NSTX

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SUBJECT: ANALYSIS OF TF FAILURE

Summary

On Friday, February 14, during the first plasma shot of the day (Shot# 110201), a Level 1 fault was annunciated in the TF system.

This was accompanied by a large bang heard on the test cell audio system, and ensuing smoke seen on the test cell video system.

Multiple protective devices tripped, any one of which would result in the Level 1 fault status:

- TF power supply fault detector section overcurrent
- TF Analog Coil Protection (ACP) overcurrent
- TF Rochester Instrument System (RIS) overcurrent
- TF ground fault (DBB4 relay)

The target level for the TF during this shot, and the operating limit in effect for the run, was 53.4kA which produces Bt=4kG. The fault occurred just prior to reaching flat top as the current passed the 50kA level.

Based on the observed evidence it is postulated that an open circuit fault initiated the sequence of events. This was followed by a single line to ground fault at or near the (+) terminal of the power supply, then by another line to ground fault at the other (-) terminal of the power supply. The double line to ground fault condition led to a spike of fault current from the power supply which shunted the coil inner leg assembly. Once the power supply tripped, the current spike decayed. This was followed by a decay of the coil current as the coil released its stored energy. However, the decay was not a simple exponential according to the nominal L and R values of the coil circuit. Instead it was modified by a series voltage drop of 125 volts and resistance of 500$\mu\Omega$. These extra series elements are attributed to an arc across the postulated open circuit. The energy dissipated in the arc was of order 1.4MJ.

Interpretation of Data

Comparison of the current waveform of shot 110201 with the prior 100% test shot 110200 indicates no anomalies during the current rise prior to the fault as shown in figure 1[1]. In addition the writer has confirmed that 110200 was essentially identical to the first 100% test shot of the run period (109272 in early January)[2].

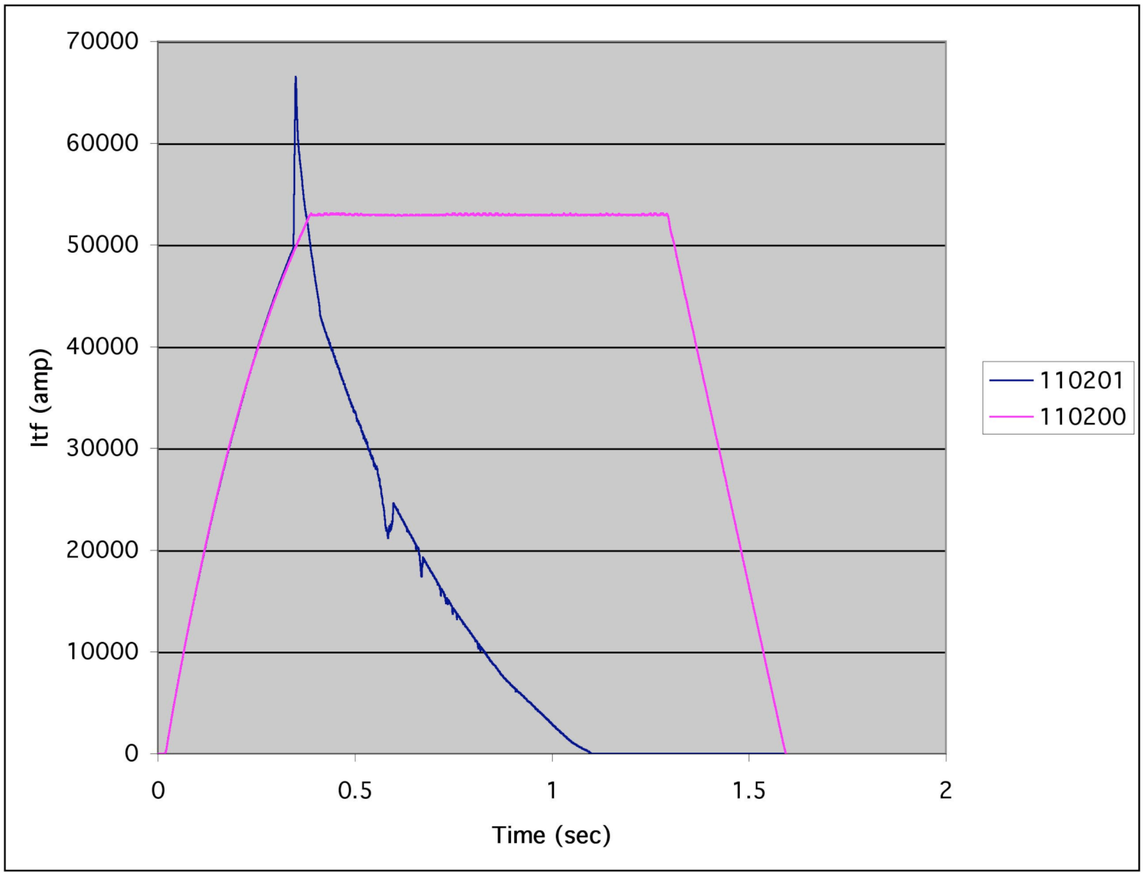

Figure 1 – Comparison of Fault Shot with Prior 100% Test Shot

[1] Obtained by overlay of the data after accounting for the difference in start time of the test shot and the plasma shot, relative to t=0

