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PERFORMANCE OF LARGE MAGNETS UNDER TRANSIENT VOLTAGES*

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Abstract

The dielectric components of a coil can be electrically stressed in two ways if a transient voltage, generated by lightning and switching, is impressed across its terminals. First, the voltage distribution along the coil would be highly nonlinear if the transient voltage has a steep front. This could cause dielectric failure between adjacent turns. Second, the coil may resonate at one of its natural space harmonics if the applied transient voltage contains such a frequency component. Under this condition, an internal point of the coil may attain a voltage peak much higher than the applied voltage. It may cause dielectric failure between parts of the coil. Studies were performed to determine the severity of transient electrical stresses in two superconducting energy storage coils. One is a 300 kJ single layer coil and the other is a 30 MJ pancake coil. The resonant space harmonics of the coils were measured at room temperature and confirmed by analysis. The first space harmonic of the 300 kJ coil was measured at 577 kHz, and its peak amplitude was about 12 times the input signal. The first space harmonic of the 30 MJ coil was measured at 7.3 kHz. The nonuniform initial voltage distribution along the 30 MJ coil was analyzed theoretically for a step-function input voltage by use of the standing-wave theory. The analysis was performed for two cases with metal and insulating dewars. The transient voltage across the first two turns of the coil with the metal dewar was almost three times as much as that with an insulating dewar. This increased voltage signifies the influence of the distributed capacitance between the coil and the dewar.

Introduction

Large magnets for energy storage are either being already used or being designed for applications in research and in electric utility grids. For reliable operation, the performance of these magnets under transient voltages must be known.

The sources of transient voltages are lightning and switching. Transient voltages generated by switching within the magnet system are of particular significance for the reliable operation of the magnet.¹

The dielectric components of a coil can be electrically stressed in two ways if a transient voltage is impressed across its terminals. First, the voltage distribution along the coil would be highly nonlinear if the transient voltage has a steep front. This would concentrate the electrical stresses at the end turns, causing a dielectric failure between adjacent turns at these locations. Second, the coil may resonate at one of its space harmonics if the applied transient voltage contains such a frequency component. Under this condition, an internal point of the coil may attain a voltage peak much higher than the applied voltage. It may cause dielectric failure between parts of the coil.

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Methods of Analysis

For transient analysis, a coil cannot be simply represented by its self inductance. The mutual inductances between parts of the coil, the capacitances between turns and between coil sections, and the capacitances between various parts of the coil to ground and return circuit must also be considered. Figure 1 shows the schematic representation of an N-section coil.

Much work has been performed over the past 50 years to study the transient performance of transformers.² The methods for transformers can be modified to apply to the study of transient analysis of magnet coils.

For transient analysis of a coil, a unit step-function voltage is usually applied across the coil terminals. The solution for any other type of applied voltage can be obtained by the application of Duhamel's theorem. When a step-function voltage is applied across a coil, it is initially represented as a capacitive network, the inductances giving infinite impedances.

This initial voltage distribution is non-uniform, being higher at the high voltage end. The non-uniformity of the initial voltage distribution is augmented by the capacitances of the coil elements to ground. The transition from the initial non-uniform voltage distribution to the final uniform distribution takes place through intermediate voltage oscillations.

Uniform Single Layer Coil

Step Response. The initial voltage distribution along a uniform single layer coil under a unit step function voltage is given by^{3,4}

$$V = \sinh \alpha (1 - x/l) / \sinh \alpha, \quad (1)$$

where V = voltage to ground of a coil element at an axial distance x from the high voltage end,
 l = length of coil,

$$\alpha = l \sqrt{C_2/C_1},$$

C_1 = series capacitance per unit length, and

C_2 = ground capacitance per unit length.

Fig. 1. Schematic representation of a magnet as a lumped circuit.

The final uniform voltage distribution is a straight line drawn from unity on the voltage ordinate to $x/l=1$ on the axial distance on coil. The intermediate oscillations may be assumed to oscillate around the final voltage distribution as the axis and with an amplitude equal to the difference between the final and initial voltage distributions, just like a simple pendulum. Therefore, the envelope of the maximum voltages along the coil can be drawn by adding the difference between the final and initial voltage distributions at each point along the coil to the final voltage distribution.

