BNL-226417-2024-TECH

CA/AP/713

AC resistance measurement of Skew Quadrupole Magnet

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December 2024

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U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP)

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December 2024

Abstract

This tech note exhibits AC resistance measurement system of the Skew Quadrupole magnet with and without a beam pipe used in the AGS ring. The measurement results are compared with a system that uses skew quad power supply for the magnet.

An introduction to ac resistance conceptualization and modeling is presented. It is followed by measurement methodology used and the results.

Introduction

A magnet when energized using pulsed currents will dissipate losses of two kinds – AC and DC losses.

$$P_{loss} = P_{dc} + P_{ac} \qquad \text{--- (1)}$$

The DC losses are ohmic losses proportional to resistance of the copper wound on the magnetic cores (R_{dc}) and the square of the rms value (I_{rms}) of the pulsed current passing through the magnet.

$$P_{dc} = I_{rms}^2 * R_{dc} \qquad \text{--- (2)}$$

While the DC loss in the magnet is a straightforward phenomenon, the AC losses are dependent on several variables and hence, they are complex. Domain wall movement in the core material causes hysteresis loss, eddy current loss is caused by the current loops in the core of the magnet. These losses, according to the general Steinmetz equation, are proportional to the frequency of the current flowing in copper coil, and the flux density. Additionally, there are copper winding losses in the form of skin effect loss, and proximity effect loss (1).

The skew quad magnet is being energized by the skew quad power supply of rated output of 450V at 275A. It is a current controlled power supply capable of pulsing trapezoidal shaped bipolar rated current at 142.5 Hz and monopolar rated current at 285 Hz. The ac current (I_{ac}) of the trapezoidal waveform is the fundamental component at 142.5 Hz and 285 Hz. The higher order current harmonics are ignored since they are smaller in amplitude compared to the fundamental component. The ac losses at fixed current pulse frequency is formulated as in equation 3.

$$P_{ac} = I_{ac}^2 * R_{ac} \qquad \text{--- (3)}$$

There are advanced ac loss models that provide insight into the ac losses of an inductor and derive ac losses over a frequency sweep (2), however, due to lack of such data from the manufacturer and limited voltage bandwidth of the power supply the individual contributions of the ac losses are lumped together as ac resistance, i.e. R_{ac} in equation 3. If we can measure the difference between the input power and output power from a magnet accurately over a cycle, then total power consumed by the magnet is the sum of DC losses and AC losses as symbolized by equation 1.

It has also been shown in (3) that the total power loss in a magnet can be derived by integration of the product of voltage across (V_L) it and the current flowing through it (I_L) over a time-period T.

$$P_{total} = \frac{1}{T}\int_{t-T}^{T} V_L\, I_L dt \qquad \text{--- (5)}$$

Now that we have conceptualized ac resistance of the skew quad magnet, the methodology of experimentally deriving the ac resistance is described in the subsequent section.

Measurement Methods

The first method uses phase difference(ϕ) between voltage and current waveform of the magnet to extract the ac resistance. A sinusoidal current at 142.5 Hz and 285 Hz is fed to the skew quad magnet using an AGS corrector power supply while measuring voltage across the output terminals. The AGS corrector power supply is a bipolar current controlled supply rated at 25 A, 50V. A phase difference measuring instrument, North Atlantic 2000 Precision Phase Meter with accuracy of ±0.03°, is used to get precise phase difference between the current passing through the magnet and voltage across the power supply waveforms by looking at their zero crossing. The frequency of voltage waveform from the power supply will be the same as the current output with a phase lead. Plugging the numbers of the table below in the phasor formula, as represented in figure1, we will derive the ac resistance of the magnet.

