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Vessel eddy current measurement for the National Spherical Torus Experiment (NSTX)*

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Abstract

A simple analog circuit that measures the NSTX axisymmetric eddy current distribution has been designed and constructed. It is based on simple circuit model of the NSTX vacuum vessel that was calibrated using a special axisymmetric eddy current code which was written so that accuracy was maintained in the vicinity of the current filaments [1]. The measurement and the model have been benchmarked against data from numerous vacuum shots and they are in excellent agreement. This is an important measurement that helps give more accurate equilibrium reconstructions.

Introduction

The National Spherical Torus Experiment is a low aspect ratio plasma confinement device that is now operational at the Princeton Plasma Physics Laboratory [2]. Toroidal magnetic plasma confinement schemes that carry finite plasma current depend heavily on knowing the value of the plasma current in order to determine the properties of the plasma equilibrium. However, in order make the toroidal vacuum chamber robust, it is (usually) made of metal and is (usually) toroidally continuous. The most direct method for determining the plasma current in such devices is to use a Rogowski coil located on the vacuum side of the (usually) conducting toroidal vacuum chamber. This avoids confusion due to the eddy currents flowing in the vessel. In NSTX, an internal Rogowski coil was not practically realizable due to the tight space constraints, coupled with the high temperature, high voltage, and high vacuum compatibility requirements.

Because of these constraints, an external vacuum Rogowski coil was used instead. In order to subtract the vessel currents from this measurement, a vessel current measurement system based on measured loop voltage distributions was devised. The idea is very basic; measure the electric field distribution on the surface of the vessel and from this and the known vessel resistance distribution infer the current distribution in the wall using Ohm's law. We will describe the modeling tools and diagnostic requirements required, and approximations used to successfully operate this system.

Measurement principles

We first break up the NSTX vacuum vessel into segments, in the manner shown in Figure 1. The line average electric field around each segment can be easily measured using a simple loop of wire usually referred to as a voltage loop (also commonly referred to as a flux loop). An idealized view of a single vessel segment-measurement loop pair is shown in Figure 2.

The electric field as measured on the surface of the vessel segment is used to approximate the average electric field inside the conductor. This approximation is valid if the following assumptions are met:

$$\frac{dE}{d\ell}\Delta\ell << E \quad and \quad \frac{dE}{dr}\Delta r << E$$

where $\Delta\ell$ and Δr are the tangential and normal dimensions of the segment. These inequalities could also be used to optimize the inter-loop spacing and the total number of required loops, although in actual fact the number and spacing of loops is often determined by other constraints.

The simple circuit

Figure 3 shows the equivalent circuit for 2 concentric conducting loops (as in Figure 2), one of which is continuous (the vessel segment), the other has a toroidal break (the voltage measurement loop). The circuit elements represent:

1) R_0 the effective vessel segment resistance

2) L_0 the effective vessel segment inductance

3) R_1 the measurement loop resistance

4) L_1 the measurement loop inductance

5) $M_{(0,1)i}$ the mutual inductance between the vessel segment/measurement loop and ith current carrying circuit element

It is not necessary to consider the other current carrying elements in the circuit, since they can be lumped together as a voltage source. It is useful to maintain the notation however, since it will make clear the impact of the approximations made in the measurement. The voltage equations for these circuits resultant from Thevenin's theorem are

$$L_0 \frac{dI_0}{dt} + I_0 R_0 + M_{01} \frac{dI_1}{dt} + \sum_{i=2}^{\infty} M_{0i} \frac{dI_i}{dt} = 0$$

$$V_{meas} + L_1 \frac{dI_1}{dt} + I_1 R_1 + M_{10} \frac{dI_0}{dt} + \sum_{i=2}^{\infty} M_{1i} \frac{dI_i}{dt} = 0$$

