PPPL Calculation Form - No: NSTX-U-CALC-53-06

Calculation # NSTX-U-CALC-53-06

Revision # 0 ________________ WP #, if any 2254 (ENG-032)

Detailed Model of Surge Testing on NSTX-U PF1A Coil

Purpose of Calculation: (Define why the calculation is being performed.)

Model the transient response of PF1A coils. Evaluate and reduce electrical risk to test PF and NSTX-U PF coils from undesired transients induced during surge testing, evaluate the effects of various theoretical coil faults during surge testing. Evaluate the ability to "see" a coil fault with surge testing.

Codes and versions: (List all codes, if any, used)

PSCAD, standard inductance and capacitance calculations for inductors and facing surfaces

References (List any source of design information including computer program titles and revision levels.)

The shape, insulation system and winding characteristics of the PF1coil are shown on Drawing NSTX-E-DC11053 R3, multiple sheets.

Assumptions (Identify all assumptions made as part of this calculation.)

See attached memo MAG-171018-AG-01

Calculation (Calculation is either documented here or attached)

Calculations and results are presented in the attached memo MAG-171018-AG-01

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

Calculation shows the probability of transient voltages being present within the PF1A coil during surge testing. Relative transient voltage distributions throughout the PF1A coil are derived from a coupled-inductor model. Means to reduce the transients are presented. The response of the surge-test system's waveforms for several faulted-coil scenarios are presented.

Cognizant Individual (or designee) printed name, signature, and date

Andy (Zhi) Gao *Zhi Gao* ________________________________

Preparer's printed name, signature and date

_______SAME________________________________

I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date

Nevell Greenough, 3/15/18 Nevell Greenough Digitally signed by Nevell Greenough Date: 2018.03.23 13:02:49 -04'00'

Checker's Response:

The attached memo, MAG-180315-NG-01, "PF1A Surge Test Modelling and Benchtop Test Results" provides backup to Andy's model and analysis using a simplified model and a different simulator. The simplified model is defended by measurements made on a physical test set consisting of standard test equipment, a surge-tester simulation circuit and H2 coils.

There are minor differences in the predicted results of the two simulations. These may be attributed to the following:

- Andy's model includes mutual inductances between turns that vary throughout the PF1A coil. My model is simplified to linear for the available analysis software and the purposes of a check. The results show similar behavior in response to surge testing.
- The values of inter-layer capacitance and turn-turn capacitance are slightly different for the two approaches. This is acceptable at this time as the effects of the encapsulating epoxy can vary 2:1 depending on the mix. Specific data is unavailable at this time.
- The transient voltages and frequencies are similar between the two approaches. There are minor differences due to the initial assumptions and the complexity of the models in use.
- My report provides backup for the nominal requested rise-time of the surge tester to be limited to 10 microseconds. Both reports show similar benefits to risetime limits.
- Worst-case calculated turn-to-turn voltages are similar for the two models. Andy's model predicts 240Vp-p for 5kV excitation. My model shows 50mV for a 1 volt excitation (equivalent to 250V for 5kV excitation).
- My report concludes that the internal circuit of a surge tester needs to be properly damped.
- My report concludes that if untreated, the transient layer-to-layer voltages can approach the applied terminal voltage. Proper damping of the surge tester and an external risetime-limiting network can reduce the transients to an acceptable level. The component values for the limiting network are reasonable.
- My report includes tests performed on physical coils that show that the "real-world" transients observed are likely to be less than either model predicts. This is a beneficial result.

MAG-171018-AG-01

TO: DISTRIBUTION
FROM: ANDY GAO
SUBJECT: DETAILED MODEL OF SURGE TESTING ON NSTX-U PF1A COIL

Due to the electrical failure of the PF1AU coil, NSTX-U is in the extended recovery period. According to the root cause analysis, it is believed that there were a few design and manufacturing defects in the original PF1AU coil, which caused turn to turn electrical faults. Therefore, the original PF1A coils have been removed from the machine and being re-designed and re-manufactured to eliminate the issues.

The newly manufactured PF coils will be tested in the field prior to installing into the machine, subjected to a set of considerably maximum voltage tests. Surge test was selected as the method of testing. The analysis documented here was performed to evaluate and optimize the design of the surge test to be performed.

Insulation Failure Modes

Electrical insulation can fail for two main reasons – electrical and mechanical. Mechanical failure modes are not discussed here. It normally fails due to excessive transient voltage applied, which exceeds the electrical withstand strength of the insulation. The insulation withstand strength can also be degraded and weakened through time due to many factors, which makes the insulation more vulnerable to electrical over voltage. Figure 1 demonstrates the lifespan of an insulation. Insulation strength weakens through time during normal operation. This is normally a slow and gradual process. Overvoltage or other events (red error on bottom) may reduce withstand strength (steps in green curve) instantaneously. Other factors such as moisture content, operational temperature, can change the rate insulation degrades (dotted line versus solid line). When the insulation strength weakens to the minimum acceptable stress (2E+1 for PPPL), it is at high risk for failure.

Test Requirement

The turn to turn electrical insulation has a turn to turn voltage withstand strength well exceeding 50kV. Based on PPPL management request, the turn to turn insulation should be tested around 5kV peak at the terminal. The maximum operational voltage correlates to two thyristor power supplies connected in series, which means a 2kV maximum operational voltage across the coil terminal. Based on PPPL common practice, therefore, the coil needs to be tested at 2E+1 kV, which is also 5kV peak at the terminal of the coil.

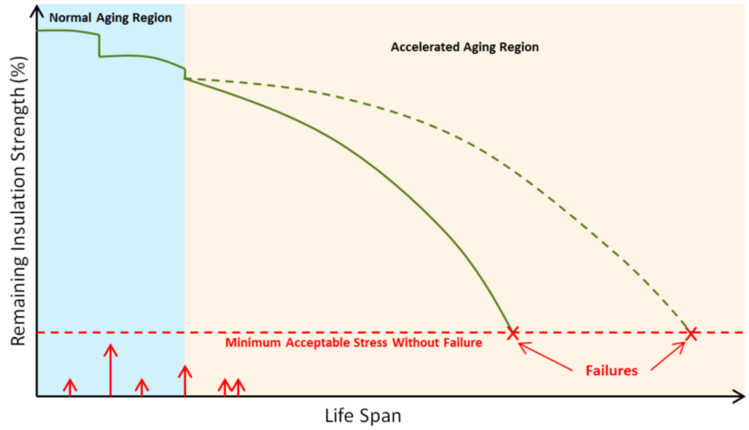


Figure 1 Demonstration of Electrical Insulation Lifetime

Surge Test

Surge test works as a capacitor discharges into a RLC network, which includes the coil structure. The energy stored in the capacitor enters the RLC network and oscillates at a certain frequency before dissipated through the circuit resistance. The peak voltage is correlated to the target voltage. The characterstic of the response voltage is unique to the circuit resistance, inductance and capacitance. Typically, the frequency of response voltage is proportional to the square root of the inductance and capacitance product. The peak response voltage is unique to the R, L and C all together. If there is a turn to turn fault, the resistance, capacitance and inductance of the coil will change, depends on the severity of the fault. But nevertheless, the response will differ comparing to a health coil. Therefore, surge test is a comparative test. To make surge test work, this test should be compared to either an identical and good coil, or same coil, with verified response at the time of installation (through time comparison).

Figure 2 shows the response voltage comparison for a shorted and a good coil. As shown, it is obvious to see the different in response waveform.

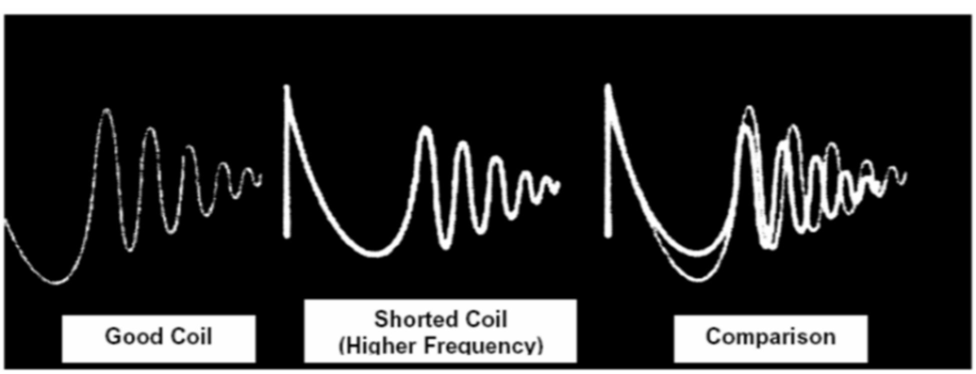


Figure 2 Surge Test Comparison

There are two aspects of the surge test need to be evaluated – terminal effects and voltage distribution inside the coil.

Terminal effect dictates the voltage applied at the terminal of the coil. As shown in Figure 3, are two voltage profiles, one with 1us rise time and the other with 10 us rise time. Both profiles peak at 5 kV. The shape of the profile is affected by the resistance, capacitance and inductance in the external circuit. To shape the voltage profile at the terminal of the coil, a circuit shown in Figure 4 below was used. Difference component value of this circuit results in different response voltage profile.

