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Analysis of the Capabilities and Practical Application of a Novel Quality Check and Test Technique Designed for the CLAS 12 Toroid Coils Production

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Abstract

The use of AC current injection in order to provide higher turn-to-turn voltage drop due to the coil inductance has proved to be effective in the detection of inter-turn shorts in an insulated coil package. This is an important quality test for the wound coil and it is not a trivial task to guess and estimate the impedance of the wound coil because even though the impedance of the whole coil changes, this change is so small and will be below the threshold of the inevitable measurement error. This paper discusses several means of quality assurance to detect this inter-turn short in the CLAS 12 toroid coils.

Background

For new studies of quark confinement, nucleon structure, the physics of nuclei and Standard Model's limits, Jefferson Laboratory is seeking to double the 6 GeV energy of the Continuous Electron Beam Accelerator Facility (CEBAF), upgrade its experimental hall and add a fourth hall. The 12 GeV upgrade project, sponsored by the department of energy will not only double the beam energy but also upgrade a range of existing facilities. For Hall B, the upgrade consists of replacing the existing CEBAF Large Acceptance Spectrometer (CLAS) detector with a new detector system, CLAS 12, which contains new magnets and detectors to capture the more forward-focused reaction products at the increased luminosity. The design of the CLAS 12 magnet is all new and specific to this project and the group here at Fermilab has been requested to prove the superconducting magnet designs for the CLAS 12 experiment at JLab. My work here is to provide an electrical test technique to detect the presence of turn-to-turn short in the coils.

Introduction

The task of detecting and locating shorted turns in an insulated coil package has always been difficult. In this paper, I will be presenting several means of detecting this turn-to-turn shorts and discussing the results I obtained from the experiments I carried out on the prototype coils available. I have carried out a series of tests on a 38-turn coil which is serving as a test bed to analyze the different measurement obtained. This technique was designed and developed specifically for the CLAS 12 toroidal coils which are wound using about 2 kilometers of mostly copper cable that are well insulated and with a total resistance of less than 0.5 ohms.

Clearly, it is impossible to reliably measure the resistance variation between coils in order to discern which one may have developed a turn-turn short during its winding and construction by simply comparing the relative or absolute resistances, since variations due to temperature, cable differences, and stretching will overwhelm the significant digits.

Therefore, we have resorted to utilize AC current injection in order to provide a higher turn-to-turn voltage drop due to the coil inductance. I have made use of a Lock-in Amplifier to reliably read single turn voltages that are free of all sorts of background noise.

It was observed that the coil impedance variation is monotone and increases as we move from one turn to the other. In a perfect coil we expect a small voltage variation between each turn with a roughly constant gradient. A sudden change of a voltage reading which recovers at the next turn showing a gradient spike is indicative of a short somewhere along that specific turn.

The system can be utilized to pinpoint the position along the turn by measuring three consecutive voltages along the coil narrowing it down to the highest gradient.