[2] Analysis of the total circuit resistance over a large number of shots has indicated a progressive trend of increasing resistance, however. See "TF Resistance Trend", M. Bell, 2/18/3

The current decay curve does not follow the normal exponential L/R decay[3] expected of the NSTX TF circuit after the power supplies go in to bypass mode (V≈0). This is depicted in figure 2[4] which shows an overlay of 110201 with a shot earlier in the run (110107) which had an abnormal termination. Also overlayed is a simple L/R decay where L=4.5mH and R=8.5mΩ. These circuit values had previously been established by calculation as well as measurement for use in estimating the follow-on $\int i^2(t)dt$ from L/R decay.

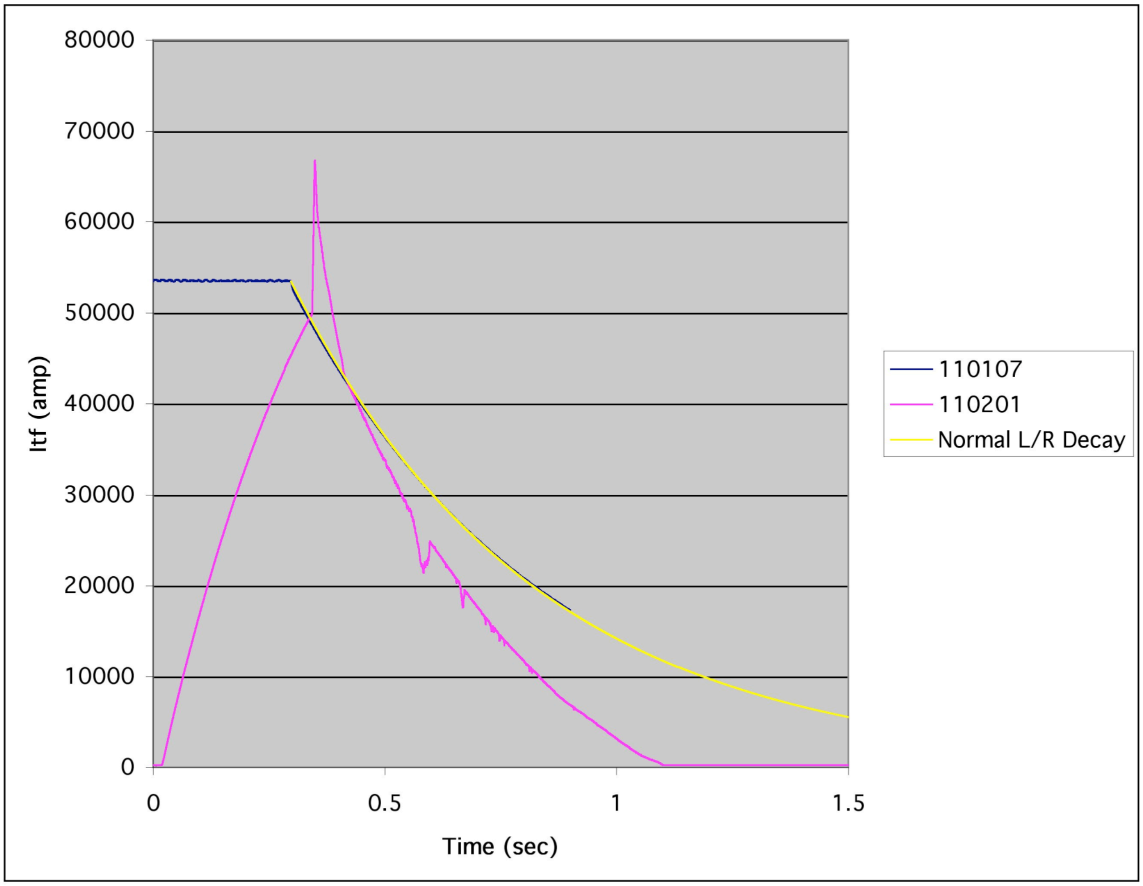

Figure 2 – Comparison of Decay Curves and Curve Fit

The center stack rogowski coils, which are located at approx. z= +/- 1.4m and measure the total amp-turns passing down the TF inner leg assembly do not show the current spike and other anomalies in the TF waveform as measured at the power supply terminals as shown in figure 3[5]. This figure shows the power supply current, rogowski current (divided by number of turns) also shows a curve fit which is based on an anomalous

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[3] One would expect $I(t) = I_0^{\varepsilon\text{-}tR(t)/L}$ where R(t) reflects the resistance variation with heating

[4] Obtained by overlay of the data so that the 50kA times are coincident.