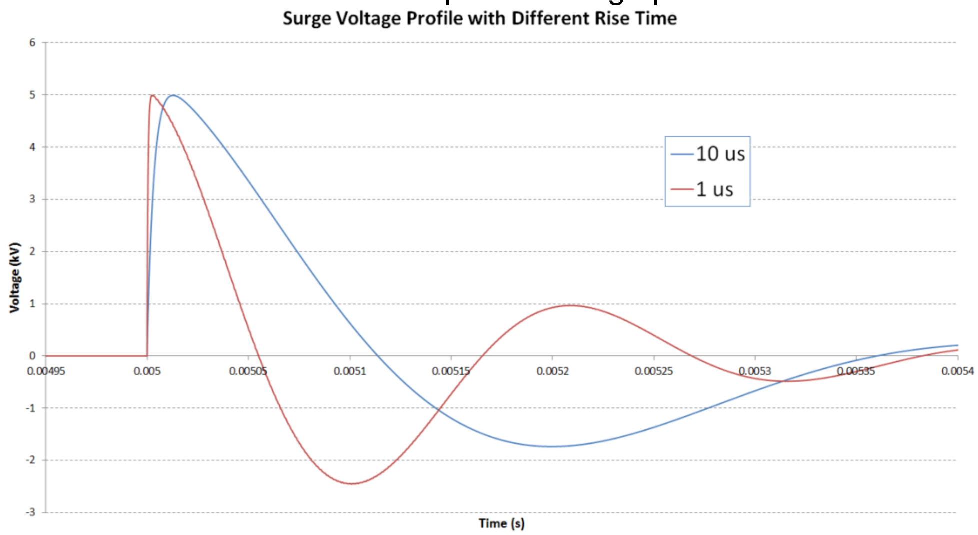


Figure 3 Terminal Surge Voltage Profiles

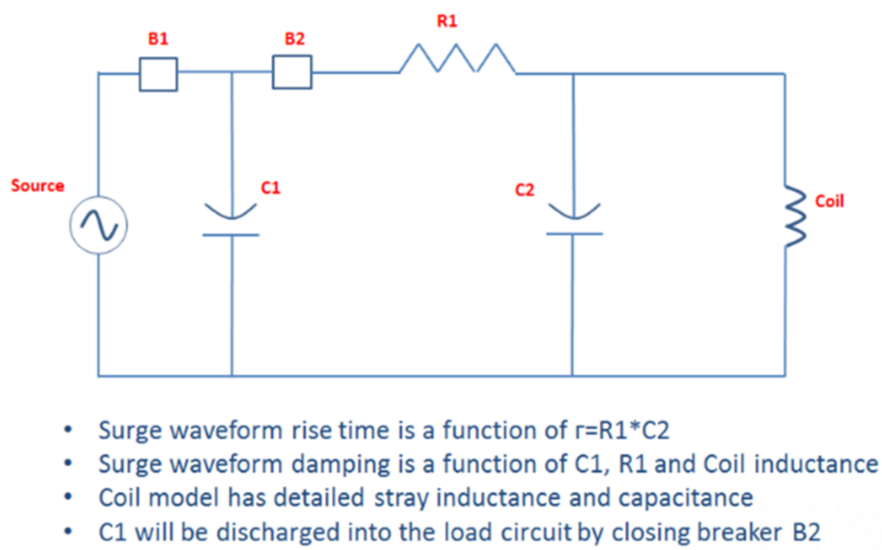


Figure 4 External Surge Testing Circuit

The second effect is the unequal voltage distribution inside the coil. Two effects determine how voltage distributes inside the coil – effective turn impedance and surge propagation effect.

Coupling of the winding turns to other passive conductive loops may change the effective resistance and inductance of each turn. Under surge condition, the voltage will therefore distribute unequally, where the distribution of voltage among the turns is proportional to the effective turn impedance, similar to how a voltage divider works. Surges prorogate inside the coil at a speed that is slower than the speed of light. The actual travelling speed depends on the capacitance and inductance among the coil turns. If the surge voltage rises is much faster than the travelling time, a bigger portion of the peak voltage will distribute across less number of turns, which means unequal voltage distribution inside the coil.

To analyze the unequal distribution of voltage inside the coil, a detailed model, which represents all resistance, capacitance and inductance down to turn level was constructed. The said model represents the self resistance and inductance of each turn, coupling effective between turns and between turns and passive conductive loops as well as the capacitance between conductive winds/structures separated by insulation material. The minimum modeling unit is one turn in this model. No smaller unit of model can be used. This is because the tools used to generate the mutual inductance matrix can not analyze anything smaller than a conductive loop, in this case, a turn. Figure 5 shows a simplified representation of the coil model. PF1A coil with mandrel structure is demonstrated here.

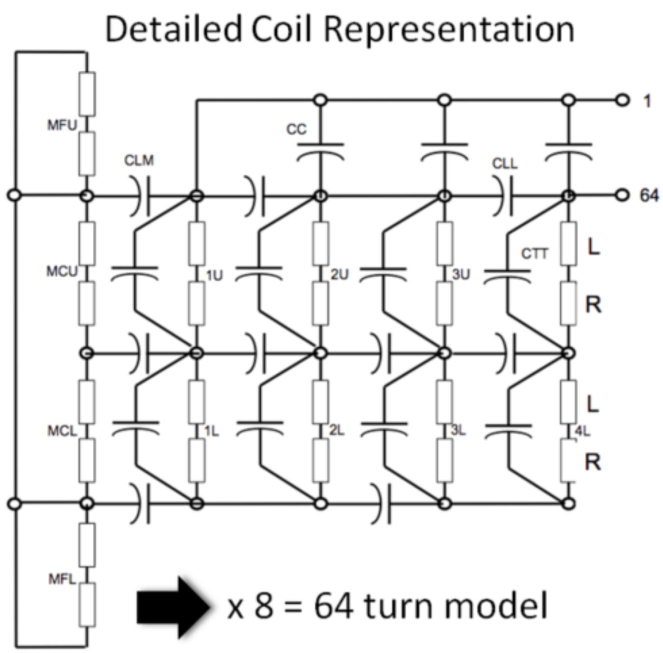


Figure 5 Simplified Representation of the Coil Turn Model

Resistance, inductance and capacitance are calculated using generic equations. Table 1 shows the calculated capacitance between turns inside each layer and between adjacent turns in two layers. Table 2 shows the calculated turn resistance in each layer. Together with mutual inductance matrix calculated for the coil, the detailed winding model was constructed.

Table 1 Calculated Capacitance inside the Coil

	Turn to Turn Capacitance (uF)		Layer to Layer Capacitance (uF)
Layer 1	9.29E-10	Layer 1-2	1.48E-09
Layer 2	8.86E-10	Layer 2-3	1.41E-09
Layer 3	8.43E-10	Layer 3-4	1.34E-09
Layer 4	8.00E-10		

Table 2 Calculated Turn Resistance for each Layer

	Resistance
Layer 1	9.83E-05
Layer 2	1.04E-04
Layer 3	1.09E-04
Layer 4	1.14E-04

Combination of the external circuit model and detailed winding model was constructed in electrical simulation software PSCAD to evaluate the transient behavior of surge inside the coil. Various simulation cases were performed to evaluate different scenarios. Using PF1A coil as an example, the result is presented here.

Impact of Surge Rise Time

Figure 6 shows the turn to turn voltage for a few different spots inside the coil. The peak voltage at the terminal of the coil is 5kV. The surge voltage rise time is 1 us. As shown here, the maximum turn to turn voltage (240V on the last turn on layer one) is far greater than the peak terminal voltage divided by the number of turns (5000/64 = 78V). This is due to the fast rate of rise of the surge voltage.

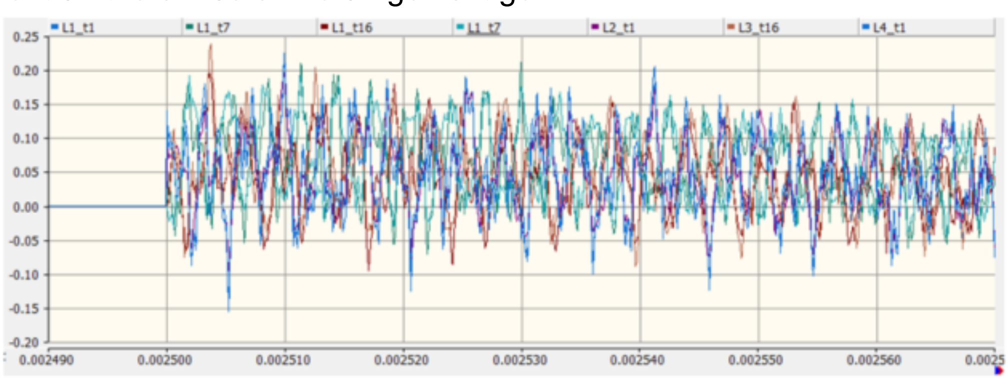


Figure 6 Few Turn to Turn Voltages inside the Coil

Figure 7 shows a plot of peak turn to turn voltage versus the applied voltage surge. Shown here, peak turn to turn voltage decreases with longer voltage surge rise time, gradually approaching 78V. Since the minimum model unit is one turn, there is a possibility that the remaining transient is due to the inability to model at finer detail. Never the less, it is obvious that the voltage surge rise time should be slow to ensure there is no voltage escalation inside the coil out of expectation.