Methods

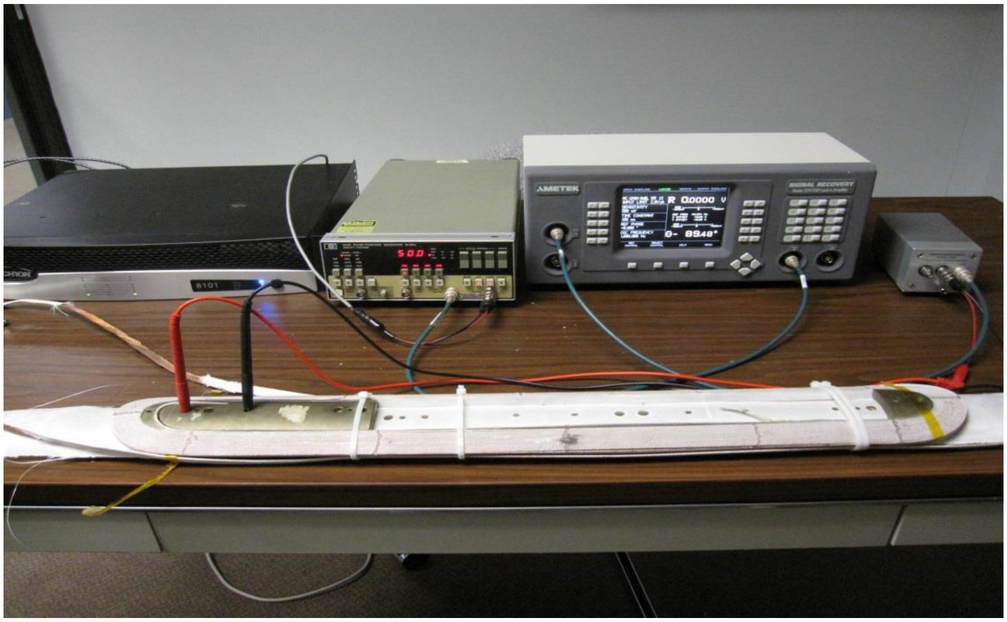

Figure 1: Experiment Setup

For this experiment, the AC current injection was via a power amplifier capable of delivering current to the order of 4 amps at a voltage output of 530 mV. A function or pulse generator was used to set and regulate the oscillation frequency of the input signal. It was also used as the low voltage source in the first phase of the experiment, providing an output voltage of up to 10mV and a frequency of 5MHz. A low noise transformer was also used in our data acquisition process. It was used to step up the very low output voltage drop obtained to a scale of 10, 100 and 1000.

A very important device in my measurement set up is the lock-in amplifier which used phase sensitive detection to measure the amplitude and phase of the signal at a reference frequency in sync with the output of the function generator. Using this technique, noise at frequencies other than the reference frequency is shut out as only input at the reference frequency results in an output. With a narrow bandwidth and with grounding and shielding, the lock-in amplifier is capable of minimizing intrinsic and extrinsic noise. Finally, two pin mouthed probes were used to poke through the insulation of the magnet coils to measure the voltage drop between any pair of turn.

Case Studies

Several cases of AC current injection have been utilized to observe this turn to turn short within the insulation coils and several conditions such as changing the oscillation frequency of the input signal and varying the step up ratio on the low noise transformer was also observed to obtain the most effective short detection technique.

Case 1: Testing with a function generator amplifier

For this case very low input voltages of the order of 10 mV was applied across the terminals of the coils and below are some of the results obtained.

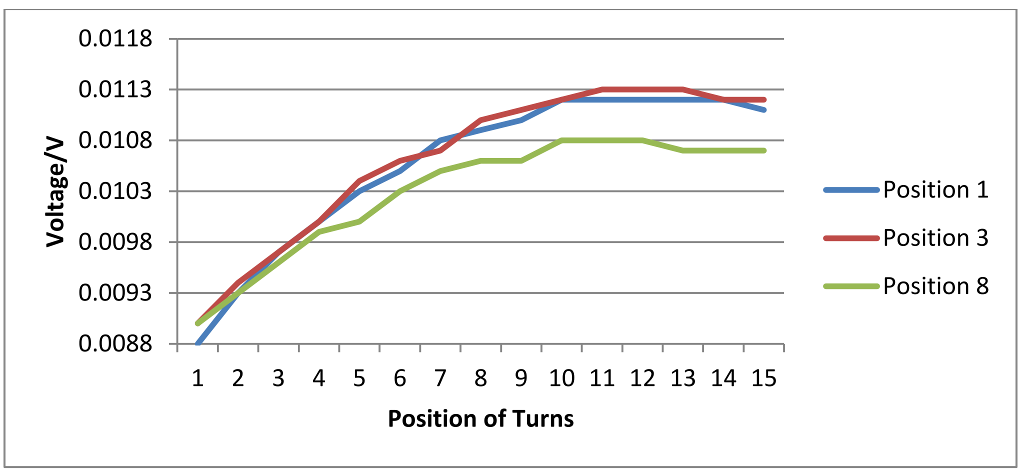

Fig. 2a: Voltage Variation at Turn Ratio of 1:10 and Oscillation Frequency of 50 Hz