It is simple to arrange a suitable termination resistor and a sufficiently low resistance in the measurement coil such that $I_1 = 0$ is an excellent approximation for timescales of interest. Eliminating terms that depend on I_1 and subtracting the two equations one finds:

$$V_{meas} = I_0 R_0 + (L_0 - M_{10}) \frac{dI_0}{dt} + \sum \left(M_{0j} - M_{1j} \right) \frac{dI_j}{dt}$$

The remaining approximation is to equate the self-inductance of the vessel segment with the mutual inductance between the measurement loop. We also equate the mutual inductances M_{0j} and M_{1j}. These approximations are reasonable if the measurement loops are mounted directly on the surface of the vessel and the height and width of the vessel segment are small compared to the radius. The approximation fails if the time-scale for voltage changes is shorter than $\tau = V_{meas}/(dV_{meas}/dt) \sim (L_0 - M_{10})/R_0$. For NSTX a typical value for this time is $\tau \sim 1$ - 2ms.

Hardware

The NSTX surface voltage distribution measurement system consists of 20 axisymmetric flux loops which are roughly equally spaced in poloidal angle (see e.g., Figure 1). Four of the loops are placed located on the internal vacuum vessel structure (referred to as primary and secondary passive plates – “passive” because the provide passive stabilization of instabilities). The signals form the loops are individually digitized, and also connected to an analog summing circuit as shown in Figure 4. The analog circuit is necessary so that real-time signals proportional to the plasma current are available to the NSTX plasma control system [3] and to hardware permissives e.g. for neutral beam injection and radio frequency heating systems. The individual signals are currently used for post-shot data analysis, and have also been incorporated into the real-time plasma control equilibrium reconstruction algorithm rtEFIT [4]. Also subtracted from the Rogowski signal is the current passing through the PF1B coil (one of the NSTX poloidal field coils – see Figure 1), for which the radial clearance to the vessel was insufficient to permit threading the Rogowski coil. Whereas the initial rationale for including the polodal field coil inside the Rogowski coil was feasibility considerations, in retrospect this provides an ideal method for calibrating the Rogowski coil.

The Model

In order to calculate the vessel segment resistances that are required to relate the measured voltages to the vessel currents a vessel model was developed [1] which accurately incorporated the various axisymmetric conducting materials which make up the NSTX device cross-section. A picture showing the salient features of the model is shown in Figure 1. A few of the important features of the model are:

1) the NSTX vessel consists of 2 parts: a center stack made of inconel and a outer vessel made of stainless steel.
2) The center stack and the outer vessel electrically isolated from each other with stringent requirements on the methods of connection between the two potentials.
3) a series of copper plates which are not axisymmetric exist inside the vessel.
4) The poloidal field coils are multi turn coils with square cross-section windings made of copper.

With this in mind, a model of the NSTX vessel was created. It includes accurate filament representations of all conducting elements with appropriate material resistivities (see Figure 1). The model then solves coupled circuit equations using accurately calculated resistances, self- and mutual-inductances. The code advances the time dependent equations using an integral method that avoids the usual time step accuracy requirements. The numerical methods employed and the inductance models used, which improve substantially on those used in the past in the past for axisymmetric time dependent flux evolution codes, will be described in a future paper.

Results

The primary goal of the measurement system is an independent measure of the magnitude of the net axisymmetric eddy current flowing in the NSTX vessel. Data from a coil-only (no plasma - shot number 112448) showing the induced vessel eddy current as measured by the Rogowski coil, is shown in Figure 5 overlaid with the measure of the same quantity as determined by the weighted sum of the loop voltages using the system described above. It is clear there is excellent agreement. The coils current waveforms for the test are shown in Figure 6.

The overall accuracy of the measurement can be estimated from the signal which represents the plasma current for the vacuum shot. For an ideal measurement system this signal would be zero. One can see that the maximum current detected in this measurement is 30kA. For the nominal maximum plasma current in NSTX of 1MA, this would correspond to a 3% error. In fact during steady state conditions the error is somewhat less than this since the primary cause of the 30kA spike observed in the total vessel current is transients due to rapid changes in coil currents. During the plasma current flattop the error is ~10kA or ~1%. It is in fact straightforward to determine the transient response of the vessel current more accurately by including the inductance terms that have been neglected in this model. This was not the primary aim of this measurement however. For truly fast events, skin effects could become important, which would preclude the use of the simple circuit model presented here.