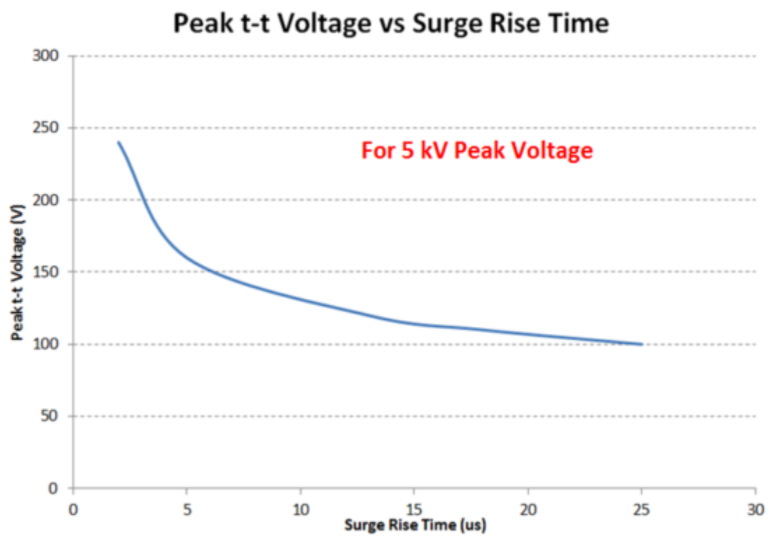


Figure 7 Peak Turn to Turn Voltage versus Surge Rise Time

To reach at slower surge rise time, larger source capacitor is needed. Therefore, the objective is to use smallest capacitor possible with acceptable peak voltage inside the coil to minimize cost.

Voltage distribution inside coil

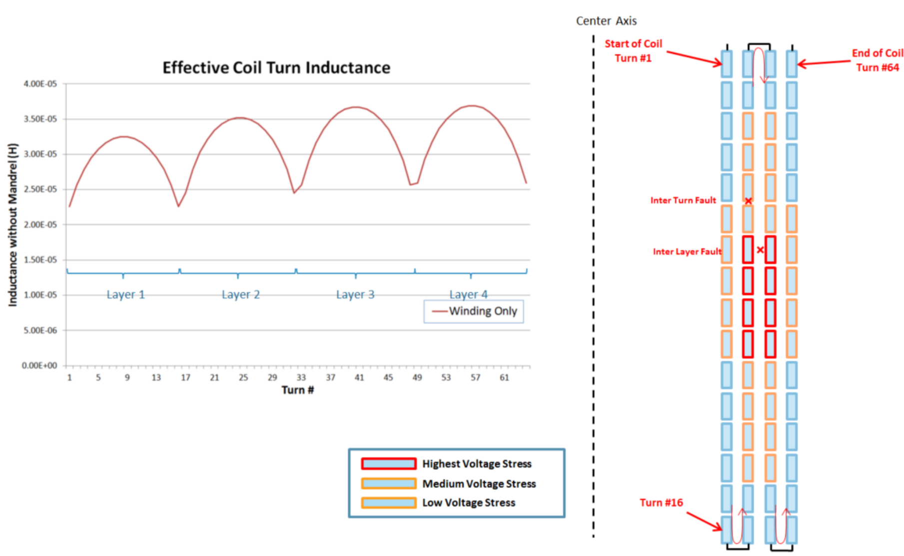


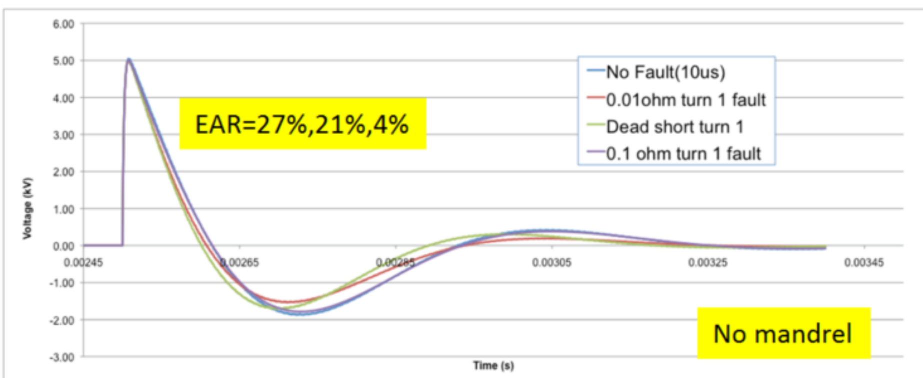
Figure 8 Demonstration of Voltage Distribution inside the Coil

Figure 8 shows the voltage distribution of inside the coil winding. As shown here, due to geometry effect of winding turns, voltage is unequally distributed. Peak voltage is higher in the center of the winding comparing to the sides. This effect can be altered if the coil is placed in the machine due to mutual couple of coil to adjacent passive structures. Future analysis should be performed if testes are going to be performed after the coil is installed.

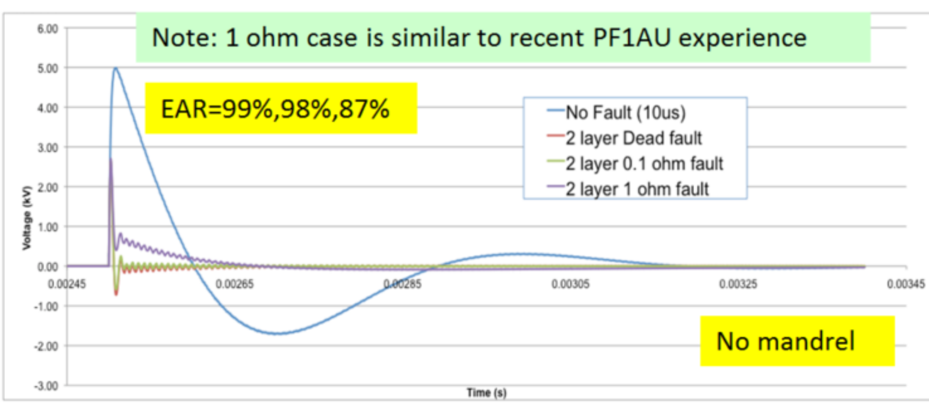
Fault Detection Sensitivity

Figure 9 shows the surge voltage response to different types of faults. The difference between curves can be identified by integrating the area below each curve. The top plot shows the voltage response due to different turn to turn fault with different fault impedance. As shown, it is easy to observe a dead turn fault or a fault with 0.01 ohm fault impedance. If the fault impedance is larger than 0.1 ohm, it is hard to detect with only 4% difference in integrated area.

The bottom plot shows the voltage response to layer to layer faults. As shown here, since more turns are involved, the difference among the response voltage is significantly larger.



Turn to Turn Fault



Layer to Layer Fault

Figure 9 Fault Detection Sensitivity

Cc:

J. Dellas
C. Neumeyer
W. Que
S. Raftopoulos
P. Titus

NSTX-U File

MAG-180315-NG-02

TO: DISTRIBUTION
FROM: NEVELL GREENOUGH
SUBJECT: SURGE TESTING

PF1A Surge Test Modelling and Benchtop Test Results

A simple SPICE model of the PF1A coil was prepared to investigate the response to surge testing. The assumptions for the model are:

- L = 2.0 millihenries
- R=0.0069 ohms at DC, conductor size 1" x 0.5"
- Turn-turn insulation = 2x.04" kapton-glass-epoxy composite
- Layer-layer insulation: 2x.04" kapton-glass-epoxy composite + 0.012" glass-epoxy composite
- Layer-ground insulation: 0.125" glass-epoxy composite + .04" kapton-glass-epoxy composite
- Relative dielectric constant of insulation: estimated 5.7 based on several test coupons using adhesive epoxy and kapton-glass insulation tapes
- 25.5" average diameter of coil, 4 layers, 18" long, 64 turns. All layers have equal areas.
- Surge tester internal energy-storage capacitor: 2.0uF
- Surge tester current-limiting inductor: 0.035mH in series with energy storage capacitor
- Measured test coupon capacitance, 0.04" thickness: ~32pF/in2 (from three test coupons) using adhesive epoxy
- The insulation-system dielectric loss will not be included as this phenomenon only occurs at very high frequencies .

These values are intended to approximate the work of Andy Gao's mutually-coupled PF1A model. The goal is to predict the major self-resonant frequencies and the major internal voltage transients within the coil. Later, a set of measurements on a test set consisting of two modified "H2" coils will be presented as indicative of the real-world responses of the PF1A coil. Several small-area test coupons were prepared to estimate the dielectric constant and standoff voltage of the insulation system. It is understood that the dielectric constant of the actual VPI epoxy may differ from standard adhesive epoxy used here. Resonant frequency measurements will be made on the final finished coils to predict the actual dielectric constant. This information will be used to modify the model if necessary.