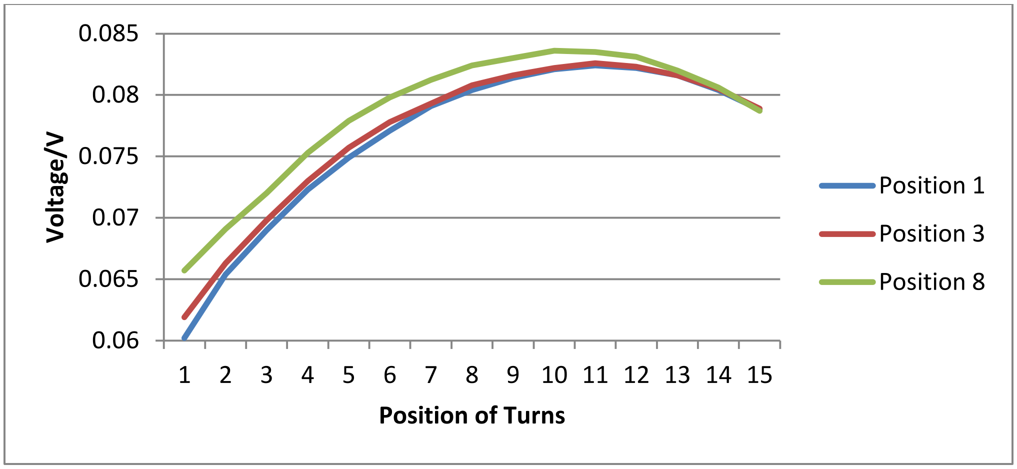

Fig. 2b: Voltage Variation at Turn Ratio of 1:10 and Oscillation Frequency of 500 Hz

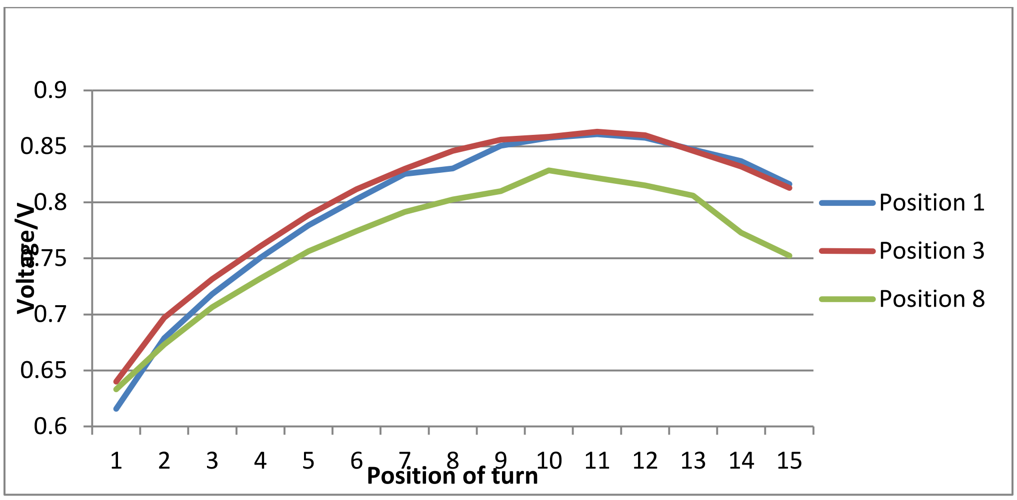

Fig. 2c: Voltage Variation at Turn Ratio of 1:100 and Oscillation Frequency of 500 Hz

The first case study illustrates how the voltage across the coil changes as we move from one turn to the next. All three conditions indicated that there was a rise in voltage as we move from turn number one through turn number nine where a peak voltage is observed and then a slight decline in the voltage drop as we poke through to the fifteenth turn. This observation is in sync with the behavior of a perfect coil in terms of voltage variation. It was also observed that an increase in the oscillation frequency of the input signal got rid of some of the noise observed previously at a lower oscillation frequency which is indicative of an improved test procedure. Finally on this note, an increase in the turn ratio of the low noise transformer from 1:10 to 1:100 allows for a better spread out of voltage from turn to turn.

Case 2: Testing with a power amplifier

The second case involves the injection of AC current into the coil via a power amplifier capable of delivering an output voltage of the order of 520 mV. This is a higher input than that of case 1 and below is the voltage variation when the input AC current was increased.