Table 1

Parameter	Symbol	Value	Units
Magnet DC resistance	R_{dc}	5.6	mohm
Magnet inductance	L	1.5	mH
Cable resistance – from power supply to magnet and back	R_{wire}	11.99	mohm
frequency	f	142.5, 285	Hz

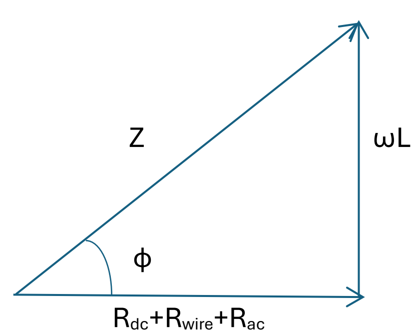

Figure 1. Phasor representation of magnet impedance at a fixed frequency

$$\varphi = \frac{180}{\pi} * a\tan\left(\frac{\omega L}{R_{dc}+R_{cable}+R_{ac}}\right) \quad \text{--- (6)}$$

Solving for R_{ac}, we get

$$R_{ac} = 2 * \pi * f * L * \cot\left(\pi * \frac{\varphi}{180}\right) - R_{dc} - R_{cable} \text{ , where } \omega = 2\pi f \quad \text{--- (7)}$$

To verify the derived R_{ac} value, the voltage and current waveforms data is captured and plotted in a Mathcad file. Subsequently, in Mathcad, we can calculate power loss over one complete period T, rms current of the magnet for dc losses, and ac rms current component of the magnet current to derive R_{ac} using equation 9.

$$P_{total} = \frac{1}{T}\int_{t-T}^{T} V_L\, I_L dt = P_{dc} + P_{ac} \quad \text{--- (8)}$$

$$P_{total} = I_{rms}^2 * R_{dc} + I_{ac}^2 * R_{ac} \quad \text{--- (9)}$$

Finally, we used the skew quad power supply, connected to the skew quad magnet and used an instrument called as Zimmer power analyzer LMG671 connected directly across the skew quad magnet. Its power measurement channel can measure up to 1000 V directly across the load with a narrow bandwidth filter of 15 kHz, sample rate of 151 kS/s with 18-bit resolution. The current is measured using PCT600 current sensor whose output is fed directly to LMG671 with an accuracy of ±0.01% up to 2 kHz. The cycle time setting of the instrument synchronizes the measurements for the measured current signal to its fundamental frequency. Once set, the instrument can measure real power, apparent power, reactive power, rms current, dc current, ac current, current crest factor, and can measure current harmonics wrt the fundamental. Therefore, the ac resistance can be derived as the instrument measures real power, rms current, ac current accurately without the need to trace current, and voltage waveform to calculate real power dissipation over a cycle.

Measurement Results

1. **AC resistance at 142.5Hz**

1.1. **Without a beam pipe in the skew quad magnet –** Measured phase difference between voltage from the power supply and current flowing through the magnet is ϕ = 86.55 degrees (see figure 1). Please note that the voltage spike at current zero crossing is because of improper minimum drive to the FET bank of the bipolar power supply. Hence, the phase difference around zero crossing is not precise but sufficient for our calculation. Plugging data from table 1 along with ϕ in equation 7, we get

R_{ac} @ 142.5Hz, without beam pipe = 63 mohms.