[5] Obtained by scaling the CS rogowski signals by -0.0277427

voltage drop and an additional resistance in series with the normal TF circuit parameters. From this figure and the curve fit it is evident that:

- the large spike in power supply current flowed in parallel with the coil, not down the inner leg
- the fault current decay in the coil exhibits an anomalous V=125 volts and R=500$\mu\Omega$ in the series loop
- the notches in the power supply current decay waveform are not evident in the inner leg coil decay waveform
- the power supply current decay waveform is slightly offset from the coil current waveform during the decay

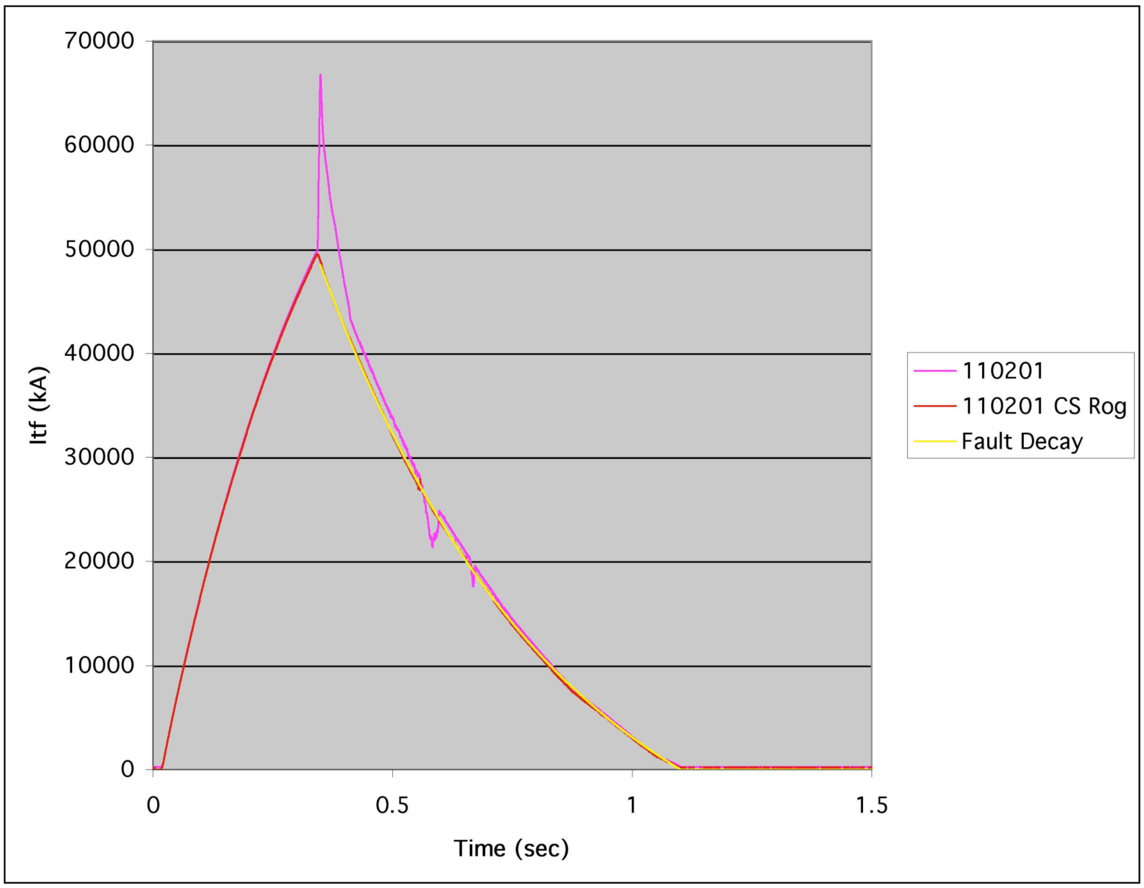

Figure 3 – Comparison of Power Supply Current Measurement with Center Stack Rogowski Measurement of Inner Leg Current per Turn and with Curve Fit

The differences between the CS rogowski waveform and the power supply current appear to be coincident with the operation of the OH coil and the plasma as shown in figure 4.

This indicates that a mutual coupling exists between power supply circuit and the OH circuit, and/or between the power supply circuit, including any fault current paths, and the plasma. One might expect to see a response in the rogowski inner leg current measurement, based on the idea that the poloidal component of Ip is linked to the TF. However, this is not evident from the waveforms, indicating a coupling to the external circuit only.