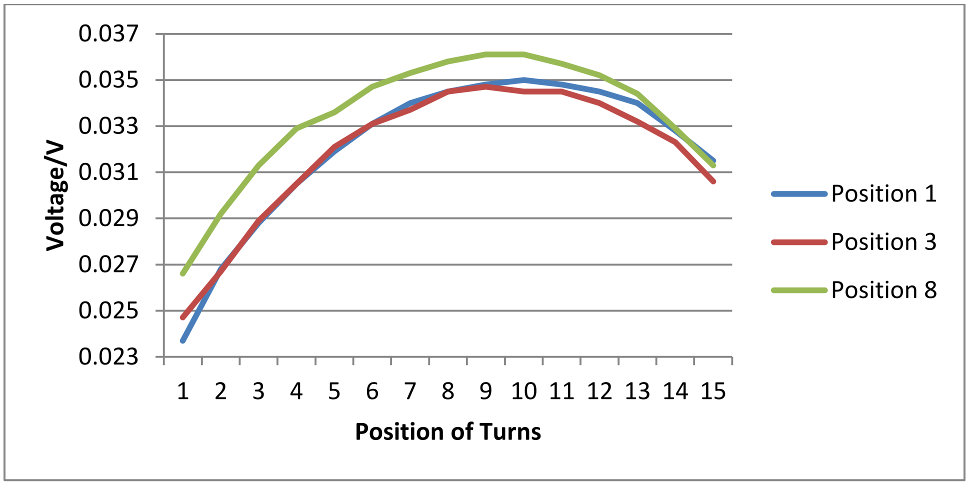

Fig. 3: Voltage Variation at Turn Ratio of 1:10 and Oscillation Frequency of 500 Hz

Deductions from case 2 include a steeper curve which would allow for an easy detection of a short compared to when using a low voltage source. A steeper curve would mean that if a short is observed at any point within the coil a deeper spike will be seen along that specific turn. Also a smoother curve with minimal background noise is observed.

Case 3: Introducing a soft short within coil turns

From cases 1 and 2 it has been established that a better and easier detection of a short can be achieved using the power amplifier, next we want to introduce a soft short within our test coil and then try to detect its position. A soft short is a low resistance wire greater than 0 ohms capable of drawing a small amount of current from the coil. This should reduce the voltage across the turn where it is introduced. We have introduced the soft short between the 9th and the 10th turn and we will also be varying the magnitude of the soft short.