The model was prepared by simplifying 64 turns of PF1A into 16 groups of 4-turn equal inductances having 1/16th the inductance of the full coil. Likewise, the calculated layer-layer capacitance was aggregated into four-turn facing surfaces based on the values from the test coupons. The turn-turn capacitance for the turn-group was calculated from each turn's facing surfaces, divided by four turns in series.

Any coil will have a number of resonant frequencies highly dependent on the layer-layer insulation, the winding geometry and the dimensions. These can be easily measured to predict the response to transients applied to the coil, such as those imposed by surge testing. The response of the coil at its various resonant frequencies is dependent on the drive applied to the coil. Parallel-resonances, being high impedances, will be driven from high-impedance sources such as lightning strikes. Series resonances, being low impedances, will be driven from low-impedance sources such as a surge tester. The lowest-frequency resonance is the first parallel resonance, occurring from the bulk inductance of the coil and its equivalent terminal capacitance from its insulation system. Next up in frequency is the first series resonance occurring from the electrical length of the coil approximating a ½-wave of transmission line. Multiple resonances follow as frequency is increased due to transmission-line effects. Modelling and experiment show that for a four-layer coil, the strongest resonance is the second series resonance for low-impedance systems. The coil is one-wavelength long at this frequency.

The surge tester we will be using has a 2 microfarad energy storage capacitor and is believed to have a 35 microhenry inductor in series to limit short-circuit currents to safe values. This is consistent with the unit's maximum short-circuit current rating. An internal power supply pre-charges the capacitor to a known high voltage, up to 7kV. A controlled switch "dumps" the capacitor-inductor network into the test coil, which rings at a frequency determined by the coil's inductance and the 2 microfarad internal capacitor. This is often called "shock" excitation. The decay of the ringing is displayed on a built-in oscilloscope.

A shock-excited real-world coil will have multiple ringing responses determined by its self-resonant frequencies. These will cause transient voltages to appear within the coil of often surprising magnitudes and is highly determined by its geometry. The model created for this report will be used to demonstrate the worst-case approximate magnitude and frequency of these voltages. Additions will be made to the model external to the coil to "tame" the excitation of transients internal to the coil. This information will be translated to a network added to our surge tester for our test program.

The Model:

The model is constructed much as the real-world coil. The inductors L1 – L16 are arranged in four horizontal layers, with a matrix of vertical capacitors C1 – C12 representing the layer-to-layer capacitance. Each inductor and capacitor represent four turns of the finished coil. The coil terminals are titled “lyr4” and the ground symbol . “lyr1” and “lyr3” are the layer-changeovers at the opposite ends of the coil. The turn-turn capacitances are represented within the inductor specifications and are not shown. Likewise, one milliohm of the conductor resistance is included in the inductor specifications. Additional conductor resistance is represented in three separate components placed at the ends of the layers, R1, R2 and R3. Capacitors C14-C22 represent the ground insulation wrap over the outside of the coil and adjacent metal surfaces.

- The surge tester is modelled by capacitor C23 and an initial condition of a 1-volt precharge. Switch S1 and inductor L17 are intended to model the discharge circuit of the actual surge tester. R6 is a damping resistor that may be added to the tester. Source V1 controls the switch S1.
- Risetime control is provided by the “snubber” network consisting of R7 and C13.
- The model was written for the freeware LTSPICE program available from Linear Technology/Analog Devices.
- The apparent resistance of the coil changes with respect to frequency due to the well-known “skin effect”. Its resistance rises as frequency is increased. Various assumptions are made for the coil resistance depending on the frequency to be analyzed. The DC resistance of the coil is about 6.9 milliohms at DC. At 100kHz, the coil’s resistance is about 170 milliohms due to the skin effect decreasing the amount of useable copper conductor. The conductor resistance at 100kHz was chosen as it is the approximate center of the range of internal resonant frequencies.
- Risetime-modifying components will be added between the surge tester and the test coil.
- The source is 1.0 volt 0-to-peak. Displayed waveforms are with respect to the source voltage.
- Internal modifications may be indicated for the surge tester. This will be determined by an examination of the unit we receive.

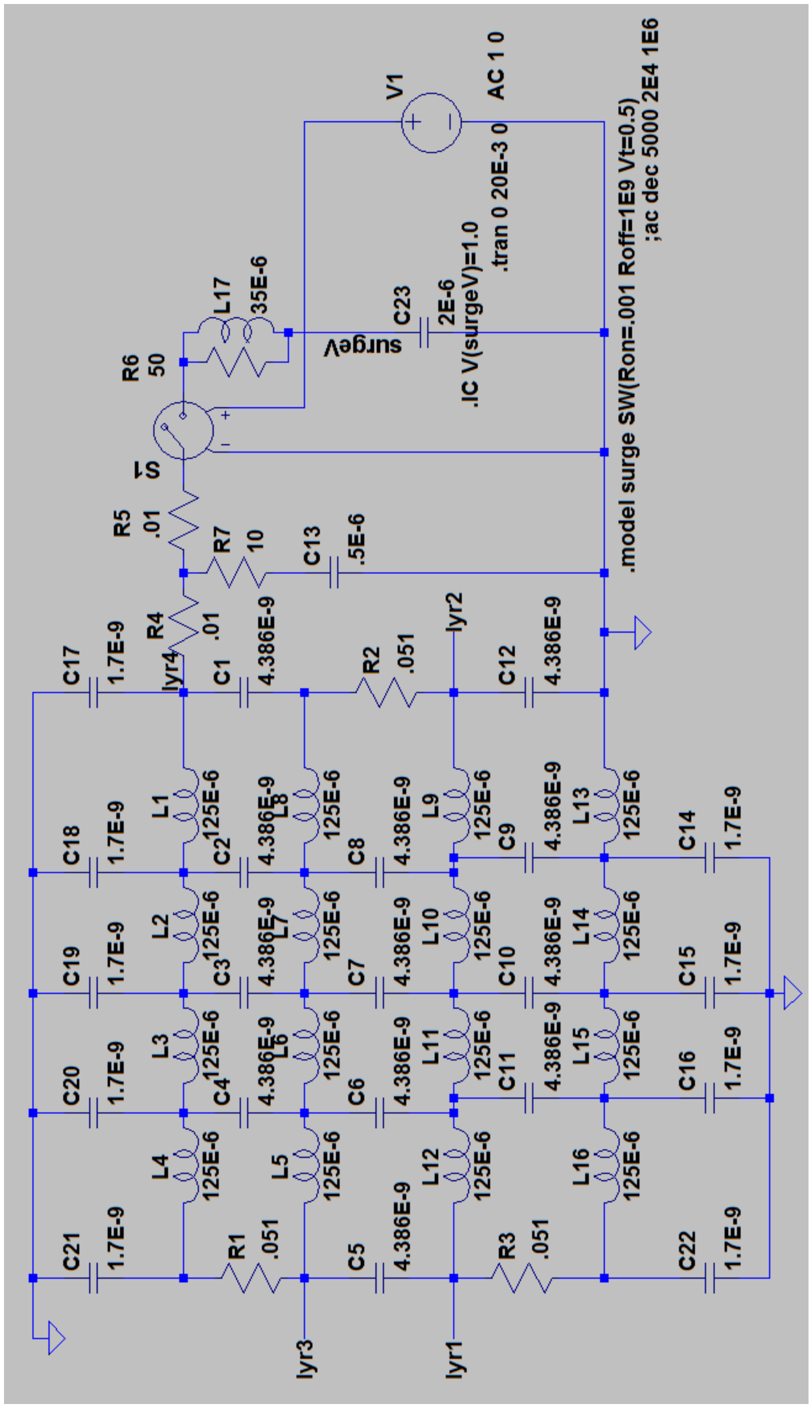


Figure 1: LTSPICE model of surge tester and PF1A coil, tailored for 100kHz

Figure 2 shows the terminal voltage when the surge tester fires. The attached coil rings with the internal capacitor in the surge tester. For PF1A, this is about 2.2kHz.

The decay of the ringing is an indication of the "Q" of the circuit and is dependent on coil resistance, insulation loss, interconnecting lead resistance and turn-to-turn isolation. The applied source voltage is 1 volt for Figures 1 through 5.