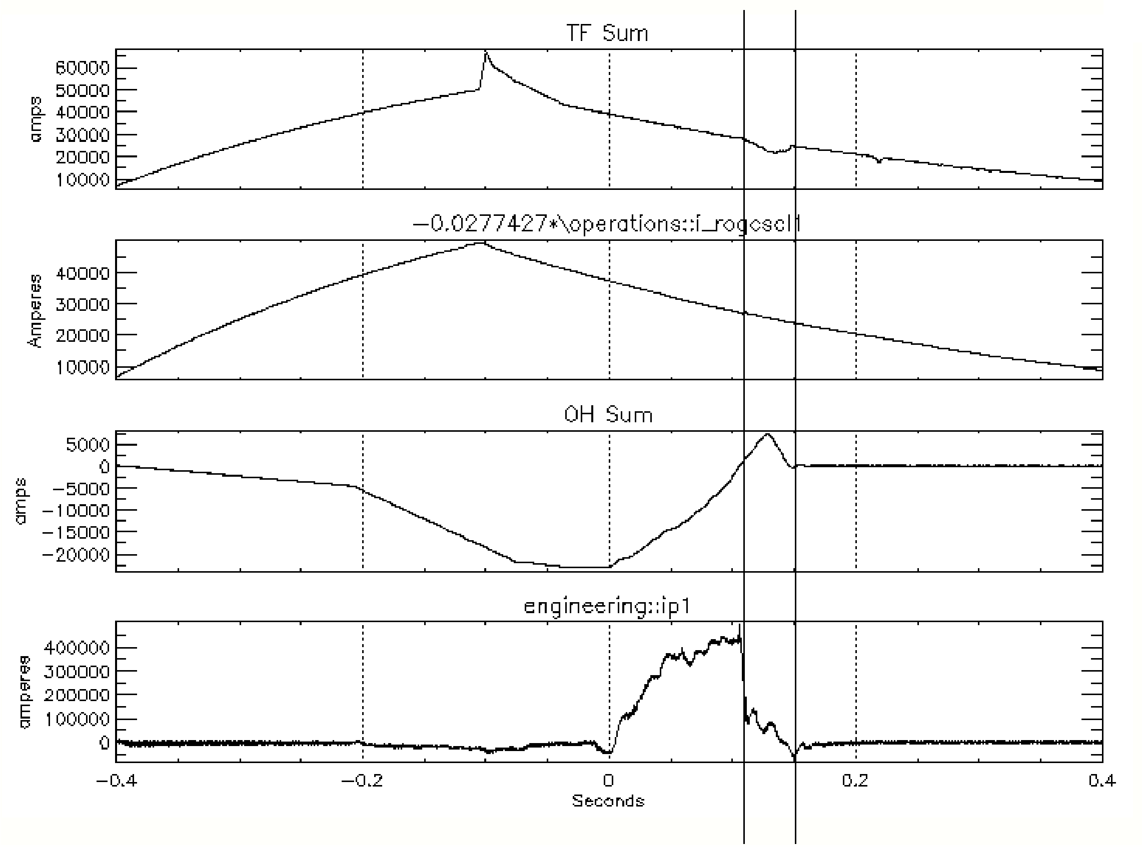

Figure 4 – TF, CS Rogowski, OH, and Ip Measurements

Postulated Sequence of Events

An explanation of the sequence of events is presented in the following paragraphs. This is aided by examination of the signals shown for the duration of the shot in figure 5. Following is a description of the signals:

TF Sum: Current in power supply loop as measured by DC current transducers (Halmars) in the four parallel power supply branches, and then summed

i_rogcscl1: Current flowing down inner leg assembly scaled to amps per turn, as measured by center stack rogowski #1 in the lower half plane.

pc_tf_sds_vd1_1- pc_tf_sds_vd2_1: This is the difference between the measured voltages to ground at the two terminals of the power supply output at the Safety Disconnect

Switches (SDS) in the power supply building (FCPC). In other words, this is the voltage produced by the power supply.

pc_tf_sds_vd1_1, pc_tf_sds_vd2_1: The individual voltages to ground at the SDS terminals

pc_tf_gndcur: This is the current flowing through the grounding resistors to the ground fault detector