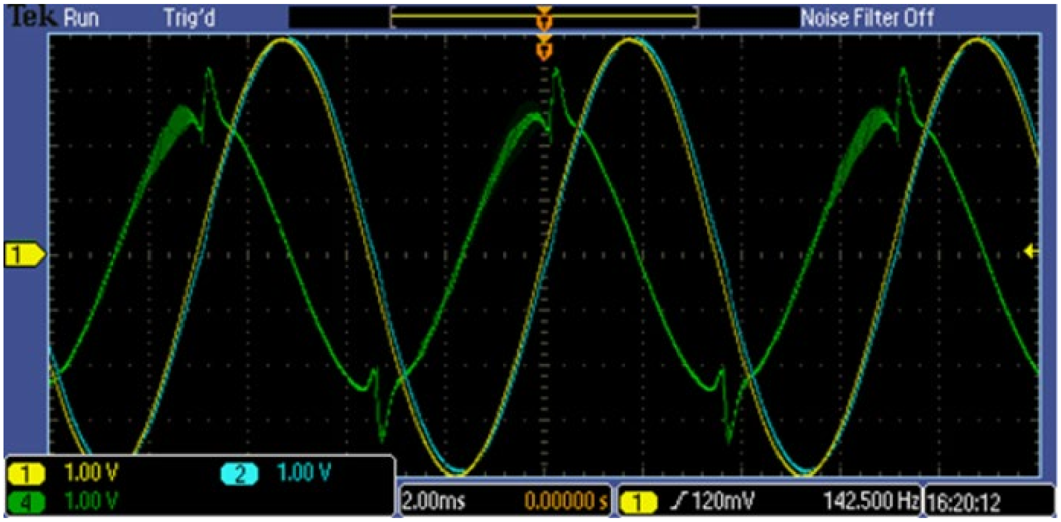

Figure 2. CH1 = 10 A current reference (2.5A/V), CH2 = 10 A output current (2.5A/V), CH4 = power supply output voltage (5V/V)

Plotting the scope capture of figure 1, in a mathcad file, see figure 2, to get power consumed (P_{aver}) by the magnet as per equation 5. For sinusoidal currents symmetric around time axis, the ac current will be equal to rms current ($I_{mag\_rms} = I_{ac}$). See figure 3, for Mathcad calculations.

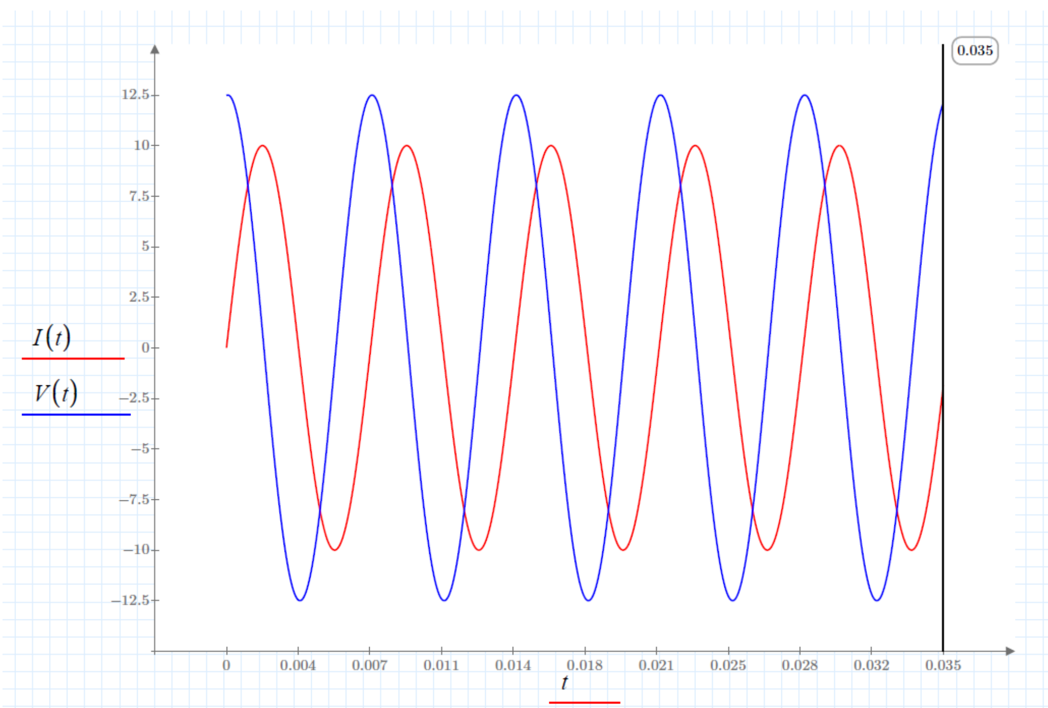

Figure 3. Plot of scope capture from figure 1. I(t) is current and V(t) is the voltage.

$$Imag\_rms := \sqrt{\frac{1}{T} \cdot \int_0^T I(t)^2 \, dt} \qquad Imag\_rms = 7.092$$

$$Paver := \frac{1}{T} \cdot \int_0^T V(t) \cdot I(t) \, dt - Imag\_rms^2 \cdot Rwire$$

$$Paver = 3.25$$

Figure 4. Mathcad calculations for power dissipation over 5 cycles, i.e. T = 35 ms

These numbers can be substituted in equation 9 and we calculate R_{ac} = 59 mohms.