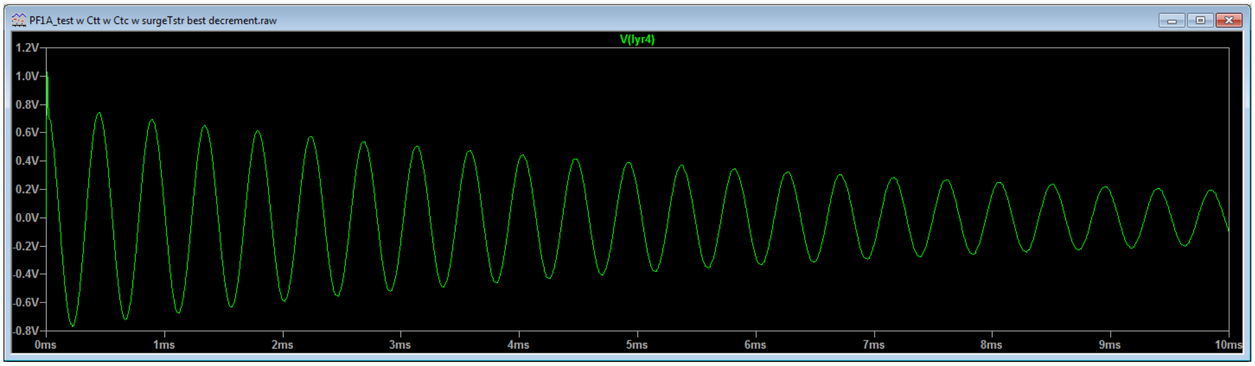


Figure 2: Coil terminal voltage response to a well-damped surge tester and risetime-control "snubber", for the model shown in Fig. 1

A look at the voltages inside the coil in Fig. 3 reveals some interesting features. For the following graphs: Green- Outer layer coil terminal; Blue- Layer4-to-layer3 crossover; Red- Layer3-to-layer2 crossover near terminals; Cyan- Layer2 to layer1 crossover. There are considerable ripples between the layer voltages even though the terminal voltage rise-time has been limited to about 10 microseconds. The major transient frequency visible is about 66kHz. The largest layer-to-layer voltages occur at the crossover between layers 3 and 4; and layers 1 and 2. These two voltages swing opposite each other with a peak magnitude of about .7 of the applied terminal voltage.

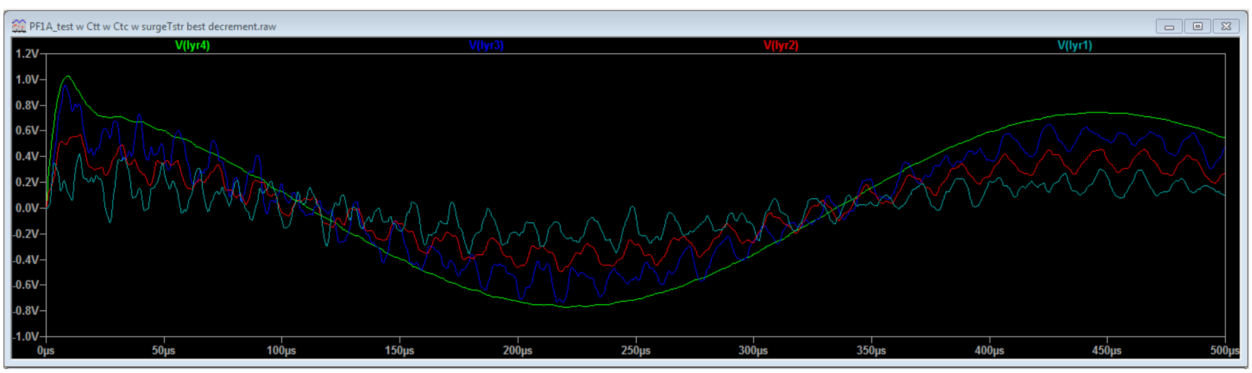


Figure 3: First 500uS of surge tester discharge, well-damped tester, approx. 10uS rise-time

What "knobs" do we have to control the transients? There are several. The values of R7 and C13 control the surge test risetime. R7 adjusts the damping factor of the first peaks of Fig. 4. C13 controls the timescale of the "rounding over" of the rise-time. But there are compromises. Too large a value for C13 costs surge voltage. Too small excites the internal transients excessively. R7 too small decreases damping (more short-term ringing) and R7 too large increases the peak voltage excursion. Actual values for the R7-C13 snubber will require tailoring in the field with the real surge tester and a sample PF1A test coil.

The surge tester's discharge circuit is believed to have a series inductor for current limiting. This inductor, if undamped, has a large effect on the transient voltage impressed on the test coil terminals. R7=0 leads to a strong 2:1 overvoltage as C13 resonates with the current-limiting inductor in the surge tester. A damping resistor was added to the model to control this effect. An internal examination of the tester will show the precautions its designer has provided.

Figure 4 shows the effect of no snubber network and an improperly-damped output inductor in the surge tester. R7=10,000 and R6=50000 ohms. The peak excursions of the transients reach 1.5x of the applied voltage and higher resonant frequencies are excited. This may result in more spot-heating of any defects present in the insulation leading to early insulation failure.

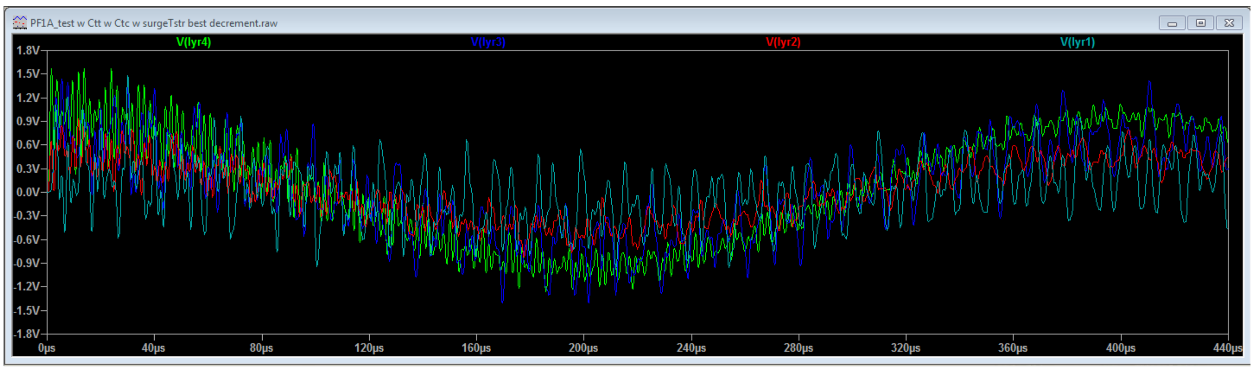


Figure 4: Undamped surge tester with no risetime-limiting snubber network

Figure 4 should be noted for its similarity to results obtained by Andy Gao in his mutually-coupled turn model. All layer-ends are challenged to the full extent or more of the terminal voltage. The most challenging is the outer ground layer of insulation. This situation is not recommended.

Turn-turn voltages:

Figure 5 shows the voltage across a 4-turn group at two locations. Blue is at the layer 4 terminal and green is at for L8 near the layer 2-3 crossover. Note the similar excursions and that the peak-peak magnitude is about $1/5^{th}$ the applied surge voltage. A single turn is expected to be $1/20^{th}$ of the applied voltage. This case is the same as Fig. 4, an undamped surge tester without a snubber network. Surprisingly, the presence of a snubber and surge tester damping has little effect on the p-p turn voltage. The peak-peak turn voltages are approximately the same throughout this simplified model with equal inductances everywhere.

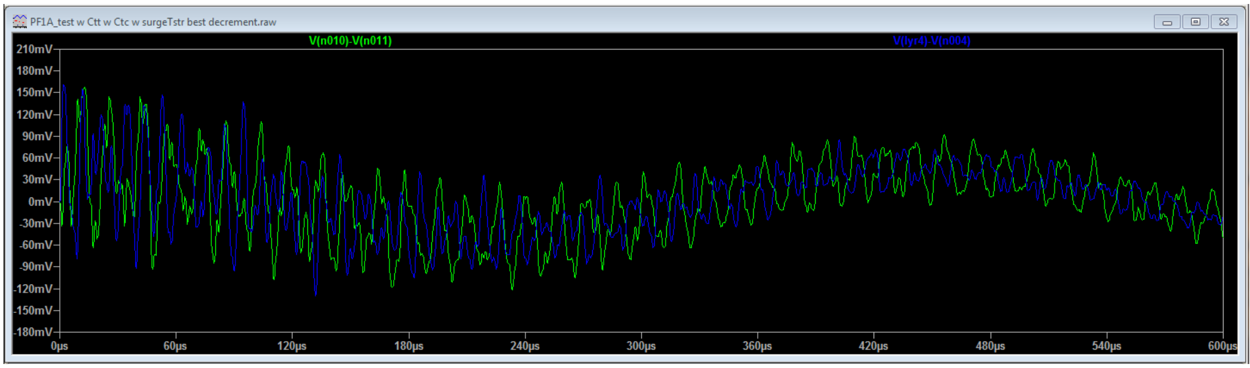


Figure 5: Turn-turn voltages for a 4-turn group of turns. Turn-turn voltage is ¼ the value shown.