A secondary goal of the measurement is to determine the vessel current distribution. This is required during equilibrium reconstruction. There is excellent agreement between the model and the data as can be seen in Figure 7.

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References

[1] Menard, J., to be submitted to J. Fusion Tech.
[2] M. Ono, S. M. Kaye, Y. -K. M. Peng, et al. Nucl. Fusion **40**, 557 (2000)
[3] D. A. Gates, D. Mueller, C. Neumeyer, J.R. Ferron, IEEE Trans. Nuclear Sci., **47,** 222 (2000)
[4] J.R. Ferron et al., Nucl. Fusion, **38**, 1055 (1998)

Captions

Figure 1 a) Picture showing a cross-section view of the NSTX vacuum vessel along with the locations of the voltage loops used for the vessel current measurements. The alternating red and blue distinguish adjacent vessel segments assigned to the different loops. b) Picture showing the location of the poloidal field coils on NSTX. The color code represents the different material resistivities with yellow = copper, blue = stainless steel, and green = Inconel.

Figure 2 Schematic representation of a vacuum vessel segment and its associated voltage measurement loop.

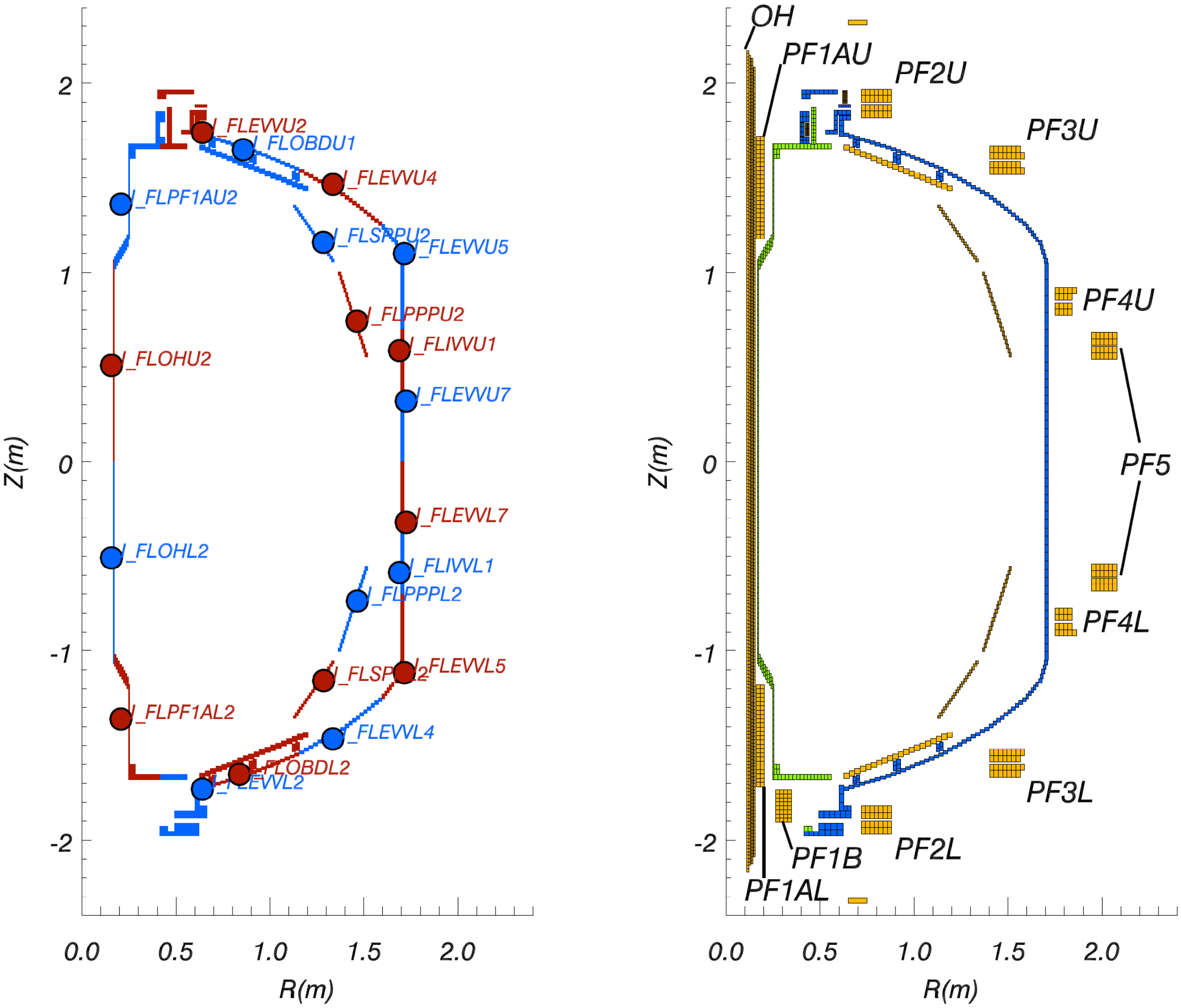
Figure 3 Electrical schematic of the coupled circuits that are 1) the vacuum vessel segment and 2) the measurement loop.