Using skew quad power supply and pulsing the magnet connected to it's output at 142.5 Hz 250 A peak trapezoidal shaped current and using Zimmer power analyzer LMG671, see figure 5, to measure real power, rms current and subtracting the dc losses as per equation 2 from equation 9 to get ac losses. The instrument measures the fundamental component of the pulsed ac current in figure 6, and we calculate R_{ac} = 62.42 mohm. Note the peak voltage of 441.81 V seen across the magnet is not equal to 376.4 as expected based on the equation, $L\frac{di}{dt} + i * R_{dc}$.

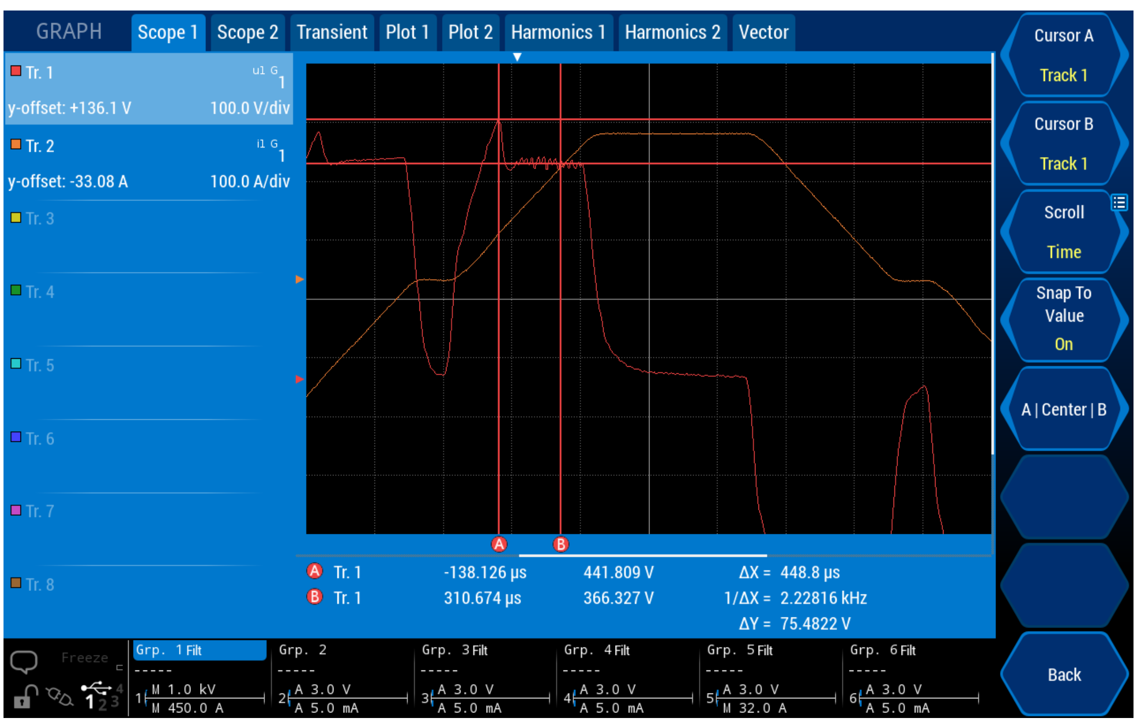

Figure 5. Tr.1 is the magnet voltage and Tr.2 is the magnet current as measured by LMG671