Benchtop Test Set:
A real-world test was constructed to determine the validity of the model and the degree of its results. This was done at the 20-volt level since our surge tester has not arrived at the time of this writing. A bidirectional switch was fabricated from several MOSFETS and a dual-output function generator. A high-quality 3 microfarad plastic capacitor, 33 microhenry inductor and 20-volt bias supply completed the test set. Two “H2” coils were obtained for the test and stacked on top of each other. The pancake two-layer winding configuration for each coil is similar enough to the layers of PF1A to allow two coils to approximate a 4-layer cylindrical winding. One coil was drilled on the inside to allow access to the joint between its two layers. Known similarities/differences:

- The inductance is somewhat smaller, 1.6mH instead of 2.0mH of the model PF1A coil
- The conductor size is smaller, ¼” x ¼” instead of 1” x ½” of the DC PF1A model
- The coil is driven with a 20V-precharged 3uF capacitor
- The series inductance is the same, ~35 microhenries
- The risetime is faster than the surge tester is likely to be
- The insulation system is similar, epoxy-impregnated glass tape
- The layer-to-layer insulation is thicker, about .25” instead of 0.09”
- Clip-lead interconnects are used instead of large-area cables
- The H2 coils are wel-abused.

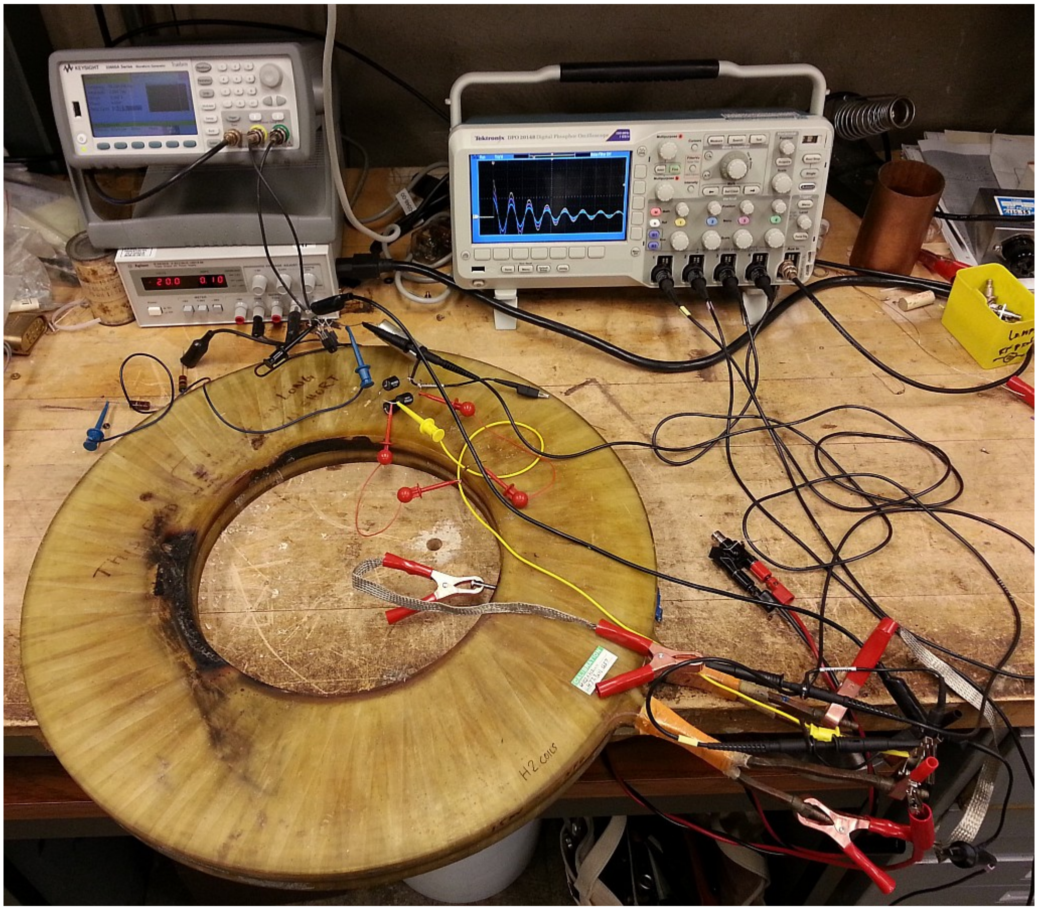


Figure 6: Dual H2-coil test set and sample waveform on oscilloscope

Figure 6 shows the H2-coil test set for PF1A. The signal generator at the left and the power supply below it are driving several MOSFETS simulating the switch of the surge tester. The coil terminals are at the lower right, interconnected with large clips and braid. The top coil is tapped with a screw on the upper layer, inside end simulating the junction between layer 3 and layer 4 of the PF1A coil.

Figure 7 shows an oscilloscope trace for a well-damped surge tester simulator and snubber network. Yellow is the outer-layer 4 coil terminal, magenta is the layer3-to-layer4 junction and cyan is the layer2-to-layer3 junction. The layer1-to-layer2 junction is unavailable in this test set. Vertical is 5V/div and a 20-volt precharge is applied to the energy-storage capacitor. C13 is 0.22uF, R7 is 12 ohms, R6 is 39 ohms. Further optimization was not necessary at this time. The test set applies 20volts to the coil.

The major ringing frequency is about 2 kHz which matches the predicted frequency of the PF1A coil and the surge tester. The decay is considerably faster which is likely due to the smaller conductors used.

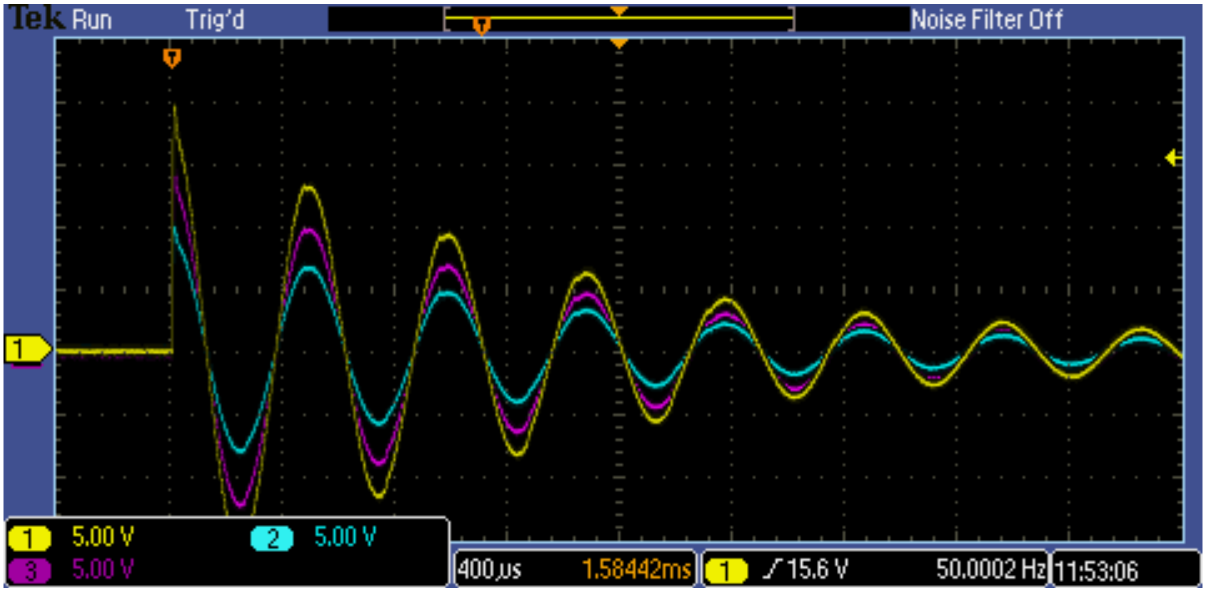


Figure 7: Measured results for a 20-volt applied surge for various layers, well-damped circuit, 400uS/div

Note that there is almost no high-frequency ringing apparent. This is likely due to the smaller size and increased losses of the benchtop H2-coils.

Figure 8 shows the first 70 microseconds of the response for the same circuit as Figure 6. Note that the snubber network chosen provides the requested 10 microsecond rise-time for the surge test system.