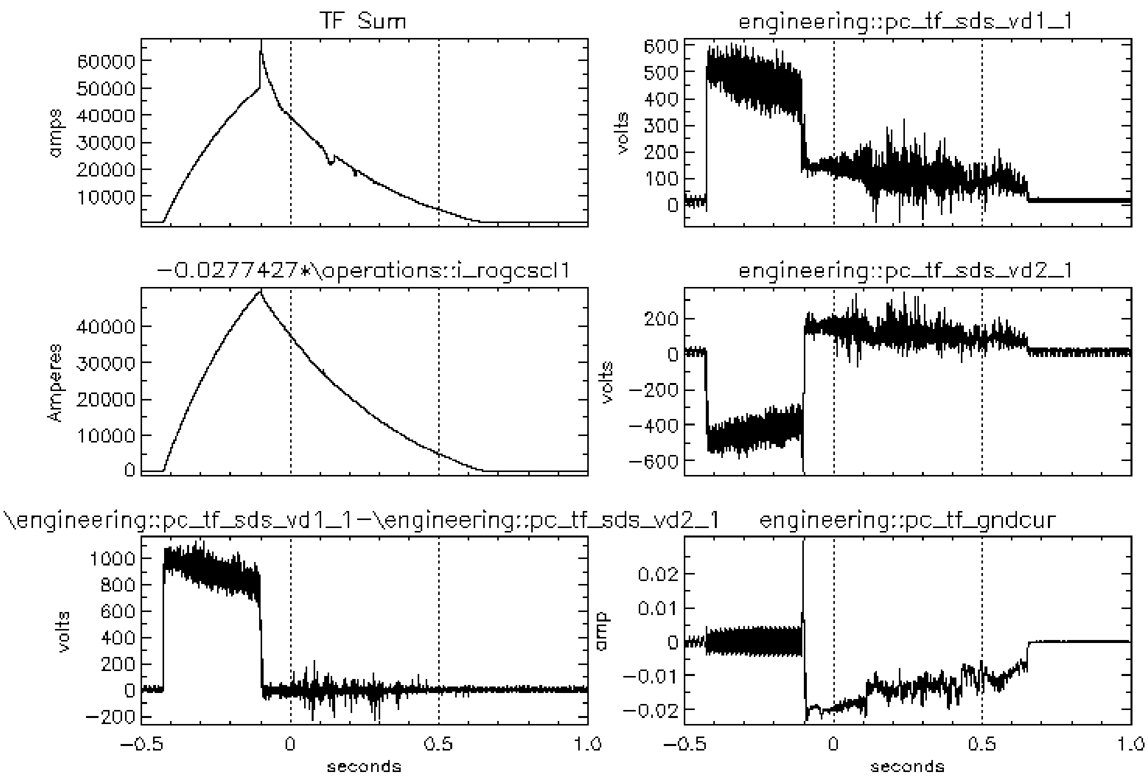

Figure 5 – Salient Signals Over Full Pulse Duration

The following is a description of the postulated sequence of events. Refer to figures 6 and 7 which give zoomed views of the signals shown in figure 5.

Prior to T1: TF current is rising, Power supply and rogowski signals are identical. Commutations in power supply voltage are evident. Power supply voltage has dropped from 1kV to around 750 volts due to regulation under load. Voltages to ground at SDS are balanced at +/-400V.

T1: An open circuit occurs at a flag joint, arcing and plasma ensue. Vd1 signal shows ground fault on (+) terminal as voltage dips toward zero. Vd2 signal goes toward the full power supply voltage. Ground fault current rises up.

T2: Vd2 signal shows additional ground fault on (-) terminal as voltage dips toward zero. Power supply voltage droops as line-line short circuit condition has developed. Current in power supply loop begins to increase rapidly, but inner leg current measured by rogowski remains flat.

T3: Power supplies have tripped, gone into suppress/bypass mode and their output voltages (four branches operating on 15 degree displaced sine waves) ride their respective sine waves toward zero.

T4: Power supply current peaks at around 67kA.

T5: Power supply voltage has reached zero, superimposed power supply spike current begins L/R decay. Vd1 and Vd2 are both at around 125V above ground, indicating that one ground fault still exists and that the coil is developing a net back e.m.f. in response to an arc voltage drop which is enhancing the current decay toward zero. Current decay is rapid due to the arcing open circuit condition.

T6: Superimposed power supply spike current is extinguished. Line-line arc is extinguished. It does not reverse direction (akin to the opening of a circuit breaker in an AC circuit).

T7: Plasma disruption creates notch in power supply current decay loop.

Timing of Events

Event	Time	Time Duration
T1	-0.1071	0.0022
T2	-0.1049	0.0034
T3	-0.1014	0.0017
T4	-0.0998	0.0070
T5	-0.0928	0.0549
T6	-0.0379	0.1453
T7	0.1074	