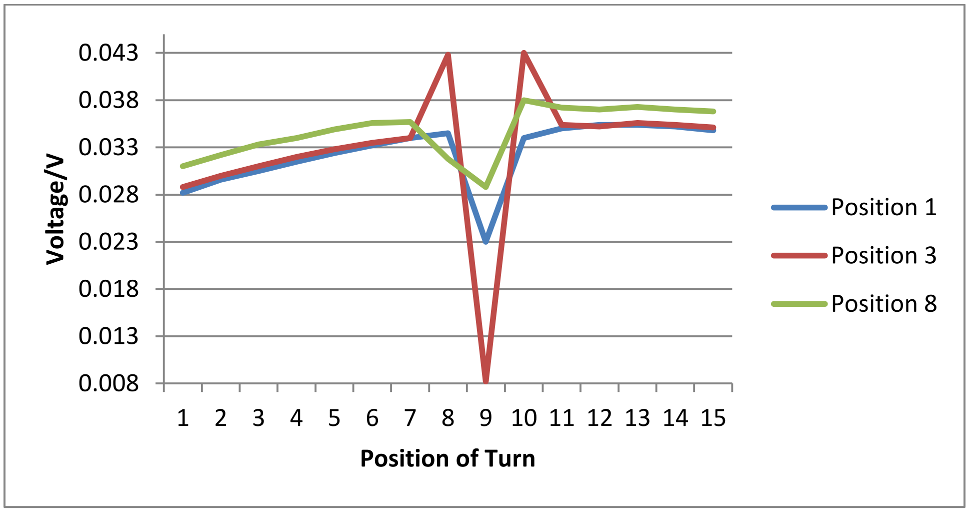

Fig. 4a: Voltage Variation using a 10 ohm soft short

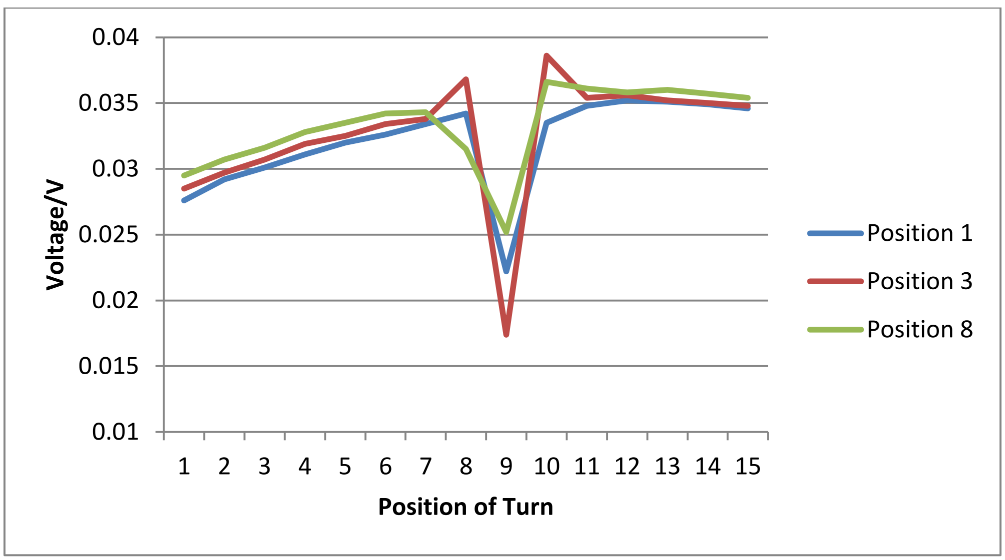

Fig. 4b: Voltage Variation using a 1.5K ohm soft short

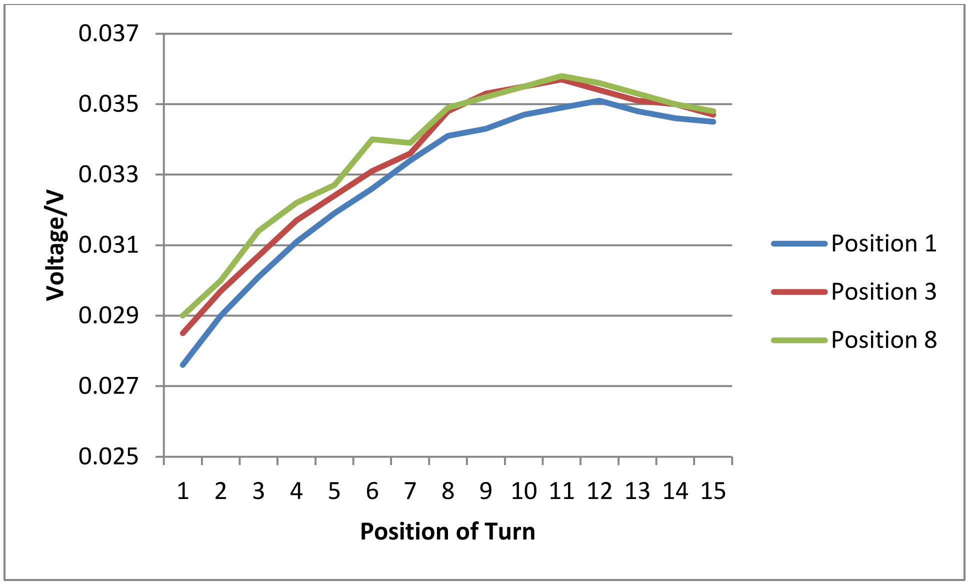

Fig 4c: Voltage variation using a 10K ohm soft short.

The introduction of the soft short has provided us with some interesting results. From the above graphs we can clearly see that the spike was deepest at a soft short value of 10 ohms and reduced in depth as we increased the soft short to a resistance of 1.5K ohms. The spikes were also deepest in all positions 3 which is the spot on the coil were we attached the soft short. Finally, it must also be noted that the soft short could not be detected at a resistance value of 10K ohms and it appeared as one of the previously obtained measurements when the short had not been introduced, meaning that at higher resistance value of the order of 10K ohms shorts within the coil would not be detected even if they are present.

Conclusion.

In summary, I have been able to establish that with an AC current injection via a power amplifier and with an introduction of a soft short of the order of 10 ohms and not greater than 1.5K ohms, turn-to-turn shorts can be effectively detected and located within the coils of the CLAS 12 toroid magnet. Finally, to obtain an easy detection of these turn to turn shorts, the oscillation frequency of the input signal should be set to 50 Hz and the step up ratio on the low noise transformer be set to 1:100.

Acknowledgement

I would like to acknowledge the contributions of certain individuals to my success in this project. First, special thanks to my supervisor Luciano Elementi, who provided me the rare opportunity of working on two career oriented projects this summer. Also, a very big thank you to Jason and Todd, for providing all the technical resources I needed for the success of this project. Finally, I want to appreciate the SIST committee for granting me the opportunity to be a part of this great internship.

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