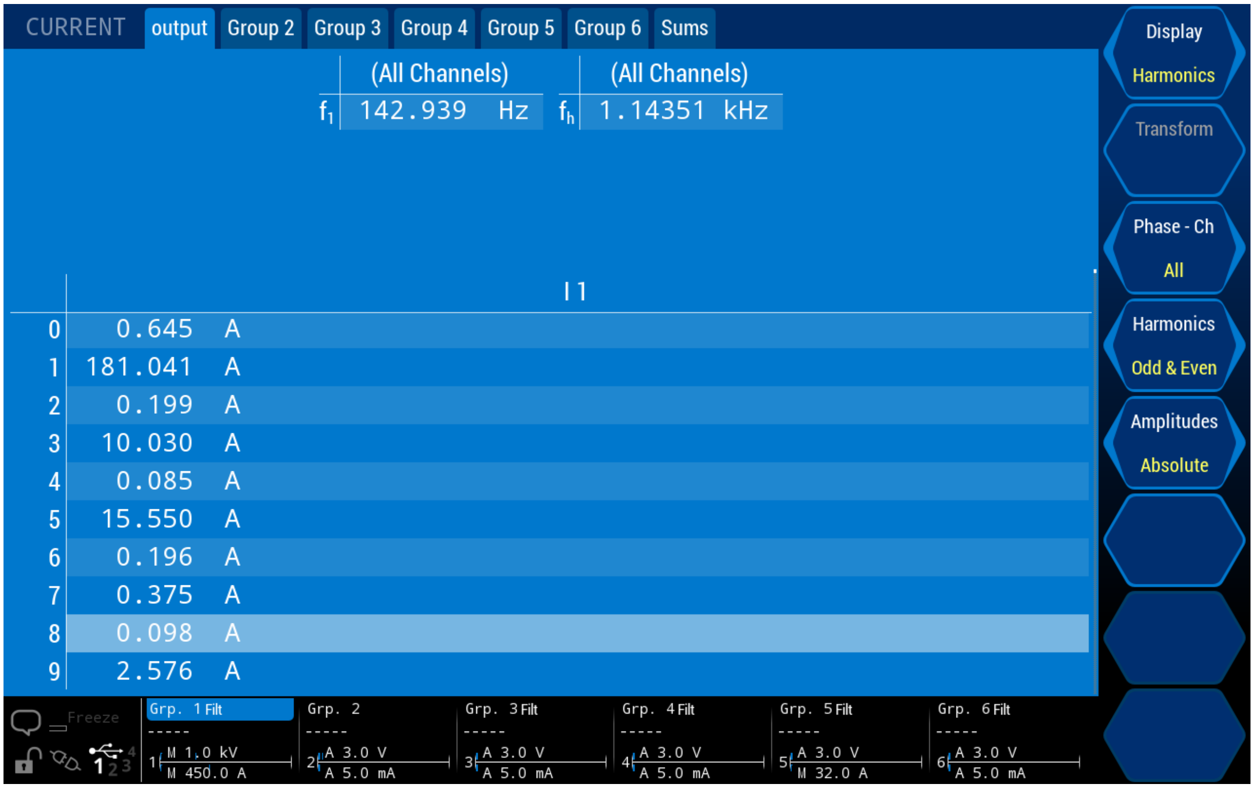

Figure 6. Fundamental component of ac current as measured by LMG671 is 181.041 A.

1.2. **With beam pipe in the skew quad magnet** – A small 2 feet portion of the actual beam pipe used in AGS ring is ran through the skew quad magnet. Same measurements as described in part 1.1. in this section were done to derive ac resistance. With a phase difference of ϕ = 85.60 degrees the scope capture is as shown in figure 7. Mathcad plots and calculations are shown in figure 8 and figure 9. Lastly, the skew quad power supply sends current pulses at 142.5 Hz with 250 A peak trapezoidal shaped current. The results have been summarized in table 2.

