STP servers, enabling comprehensive testing of the system.[12]

Figs. 4 and 5 display the results of two Autotester discharges on NSTX-U for cases with 15 and 1 shorted turns, respectively, along with a zoomed-in view of the corresponding region at 0.25 s. In both instances, the fault signal changed from 0 to 1 at the moment the fault was artificially introduced. Fig. 6 presents a table and plot of the faulted signal value reached at 0.25 s for the different numbers of shorted turns tested in real-time. A clear linear relationship between the number of shorted turns and the fault signal value is observed.

6. Conclusions and future work

In 2024, NSTX-U will conduct vacuum discharges to test the device's functionality, with the poloidal field (PF) coils energized to nominal values, and the STP system will undergo testing in real-time. Unlike previous tests that relied on data from past discharges stored in MDSplus, this round of testing will use live data generated concurrently with the STP system's operation. This will be the first time the STP is protecting an actively functioning machine, as it will respond in real-time to actual operating conditions rather than pre-recorded data.

The advantage of having a protection system like the STP separate from the plasma control system lies in enhanced safety, increased reliability, and isolation from other control tasks. During the commissioning

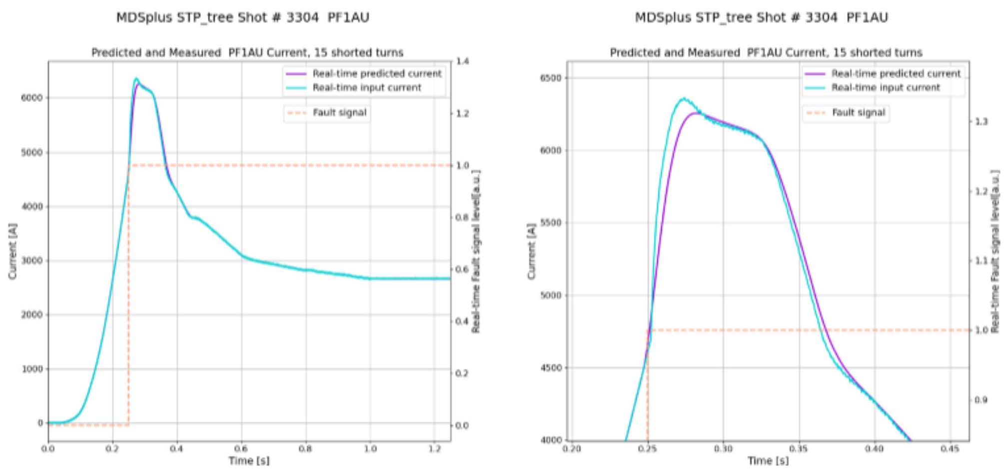

Fig. 4. Real-time plot results for a 15-turn short on the PF1AU coil at 0.25 [s] are shown. These signals are stored in an MDSplus tree shot. Predicted and input current time traces are displayed alongside the fault signal.

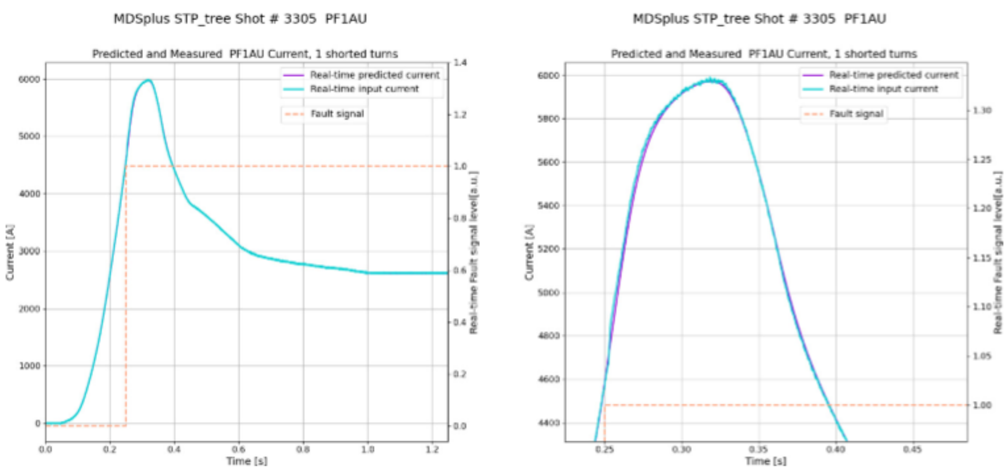

Fig. 5. Real-time plot results for a 1-turn short on the PF1AU coil at 0.25 [s] are shown. These signals are stored in an MDSplus tree shot. Predicted and input current time traces are displayed alongside the fault signal.

Number of Shorted Turns	Faulted Signal Value [a.u.]
20	97.34
15	77.75
7	37.70
5	22.70
3	10.30
1	1.51

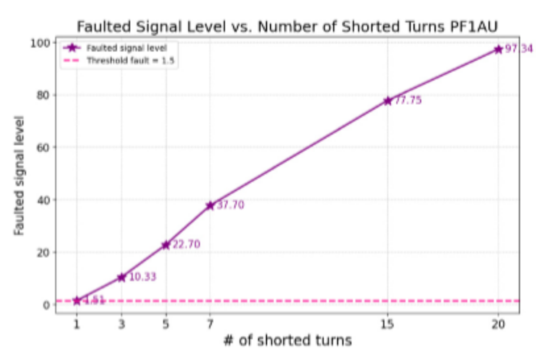

Fig. 6. Faulted signal value reached at 0.25 s for the different numbers of shorted turns tested in real-time.

of NSTX-U, the STP system will allow for quick implementation and deployment of various models (e.g., changes in passive elements or the addition of coils).

CRediT authorship contribution statement

D. Corona: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Data curation, Conceptualization. **D. Boyer:** Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation. **M. Comanescu:** Validation, Software, Investigation. **F. Hoffmann:** Validation, Supervision, Software. **S. Gerhardt:** Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Getliner in order to improve grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the U.S. Department of Energy under contract number DE-AC02-09CH11466. The United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

Data availability

The authors do not have permission to share data.

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