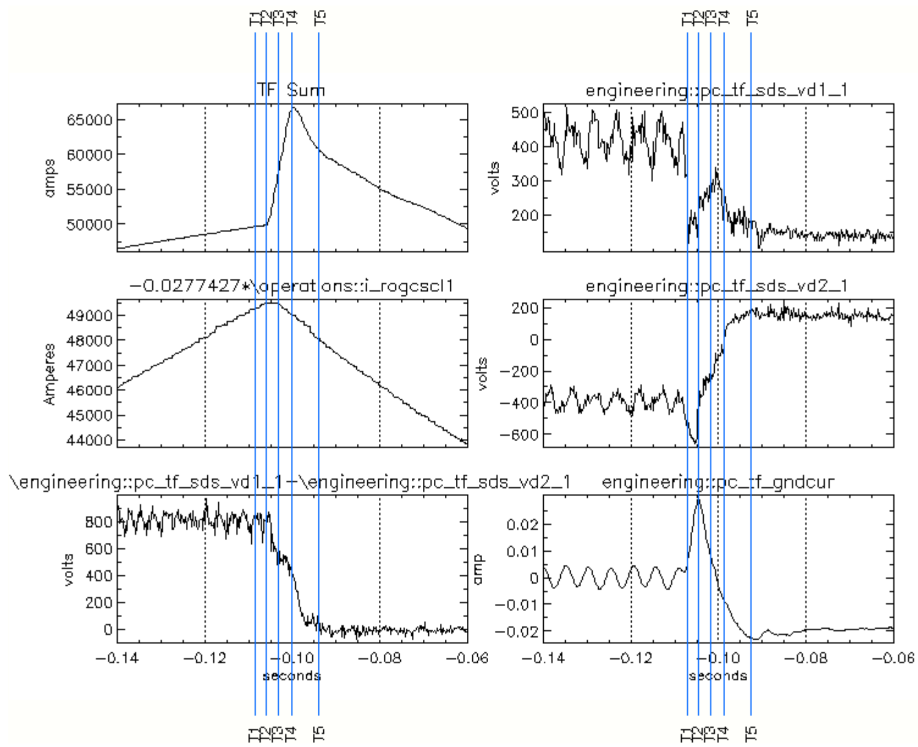

Figure 6 – Zoomed over 80mS

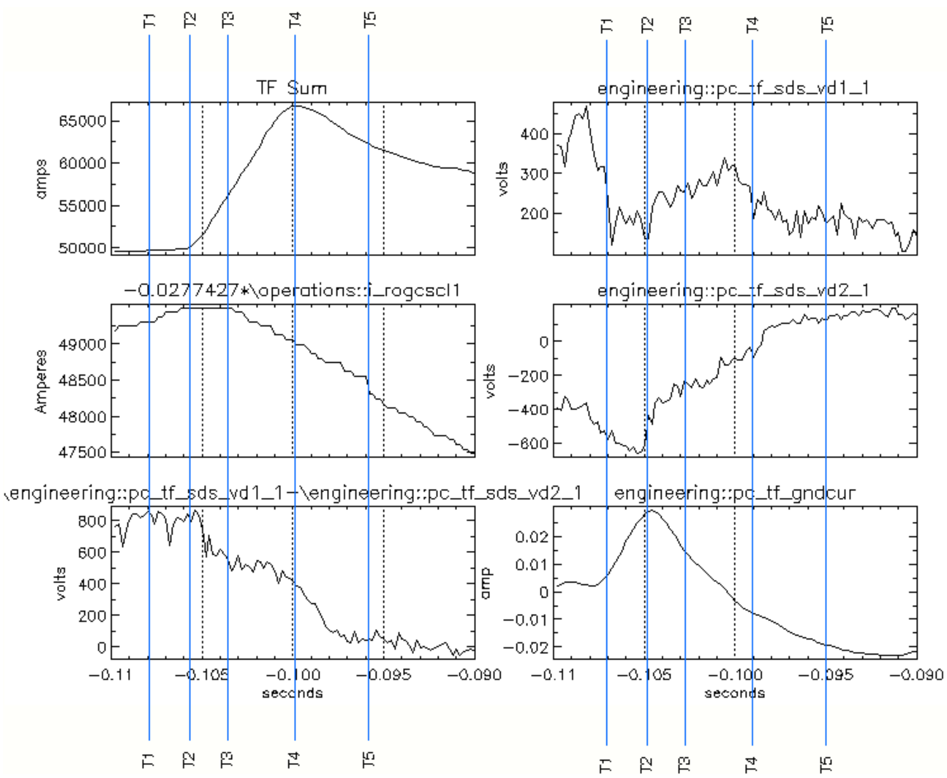

Figure 7 – Zoomed over 20mS

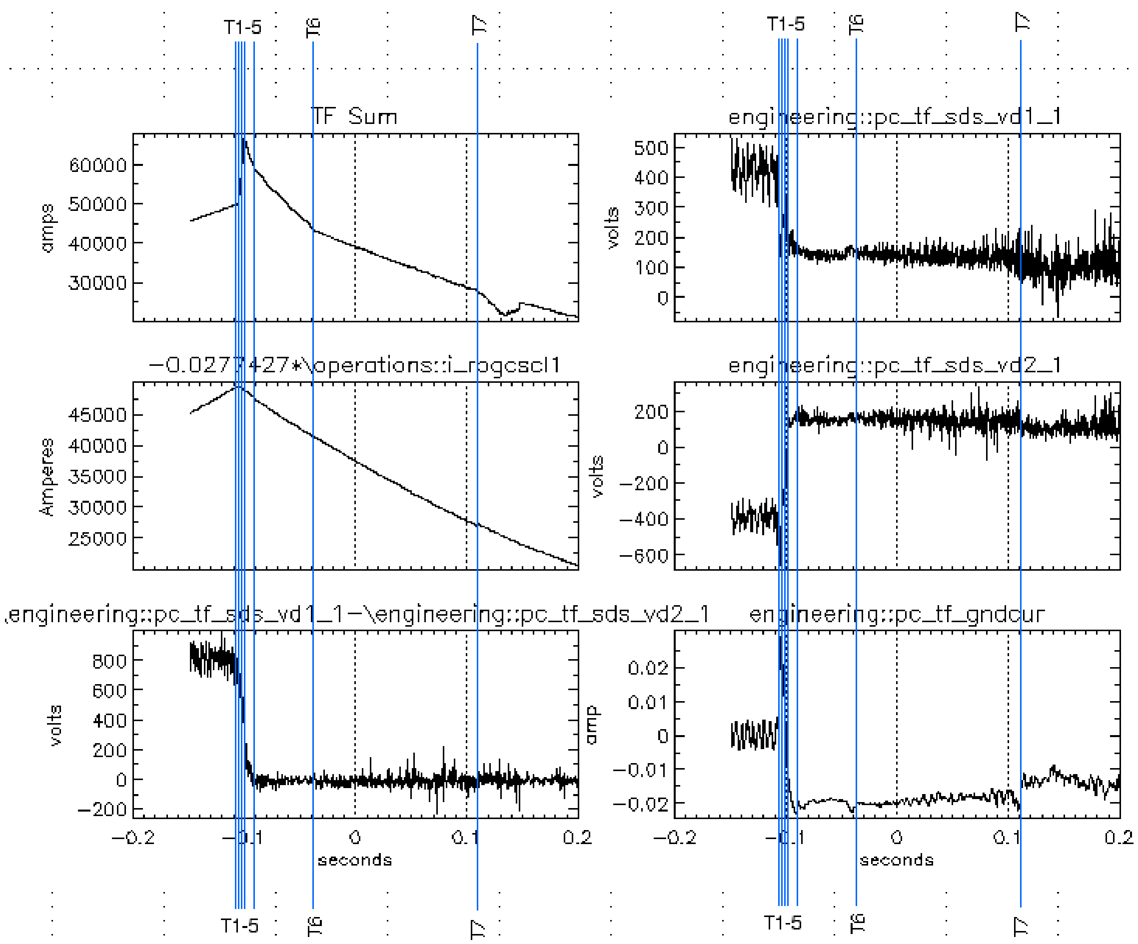

Figure 8 – Zoomed over 400mS

Correlation of Observations with Coil Layout

The winding pattern shown in figure 9 along with the circuit diagram shown in figure 10 can be used to postulate the physical location of the faults.

Examination of the damage to the TF coil revealed that the bottom end flag of turn 8A, which is the 3rd turn in the winding sequence, was ejected from its normal position in the hub assembly. Thus, in figure 10, coil section #1 probably consisted of turns 1-3, and section #2 of turns 4-36, i.e. the open circuit fault probably occurred where, on the bottom of the machine, the current exits turn 3 to go to the outer leg corresponding to turn 4. No matter the location, an open circuit in the loop would behave the same, but since turn 3 is so physically close to the (+) and (-) terminals of the coil it seems quite likely that the arcing and plasma generated by the open circuit would quickly result in a single line to ground fault from the positive coil terminal to the grounded hub assembly, followed by a second line to ground fault from the negative terminal to the grounded hub assembly.