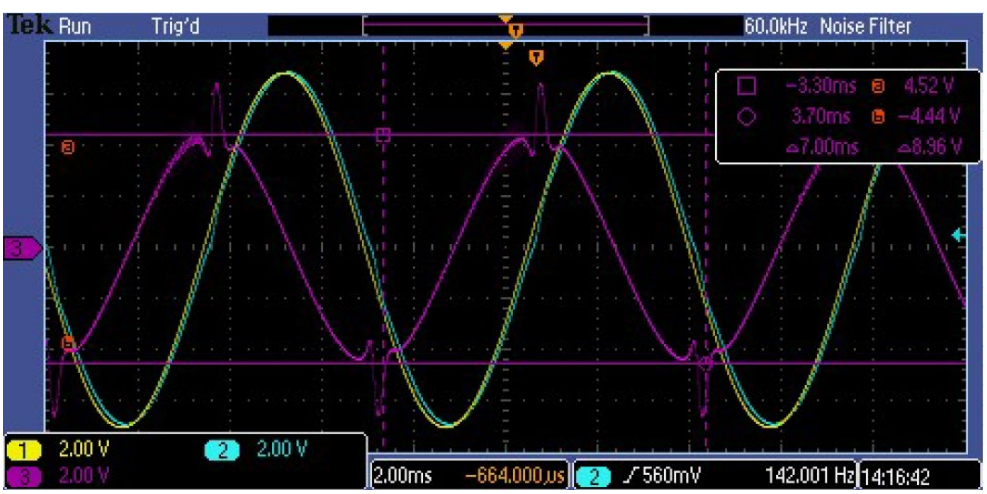

Figure 7. CH1 = 17.5 A current reference (2.5A/V), CH2 = 17.5 A output current (2.5A/V), CH3 = power supply output voltage (5V/V)

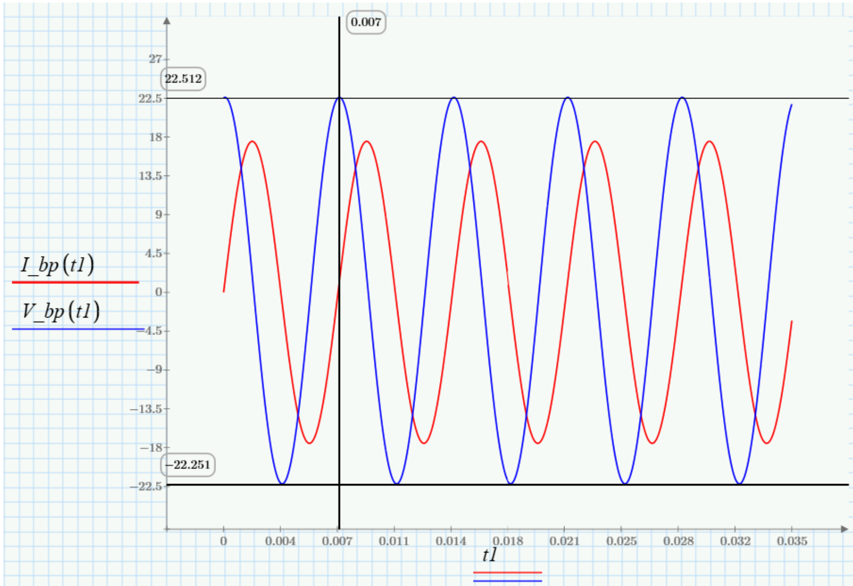

Figure 8. Plot of scope capture from figure 7. I_bp(t) is current and V_bp(t) is the voltage.

$$Imag\_rms\_bp := \sqrt{\frac{1}{T1}\cdot\int_0^{T1} I\_bp(t1)^2 \, dt1} \qquad Imag\_rms\_bp = 12.411$$

$$Paver\_bp := \frac{1}{T1}\cdot\int_0^{T1} V\_bp(t1)\cdot I\_bp(t1) \, dt1 - Imag\_rms\_bp^2 \cdot Rwire$$

$$Paver\_bp = 13.5$$

Figure 9. Mathcad calculations for power dissipation over 5 cycles, i.e. T = 35 ms

2. AC resistance at 285Hz

2.1. **Without a beam pipe passing through the skew quad magnet** - Measured phase difference between voltage from the power supply and current flowing through the magnet is ϕ = 85.50 degrees (see figure 10). The current has been given a dc offset which shifts magnetic hysteresis to a different position along the BH curve. Mathcad plots and calculations are shown in figure 11 and figure 12. When pulsing the magnet using skew quad power supply at 285 Hz with 250 A peak trapezoidal shaped current, no dc offset was given. The results have been summarized in table 2.