Figure 4 Circuit diagram showing the analog circuit used to create the real-time vessel eddy current signal.

Figure 5 a) Total vessel eddy current measurement from vacuum shot 112448 overlaid with the sum of the inferred vessel currents from the loop voltage measurements. Rogowski data is shown in red, and summed loop voltage data results in black.

Figure 6 The poloidal field coil currents for shot 112448. Note that that the PF5 coils are connected in series and that the PF4 coils are not routinely used.

Figure 7 The individual segment currents as determined from the loop voltage measurements (black) compared the filament current model (red).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I_FLEVVU7
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I_FLOHL2
I_FLIVVL1
I_FLPPPL2
I_FLSP 2
I_FLEVVL5
I_FLPF1AL2
I_FLEVVL4
FLOBDL2
I_FLEVVL2
Z(m)
2
1
0
-1
-2
0.0
0.5
1.0
1.5
2.0
R(m)
OH
PF1AU
PF2U
PF3U
PF4U
PF5
PF4L
PF3L
PF2L
PF1B
PF1AL
Z(m)
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-2
0.0
0.5
1.0
1.5
2.0
R(m)

Figure 1

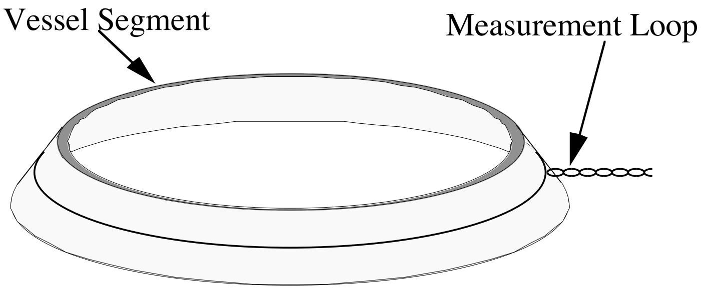


Figure 2

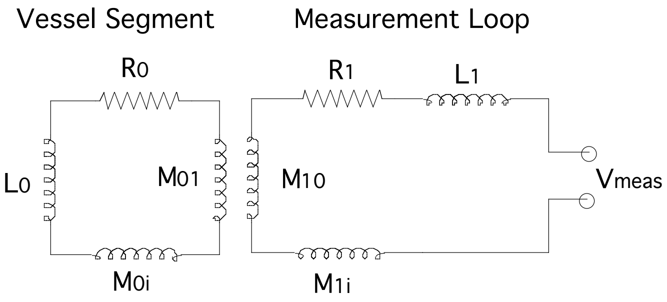
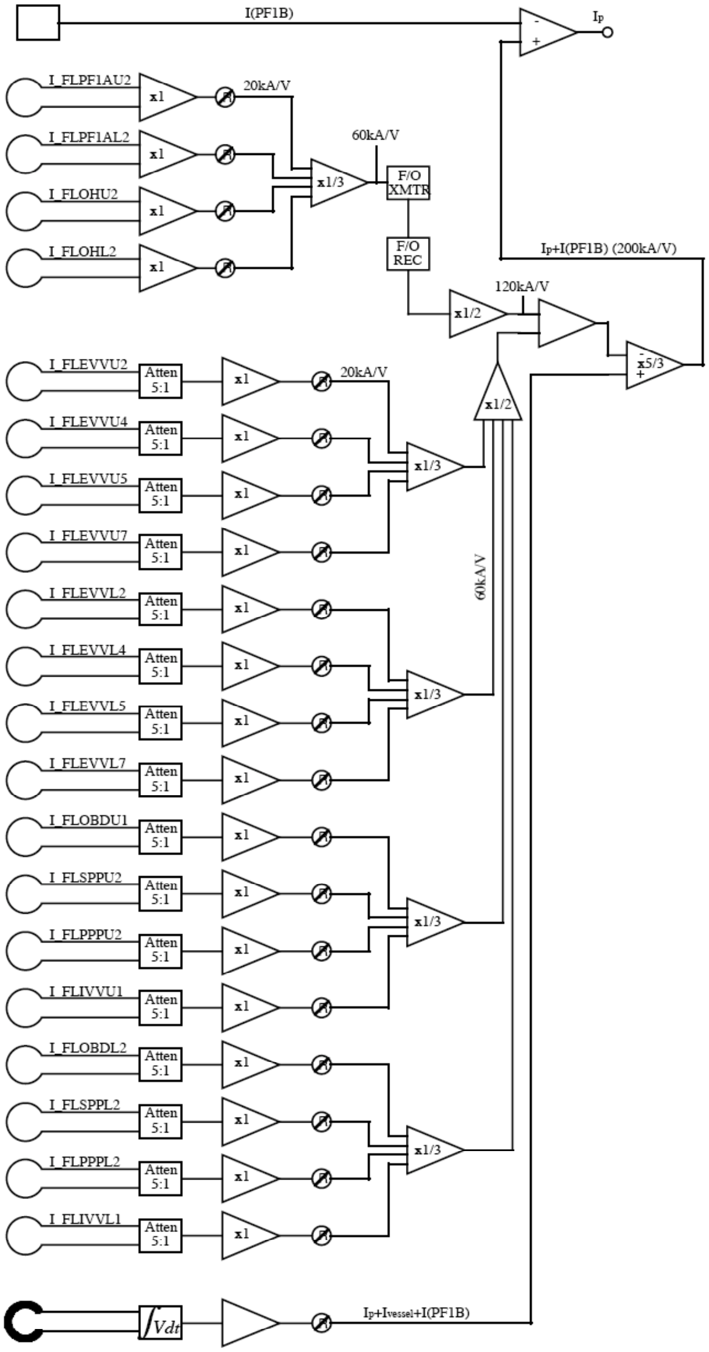