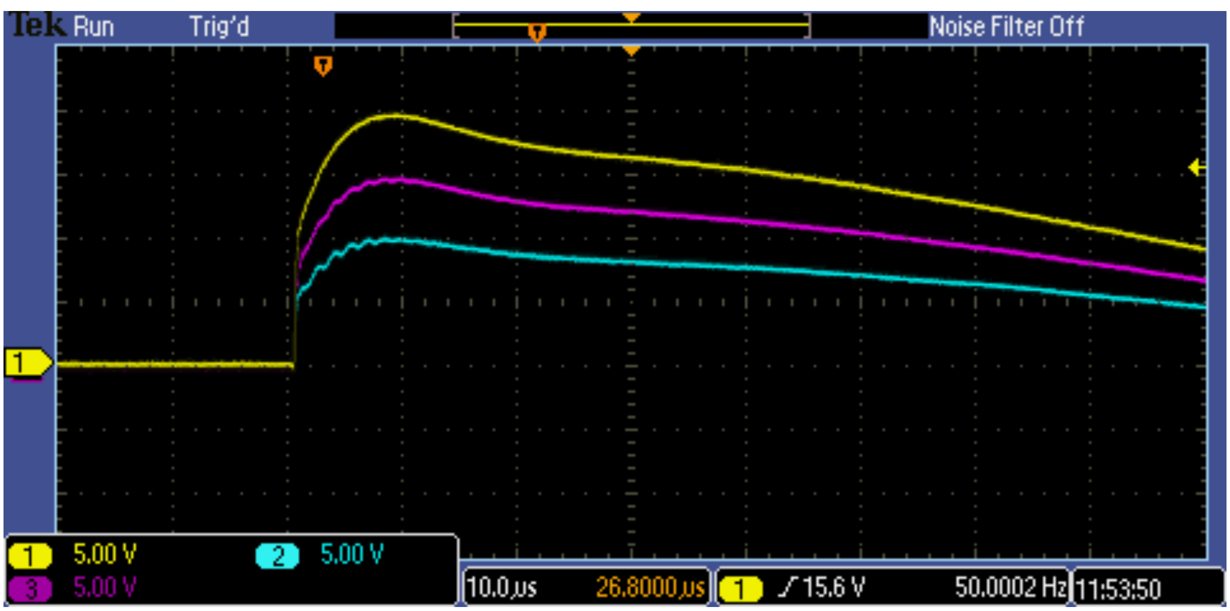


Figure 8: Rise-time of the surge tester with damping and snubber applied, 20-volt source, 10uS/div

Note the suggestion of a high-frequency transient response on the cyan and magenta traces. This is similar to that shown in Fig. 3 although the magnitude is much smaller.

Figure 9 shows the result of no snubber network on the surge tester output (R7-C13). A slightly-larger transient is apparent in response to a very-fast surge test waveform (~100nS). Note that the amplitude and duration is much less than that predicted by the model.

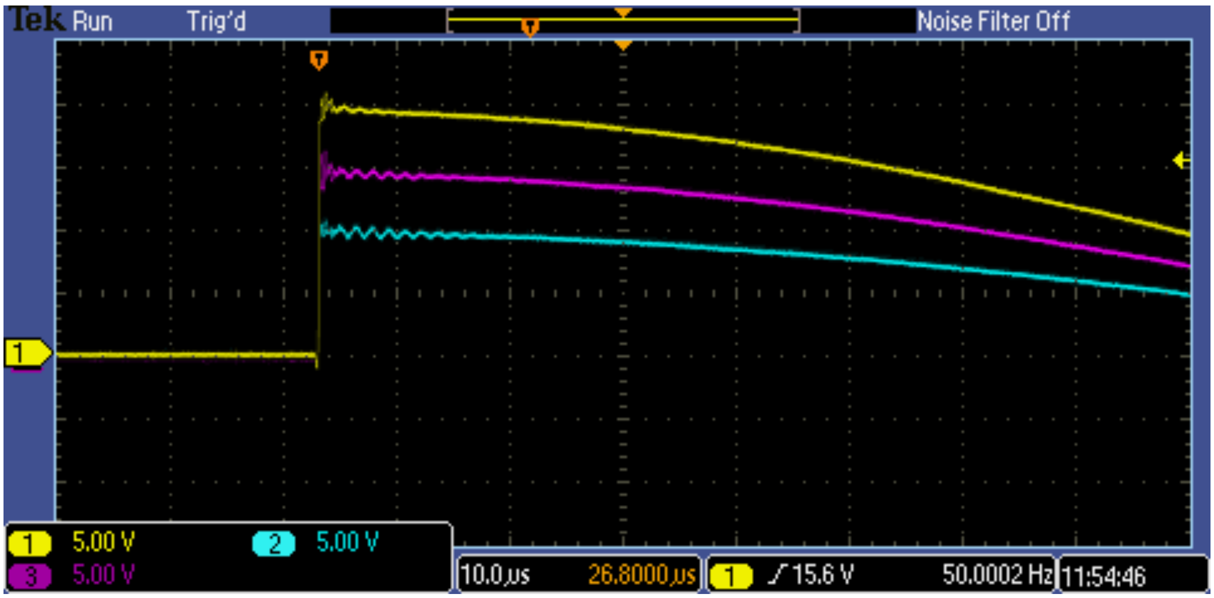


Figure 9: Response of the test set with no snubber network at the surge tester output, 20-volt source, 10uS/div

For the above traces, a damping resistor has been added to the surge tester simulator circuit output inductor. Some form of damping is needed to control the output voltage swing of the surge tester. Without damping the output inductor resonates with the combination of the test coil's winding capacitance and the energy storage capacitor. Figure 10 shows the result of an undamped surge tester output inductor and no snubber network in place. Note the presence of higher-amplitude and higher-frequency transients.

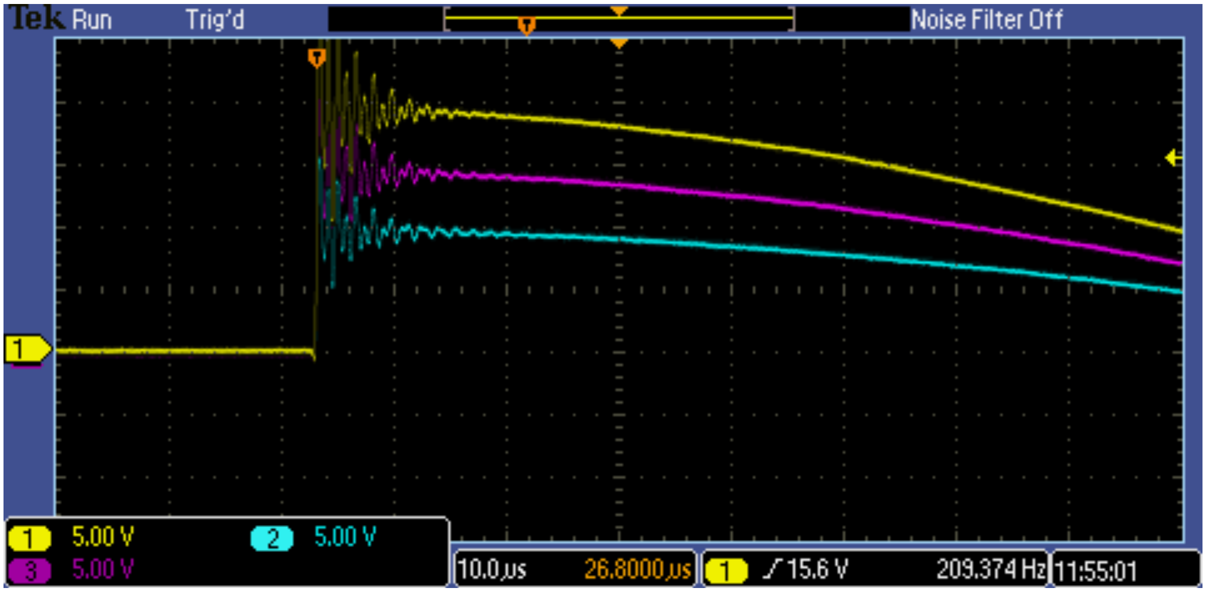


Figure 10: High-frequency transients induced by an undamped surge tester and no snubber, 20-volt source, 10uS/div

This compares with Figure 4 of the model although the duration of the transients is much shorter. Note that the peak value of the terminal voltage approaches 150% of the applied voltage of the surge tester. A closer view is shown in Fig. 11 at 2uS/div.

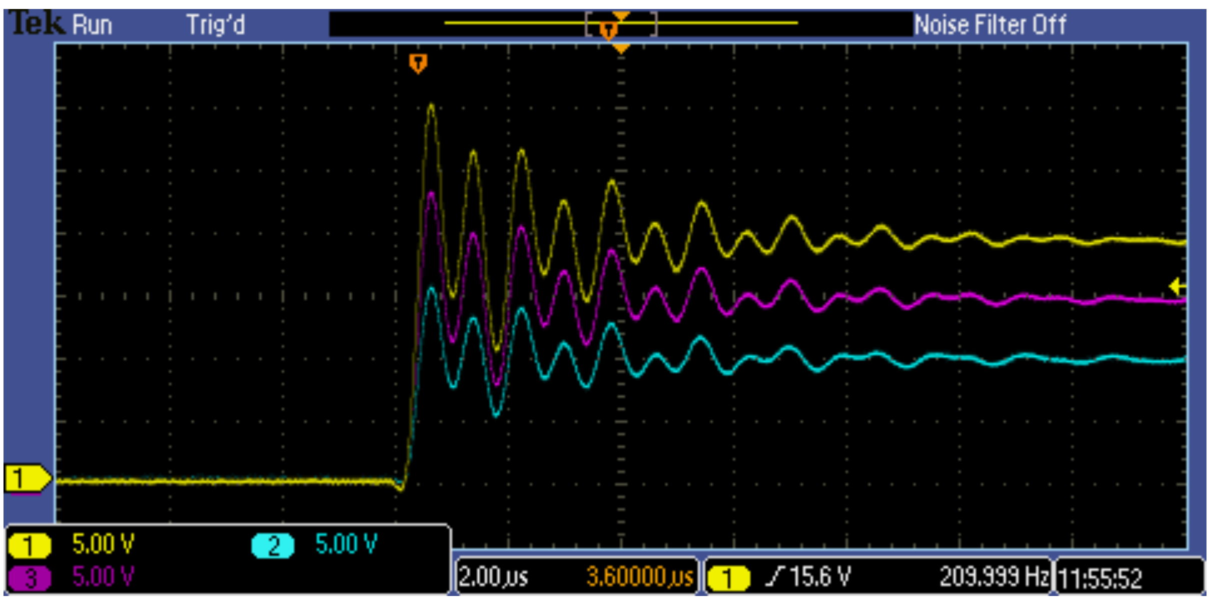


Figure 11: Same as Figure 9, 2uS/div

Care should be taken to provide a series resistor with the snubber capacitor. Figure 12 shows a very large transient when R7 approaches zero and the surge tester is undamped. This situation should be avoided. The overshoots almost double the applied test voltage of 20V.