Natural Frequencies. The calculation of natural frequencies is more difficult and controversial. The difficulty arises from the assumptions regarding the inductance and series capacitance elements. For instance, Wagner calculated the natural frequencies of coils by neglecting the mutual inductances between coil parts.⁵ According to his analysis, a coil would have a critical natural frequency, above which no oscillations can be sustained by the coil. According to Blume-Boyajian analysis, which takes the mutual inductances into account, no such critical frequency exists.⁶ As the mutual inductance is an important parameter in the transient analysis of coils,² we have used the Blume-Boyajian equation for calculating the natural frequencies of uniform, single layer coils. This is given by

$$\omega_n = a_n^2 / [L c_g (1 + a_n^2 c_s / c_g)]^{1/2}, \quad (2)$$

where ω_n = nth natural frequency, radians/s,
 $a_n = n\pi/l$, ($n = 1, 2, 3, \dots$),
 $L = \mu_0 (N_c/l)^2 (2\pi R_m/h)$,
 $\mu_0 = 4\pi \times 10^{-7}$,
 N_c = total number of turns in coil,
 l = axial length of coil,
 R_m = mean radius of a turn,
 $h = b + l/3n$, ($n = 1, 2, 3, \dots$), and
 b = radial thickness of coil.

Disk or Pancake Coil

The schematic of a double disk or pancake coil is shown in Fig. 2. The entire coil is made up of pancake

Fig. 2. A multiple pancake coil.

shaped coils, each pancake being wound in a flat spiral. In a simple double pancake coil, the innermost turn of one pancake is connected to the innermost turn of the next pancake. In a pancake coil, subdivided into pairs of such double pancakes, the pairs are connected at the outermost turns. The simple standing wave theory cannot be applied when the winding structure is as complex as the multiple pancake coil assembly.

Step Response. The initial voltage distribution was determined in two steps.⁷ First, the major voltage distribution from each pancake to ground was determined from the total ground and series capacitances of the entire coil. Thus, the voltage across the first pancake at the high voltage end was determined. Second, knowing the voltage across the first pancake, the voltage across the high voltage end turns was determined from the turn-to-turn and pancake-to-pancake capacitances.

The initial voltage of each pancake to ground was determined from Eq. 1. The voltage across the first two pancakes at the high voltage end, as per unit of the voltage across coil, is given by

$$V_1 = 1 - \exp(-2B) - (2 \sinh 2B) / [1 - \exp(2a)], \quad (3)$$

where $a = \sqrt{C_g/C_s}$,

$B = a/N_p$,
 C_g = total ground capacitances of coil,
 C_s = total series capacitance of coil, and
 N_p = number of pancakes.

Similarly, the initial voltage between the first two turns of a pancake, as per unit of the pancake voltage, is given by

$$V_1 = \gamma \cosh(\gamma - \gamma/2n) / n \sinh \gamma, \quad (4)$$

where $\gamma = \sqrt{2C_p/C_t}$,

C_p = total capacitance between pancakes,
 C_t = total capacitance between turns in a pancake, and
 $n+1$ = total number of turns in a pancake.

Natural Frequencies. The natural frequencies of a complex coil, such as the multiple pancake coil, can be determined by considering the coil as a lumped network as shown in Fig. 1. Once the coil has been divided into an N-section ladder network, a convenient way of solving the network is by the state variable method. Thus,⁸

$$dX/dt = AX + BV, \quad (5)$$

$$U = SX + DV, \quad (6)$$

where $X(t)$ = state vector,
 $U(t)$ = output vector of node voltages,
 $V(t)$ = applied voltage, and
 A, B, D and S = matrices of constant coefficients.

The eigenvalues of the matrix A are the natural frequencies of the coil. This analysis has the advantage that the output voltage at each node of the network can also be obtained for any type of applied voltage.

Computation

Two energy storage superconducting coils were studied. One coil is a 300 kJ single layer coil,⁹ and the other is a 30 MJ multiple pancake coil.¹⁰ The 30 MJ superconducting magnetic energy storage (SMES) coil will be installed in the Bonneville Power Administration (BPA) electrical power transmission system for line stabilization. In both coils the return conductor rises vertically from the bottom of the coils. A nonmetallic dewar was assumed for the 300 kJ coil; both metallic and nonmetallic dewars were assumed for the 30 MJ coil. For the nonmetallic dewars, the only ground capacitance of the coil is between the coil and the return conductor. For the metallic dewar of the 30 MJ coil, the added capacitance between the coil and the inner and outer walls of the annular shaped dewar was taken into consideration.

The various capacitances were calculated, with assumed cylindrical symmetry or parallel plate configuration and consideration of the different dielectric constants included for the various materials used for the coil structure.