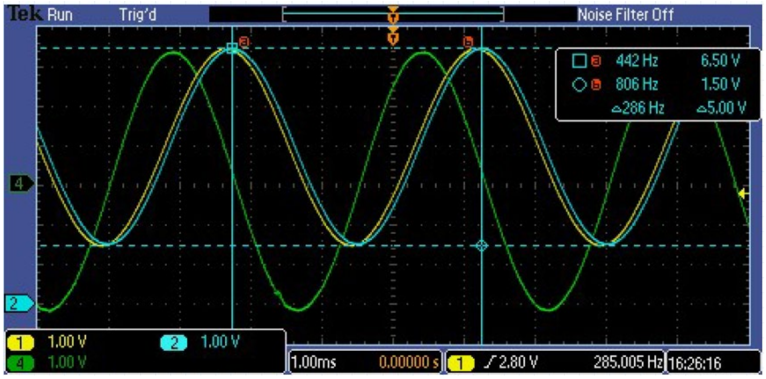

Figure 10. CH1 = 16.25 A peak current reference with 10 A dc offset (2.5A/V), CH2 = output current (2.5A/V), CH4 = power supply output voltage (5V/V)

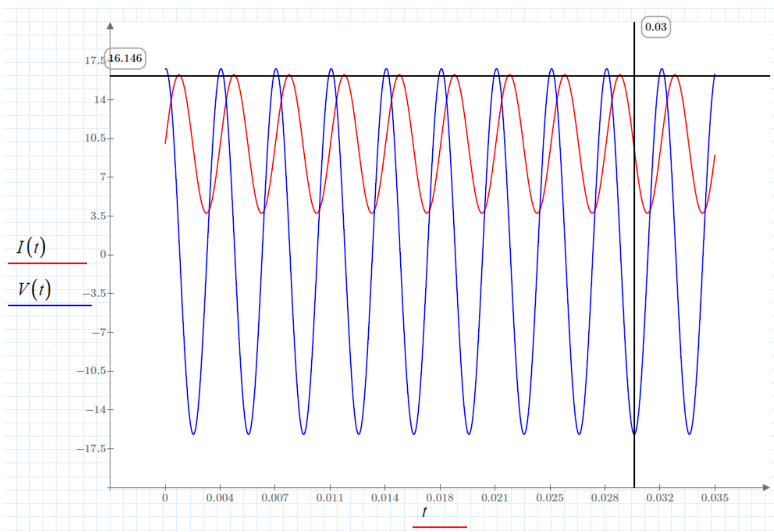

Figure 11. Plot of scope capture from figure 10. I(t) is current and V(t) is the voltage.

$$Imag\_rms := \sqrt{\frac{1}{T} \cdot \int_0^T I(t)^2 \, dt} \qquad Imag\_rms = 10.936$$

$$Paver := \frac{1}{T} \cdot \int_0^T V(t) \cdot I(t) \, dt - Imag\_rms^2 \cdot Rwire$$

$$Paver = 5.234$$

Figure 12. Mathcad calculations for power dissipation over 5 cycles, i.e. T = 35 ms

2.2. **With a beam pipe passing through the skew quad magnet** - Measured phase difference between voltage from the power supply and current flowing through the magnet is ϕ = 83.36 degrees (see figure 13). The current has been given a dc offset which shifts magnetic hysteresis to a different position along the BH curve. Mathcad plots and calculations are shown in figure 13 and figure 14. When pulsing the magnet using skew quad power supply at 285 Hz with 250 A peak trapezoidal shaped current, no dc offset was given. The results have been summarized in table 2.

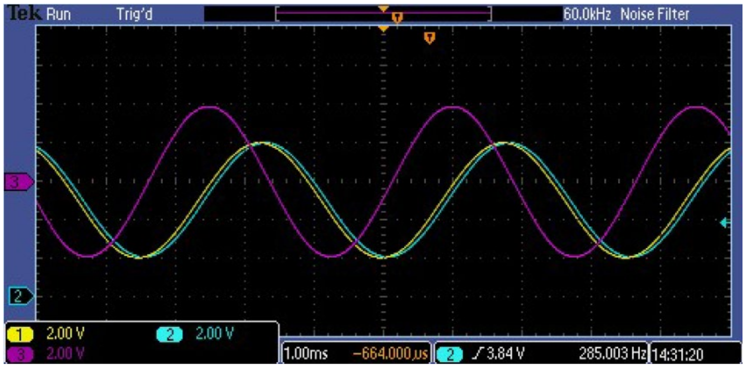

Figure 13. CH1 = 20 A peak current reference with 12.5 A dc offset (2.5A/V), CH2 = output current (2.5A/V), CH3 = power supply output voltage (5V/V)