Vessel Segment
Measurement Loop
R0
R1
L1
L0
M01
M10
Vmeas
M0i
M1i

Figure 3


I(PF1B)
Ip
I_FLPF1AU2
I_FLPF1AL2
I_FLOHU2
I_FLOHL2
x1
20kA/V
60kA/V
x1/3
F/O XMTR
F/O REC
Ip+I(PF1B) (200kA/V)
120kA/V
x1/2
x5/3
I_FLEVVU2
I_FLEVVU4
I_FLEVVU5
I_FLEVVU7
I_FLEVVL2
I_FLEVVL4
I_FLEVVL5
I_FLEVVL7
I_FLOBDU1
I_FLSPPU2
I_FLPPPU2
I_FLIVVU1
I_FLOBDL2
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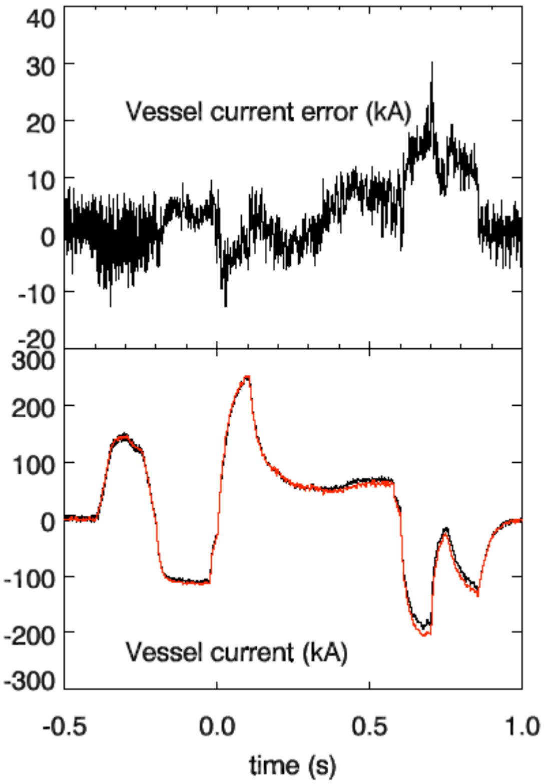
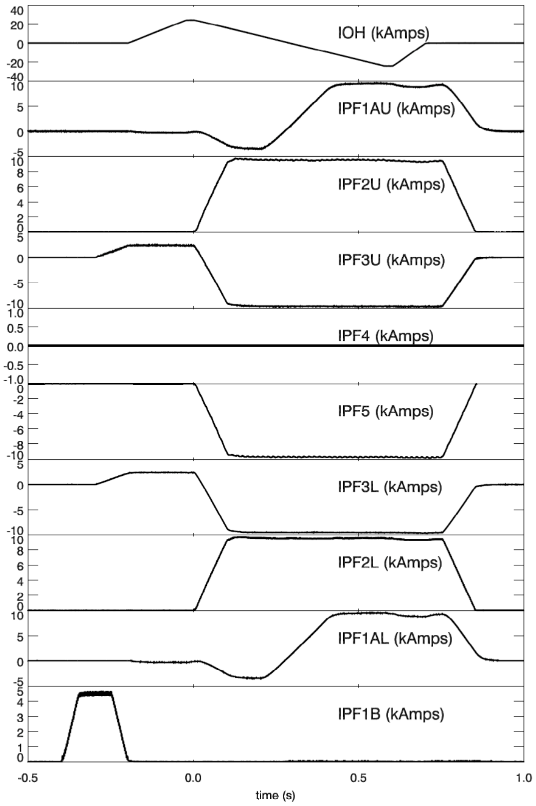
Atten 5:1
60kA/V
∫Vdt
Ip+Ivessel+I(PF1B)