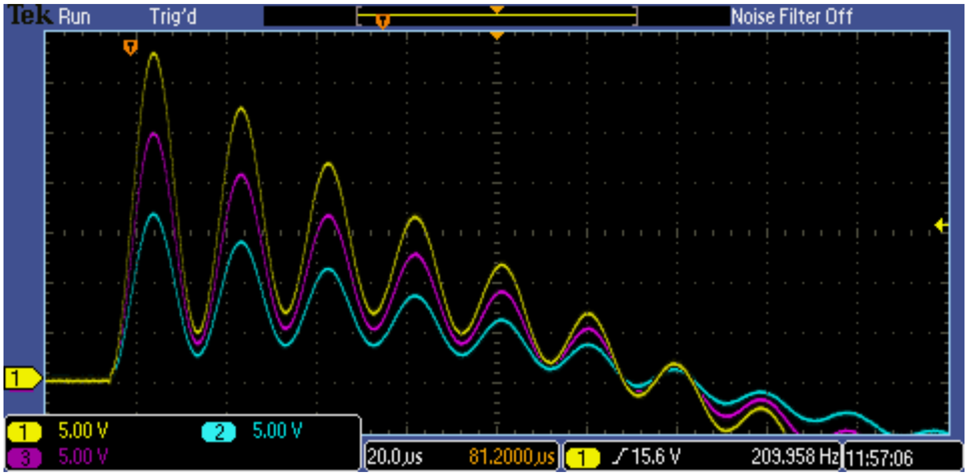


Figure 12: Large transients induced by no resistance in series with snubber capacitor

Hipot Tests:

A small 5-sq. in test coupon was prepared for megger and hipot tests. It consists of two half-lapped layers of Kapton-glass composite plus one half-lapped layer of glass tape, sandwiched between copper foils. “Double-bubble” adhesive epoxy was applied to each layer in the stack for impregnation followed by clamping with a vise for curing. The resulting insulation thickness for this sample is 0.05”. This approximates the insulation system applied to the conductor before winding. Adjacent turns will have two such insulating systems between conductors. Adjacent layers include an additional layer wrap. Figure 13 shows the test coupon.

Figure 13: 5 sq. in. Er and hipot test coupon, 0.05” thick Kapton-glass-epoxy composite

Megger tests showed much greater than 100G-ohm at 5kV applied voltage. Further hipot tests showed standoff to 17kV, followed by a flashover at the shortest path around the lower edge insulation at 20kV. No punch-throughs were observed and the sample again showed greater than 100G-ohm @5kV following the hipot test. The dielectric constant of this sample is about 5.8-5.9 following equations described in Appendix A , neglecting fringing capacitance.

Conclusions:

- A simplified model has been constructed and analyzed with LTSPICE. The model shows the approximate responses of the layers of a PF1A coil to various applied surge test scenarios.
- The largest voltage stress is at the layer 1-2 crossover versus the layer3-4 crossover point. A larger voltage excursion appears across layer 3-4 crossover to ground, but the insulation is thicker at this location.
- The model predicts that turn-turn transient p-p voltages are expected to be about 1/20th of the applied voltage.
- An approximate snubber network has been found that will hold the model's predictions of layer voltages to values that approach but do not exceed the PF1A coil applied terminal voltages. The values are reasonable, ~.2 to .5 microfarad, 5-20 ohms.
- The surge tester's internal discharge circuit needs to be examined for proper damping of its current-limiting output inductor.
- A benchtop test set has been constructed and examined. The benchtop simulator shows similar responses to the model, although to a lesser degree.
- In general, the benchtop test set's waveforms show much "tamer" results than the model. The durations and amplitudes of the transients are much less apparent. The results obtained on a "real" PF1A coil may be larger due to its larger conductor size and improved insulation materials. This should be taken into account when planning the surge tests for the PF1A coils.
- Radiative losses are not considered in the model. The test set's transients are as high as 1MHz (Figure 10) and radiative losses may account for its improved damping.
- The insulation system can withstand greater than twice 20kV for small samples. The leakage resistance at 5kV is unmeasureable for small areas.
- The Hioki brand L-C-R meter available for coil testing is capable of making detailed impedance-versus-frequency sweeps up to 200kHz. This should be employed to find the major resonances of a finished PF1A test coil. Other equipment is available to make higher-frequency measurements if needed.

Appendix A: Calculations Used for Simulation

Equations for calculating the approximate inductance of a multi-layer coil can be found in many texts and handbooks. The most popular is:

LuH=0.2*(avg. diam)^2*N^2/(3*(avg. diam)+9*(length)+10*(winding thickness))

(from Radio Amateur's Handbook 1949, p.30), all units inches

The PF1A coil average diameter is approximately 25.5 inches, length 18", thickness 2.56", 64 turns. This calculates to an inductance of 2.015 millihenries.

The capacitance in picofarads of facing surfaces can be calculated by:

CpF=0.224*(facing area)* (dielectric constant)/(spacing)

(from Radio Amateur's Handbook 1949, p.27, for 1 facing surface), all units inches

4 turns of 1" conductor, 25.5" average diameter is about 320 square inches. All layers are assumed to have the same area to simplify the model. The thickness of the insulation layers is 0.040" on each conductor plus 0.012" layer insulation. This equates to approx. 4380pF for four facing turns and a composite dielectric constant of 5.7. This number is assumed and subject to wide variability as the dielectric constant of the CTD-425 epoxy proposed for the encapsulant is unknown at this time.
Likewise, the capacitance of four turns of 1" wide conductor and one set of tapes plus 0.125" of epoxy-impregnated ground wrap is about 1700pF.

Skin-depth resistance values were obtained using standard equations programmed into a web calculator. References are provided on its webpage.

http://chemandy.com/calculators/skin-effect-calculator.htm

Standard textbook equations were used for L-C resonant frequencies and reactances.

Appendix B: Dielectric Measurements on CTD425 Kapton-Glass Insulation System

Capacitance measurements were made on a section of the test "log" consisting of 24 copper bars wrapped with 0.040" composite kapton-glass tape, impregnated with CTD425 epoxy. For this test, four center bars were connected together and measured versus the surrounding 14. The 4 corner bars and the top row were not included in the capacitance calculations as they contribute very little fringing capacitance. "Log" bar numbering:

13	14	15	16	17	18
7	8	9	10	11	12
1	2	3	4	5	6

1 to 6, 7, 12, 13-18 connected together and to "-" of C meter
8-11 connected together and to "+" of C meter
Capacitance measured with Agilent U1733 LCR meter, = 633pF

Capacitance:	633	pF
Length:	11.36	inches
Bar width:	1.086	inches
Bar height:	0.564	inches

A "segment" calculation was made for each facing surface using standard capacitance equations of Appendix A. The composite dielectric constant was adjusted such that the total calculated capacitance matched the measured capacitance. Individual insulation thicknesses were measured for each bar.

Surface	Spacing	Width	FaceArea	Seg. Capac.
2-8	0.145	1.086	12.34	61.0
3-9	0.122	1.086	12.34	72.5
4-10	0.127	1.086	12.34	69.6
5-11	0.122	1.086	12.34	72.5
11-12	0.128	0.564	6.41	35.9
11-17	0.13	1.086	12.34	68.0
10-16	0.135	1.086	12.34	65.5
9-15	0.13	1.086	12.34	68.0
8-14	0.12	1.086	12.34	73.7
8-7	0.096	0.564	6.41	47.8
			Calc. total,pF:	**634.6**

Dielectric Constant for above: Approximately 3.2.

This will raise the calculated resonant frequencies presented in the body of this document by a factor of (5.7/3.2)^.5 or about 1.3. This is beneficial as the energy in a step function approximation to the surge test declines with increasing frequency. This reduces the transient voltages induced. A further reduction in transient voltages results from increased copper losses at higher frequency.

Revision History:
Draft: 3/9/18
MAG-180315-NG-01 3/15/18: Added Appendix A and H2 coil test results
MAG-180315-NG-02 3/23/18: Added Appendix B with dielectric constant tests

<u>Distribution</u>

C. Neumeyer
A. Gao
J. Dellas
W. Que
S. Raftopoulos
P. Titus
.
.
.
NSTX-U File