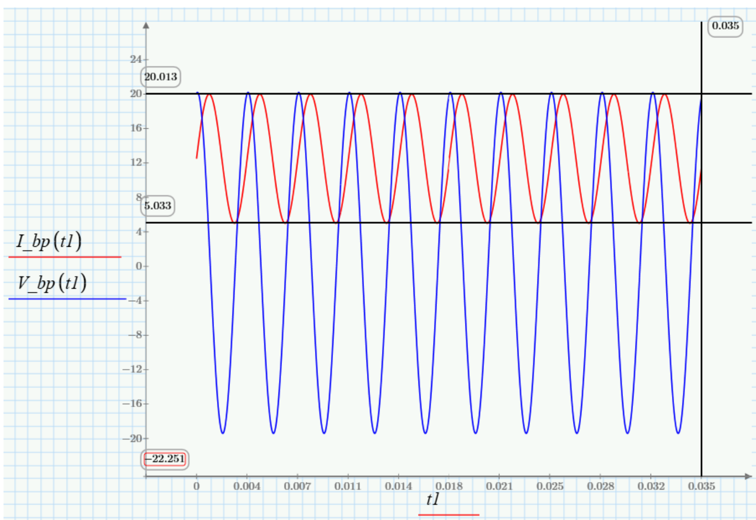

Figure 14. Plot of scope capture from figure 13. I_bp(t) is current and V_bp(t) is the voltage.

$$Imag\_rms\_bp := \sqrt{\frac{1}{T1} \cdot \int_0^{T1} I\_bp(t1)^2 \, dt1} \qquad Imag\_rms\_bp = 13.582$$

$$Paver\_bp := \frac{1}{T1} \cdot \int_0^{T1} V\_bp(t1) \cdot I\_bp(t1) \, dt1 - Imag\_rms\_bp^2 \cdot Rwire$$

$$Paver\_bp = 10.816$$

Figure 15. Mathcad calculations for power dissipation over 5 cycles, i.e. T = 35 ms

Table 2

	AC resistance at 142.5 Hz		AC resistance at 285 Hz	
Method used	**without beam pipe**	**with beam pipe**	**without beam pipe**	**with beam pipe**
Phase difference	63 mohm	85 mohm	194 mohm	295 mohm
Mathcad	59 mohm	83 mohm	234 mohm	348 mohm
LMG671	62.42 mohm	86.69 mohm	177.5 mohm	267.67 mohm

The measured results of LMG671 match closely with the phase difference method at 142.5 Hz bipolar current. The results at 285 Hz with phase difference method is different than LMG671 due to dc offset in the currents which shifts the magnetic hysteresis on the BH curve which leads to more ac losses in the magnet resulting in higher value of ac resistance. The introduction of beam pipe in the magnet causes distortion in the magnetic field which increases the ac resistance compared to, without the beam pipe measurements.

Effect on Power Supply

The power loss on the magnet when pulsing current through it must be satisfied by the dc link capacitor bank of the skew quad power supply. AC resistance calculation becomes critical to determine the cap bank energy required for pulsing the magnetic load at a particular frequency. If the capacitor bank is sized without considering the ac loss effects, then at high frequency magnet load currents the ac resistance effects may cause load voltage saturation which in turn may lead to instability of the control loop to regulate the load current as per the spec requirement of the power supply. This is seen in figure 5 where the peak voltage is not equal to $L\frac{di}{dt} + i * R_{dc}$.

Conclusion

The ac resistance of skew quad was measured using phase difference method and LMG671 at two current pulsing frequencies of 142.5 Hz and 285 Hz, both with and without beampipe. As seen in table 2, the measurement results are nearly identical at 142.5 Hz but varies more at 285 Hz using phase difference method because of dc offset in current. The measurement using LMG671 is much more reliable than phase difference method at both frequency as the skew quad power supply with actual waveform of the pulsed current was used to energize the magnet. However, LMG671 is an expensive instrument compared to instruments used in phase difference method. Additionally, the skew quad power supply was not available when the skew quad magnet was available. Therefore, the phase difference method is a good approximation for ac resistance based on this experiment and can be modeled into simulations to determine the optimal capacitor bank energy and voltage requirements of the power supply.

References

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