Figure 4



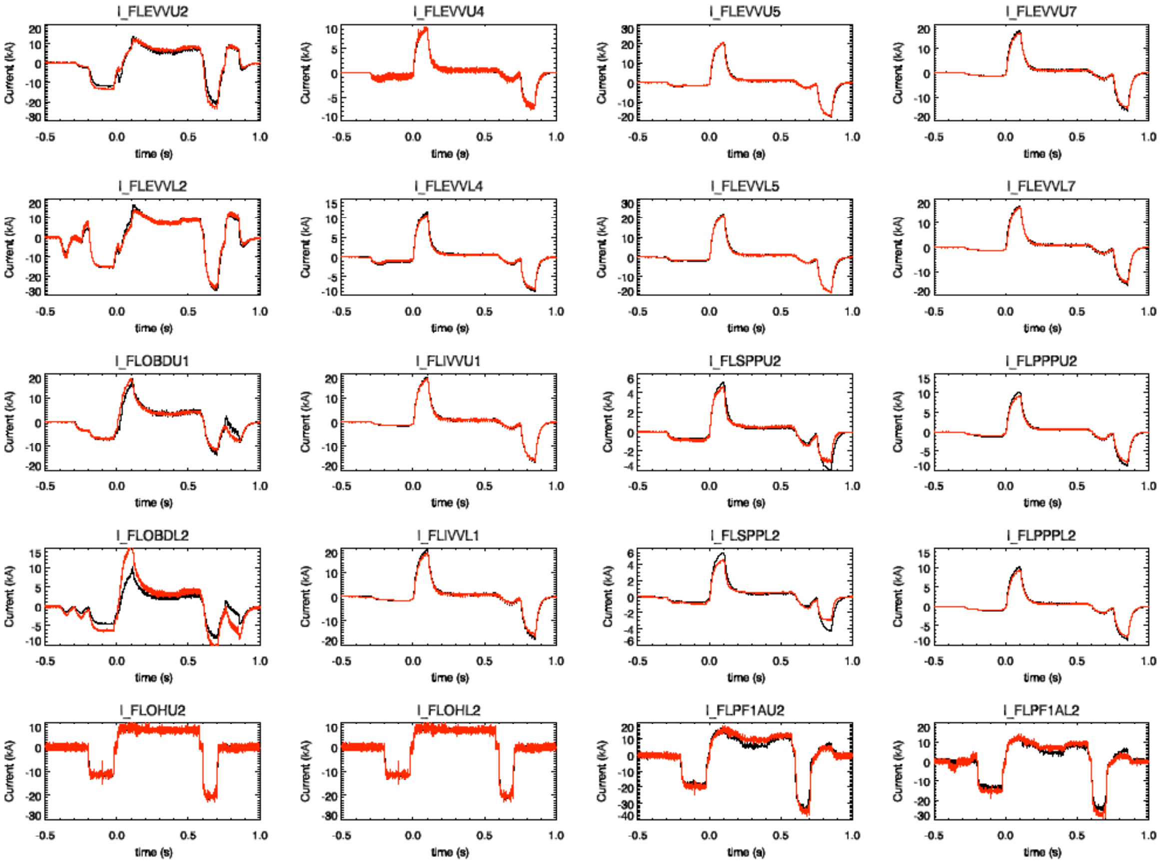
40
30
20
10
0
-10
-20
Vessel current error (kA)
300
200
100
0
-100
-200
-300
Vessel current (kA)
-0.5
0.0
0.5
1.0
time (s)

Figure 5



IOH (kAmps)
40
20
0
-20
-40
IPF1AU (kAmps)
10
5
0
-5
IPF2U (kAmps)
10
8
6
4
2
0
IPF3U (kAmps)
5
0
-5
-10
IPF4 (kAmps)
1.0
0.5
0.0
-0.5
-1.0
IPF5 (kAmps)
0
-2
-4
-6
-8
-10
IPF3L (kAmps)
5
0
-5
-10
IPF2L (kAmps)
10
8
6
4
2
0
IPF1AL (kAmps)
10
5
0
-5
IPF1B (kAmps)
5
4
3
2
1
0
-0.5
0.0
0.5
1.0
time (s)

Figure 6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I_FLEVVU4
I_FLEVVU5
I_FLEVVU7
I_FLEVVL2
I_FLEVVL4
I_FLEVVL5
I_FLEVVL7
I_FLOBDU1
I_FLIVVU1
I_FLSPPU2
I_FLPPPU2
I_FLOBDL2
I_FLIVVL1
I_FLSPPL2
I_FLPPPL2
I_FLOHU2
I_FLOHL2
I_FLPF1AU2
I_FLPF1AL2
Current (kA)
time (s)
-0.5
0.0
0.5
1.0

Figure 7

External Distribution

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