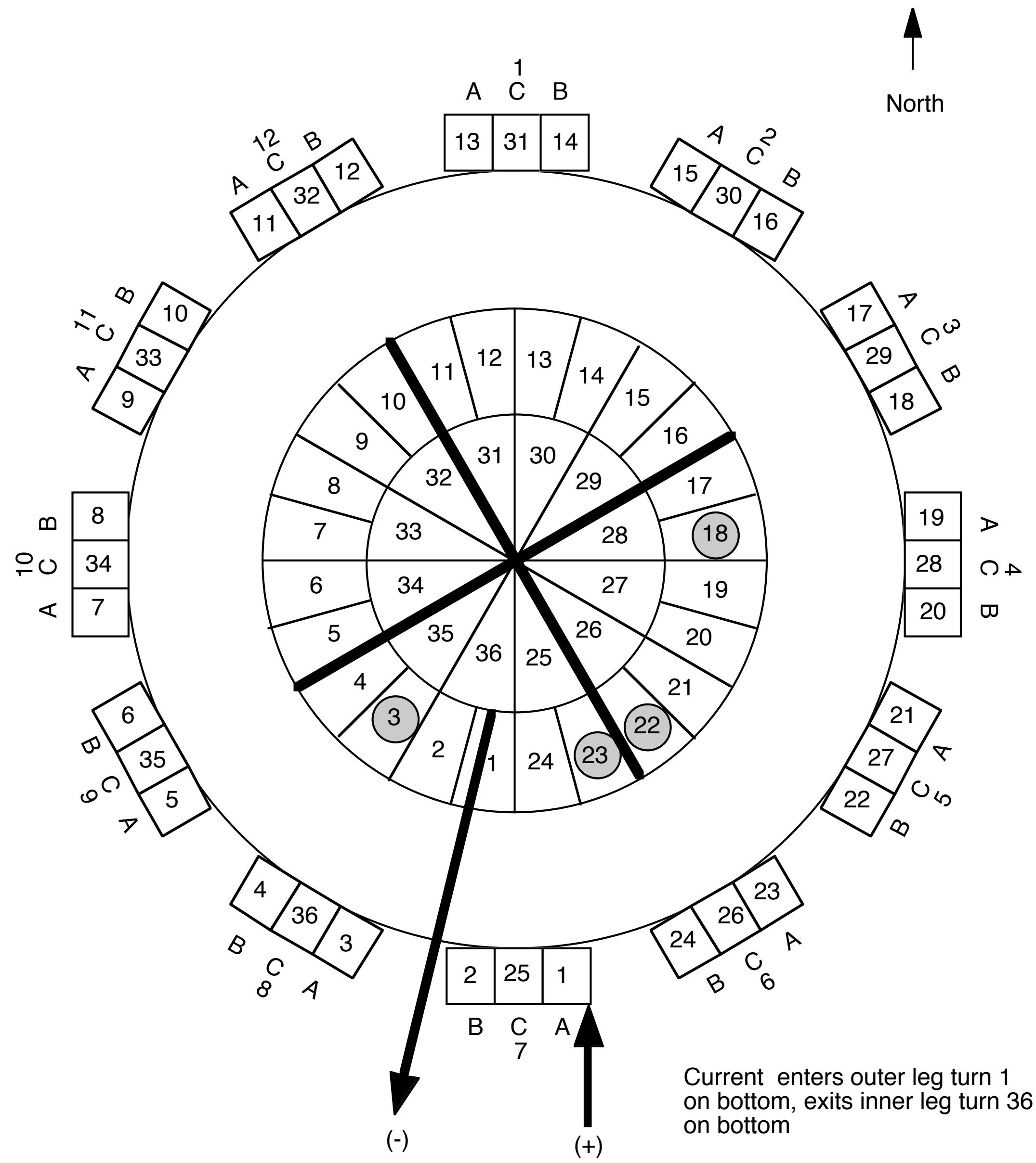

Figure 9 – TF Winding Pattern

(Note: Darkened numbers indicate conductors which had coolant leaks)

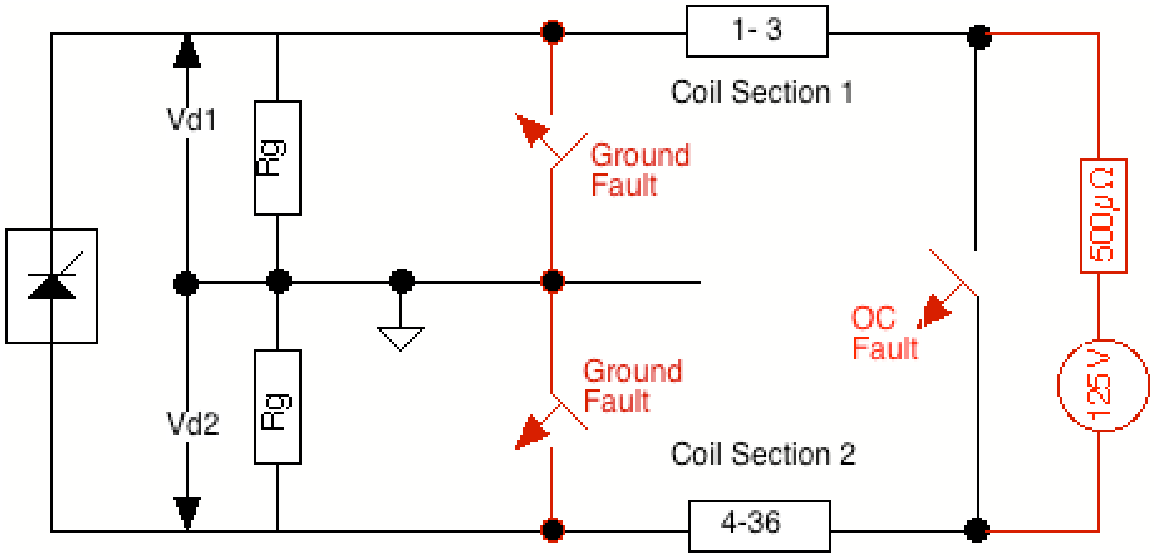

Figure10 – Simplified TF Circuit Schematic Showing Fault Locations

Circuit Simulation

The postulated sequence of events was simulated using an electrical circuit analysis program called PSCAD. The circuit model included the known coil and power supply parameters along with the postulated resistance and arc voltage drop associated with the open circuit fault. The effect of mutual coupling with the OH and plasma was not included. The results were in agreement with the observations, except for the features attributed to the OH/plasma mutuals.

In addition, a feature was included in the modeling to simulate the effect of a turn-to-turn short circuit. Using this modeling it was confirmed that the observed waveforms do not correlate with those which would be expected from turn-turn shorts.

Energy Dissipation

Based on the TF coil inductance of 4.5mH and an initial current of 50kA, the total stored magnetic energy at the time of the fault was 6.4MJ. However, taking the integral $\int[(i(t)*V_{arc}+i^2(t)*R_{fault}]$ the fault energy is calculated to be 1.4MJ. This amount of energy would be sufficient to bring 3.3kG (7.2lbs) of copper to the melting point.

It is noted that, had the open circuit fault not caused ground fault(s) or overcurrents, much more energy might have been dissipated, as the power supply would have continued to attempt to produce the requested current waveform.

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