The total series capacitance, C_s , of the coil had to be determined to evaluate Eqs. 3 to 6. The total series capacitance of a pancake coil includes the turn-to-turn capacitance in each pancake and the capacitance between the pancakes. As existing analyses¹¹ were not suitable for our application, we derived the equation as follows

$$C_s = 2C_e C_e' / [4C_e + (N_p - 2) C_e'] \quad (7)$$

where C_e , $C_e' = c_p [1 + (\coth(n+1)\theta) (\coth(\theta/2))]$,

$\theta = \cosh^{-1}(1 + k/c_t)$,

$k = 2c_p$ for C_e ,

$= c_p$ for C_e' ,

c_p = capacitance between two corresponding turns on neighboring pancakes, and

c_t = capacitance between two neighboring turns within a pancake.

Measurement

Two methods were used to measure the natural frequencies of the coils.¹² For both methods, a variable-frequency sinusoidal voltage source was connected across the coil. The applied voltage and the coil current were observed on a dual-beam cathode ray oscilloscope during the first method of test. The coil current showed maxima at resonant frequencies. The voltages at the 1/4, 1/2 and 3/4 points along the coil were measured during the second method. The midpoint of the coil showed a maxima at the first space harmonic. The 1/4 and 3/4 points showed maxima at the second space harmonic. A capacitive probe was used for the 300 kJ coil because its turns were imbedded in insulation. The various points along the 30 MJ coil were directly accessible. All tests were performed at room temperature and in air without any dewar.

Results

Table I shows the measured and calculated values of the first three space harmonics of the 300 kJ coil. Figure 3 shows the calculated initial values of voltages along the 30 MJ coil with unit step-function excitation for both metal and nonmetallic dewars. This figure also shows the envelope of possible maximum voltage oscillations along the 30 MJ coil.

TABLE I

Resonant Frequencies of
300 kJ Single Layer Coil without Dewar

Measured MHz	Calculated MHz	Deviation from Measured Values, %
0.577	0.532	- 7.8
0.970	0.821	15.4
1.292	1.039	-19.6

Fig. 3. Coil voltages as function of distance from high voltage terminal of the 30 MJ multiple pancake coil.

The calculated voltages across the first two turns and across the first two pancakes at the line end of the 30 MJ coil are shown in Table II.

Table III shows the calculated values of the first two space harmonics of the 30 MJ coil. The first two space harmonics were measured at about 7.3 kHz and 15.3 kHz when the voltages at 1/4, 1/2 and 3/4 points of the coil were measured. However, no resonances were detected at these frequencies when the coil current was measured with a 10-ohm resistor. Both methods of measurement gave strong evidence of resonance again at about 335 kHz and 607 kHz.

TABLE II

Voltages in 30 MJ Coil with
10 kV Applied Step-Function Voltage

	Metal Dewar V	Insulating Dewar V
Voltage across first two turns	387	134
Voltage across first two pancakes	1633	585

TABLE III

Calculated Resonant Frequencies of 30 MJ Coil

	First Harmonic kHz	Second Harmonic kHz
Insulating Dewar	8.8	15.8
Metallic Dewar	5.1	13.6

Discussion

When a coil is represented by an N-section lumped circuit, more accuracy in the analysis can be obtained by increasing N. However, the larger N is, the longer and more expensive will be the computation time. A compromise is generally made by performing the computations with increasing N. The computation is stopped when the required data are within the acceptable tolerances for two successive N's. Computations for the 30 MJ coil were made at N = 5 and N = 10. The differences in the first two harmonics for the two cases were small. The higher harmonics diverged gradually for the two cases.

The presence of resonance in the coils even without a metal dewar shows the significance of the various capacitances within the coils.

For the 300 kJ coil, the voltage at the midpoint of the coil was about 12 times the input signal at its first resonant frequency. This magnitude will be even higher when the coil is immersed in liquid helium. This shows the importance of avoiding resonant conditions within the coil. For the 30 MJ coil, the midpoint voltage was little higher than the input voltage at its first resonant frequency. It is anticipated that the room-temperature resistance of the large coil damped the voltage amplitude considerably. At liquid helium temperature, the amplitude is expected to be much higher. This could endanger the major insulation of the coil.

The natural frequencies of the 30 MJ pancake coil were found to be sensitive to the inductance L and series capacitance C_s elements, and the step response to the ratio between the ground capacitance C_g and the series capacitance C_s .

The difference between the metal and insulating dewars is clearly shown in Fig. 3 and Table II. The non-uniformity of the initial voltage distribution is augmented by the capacitances of the coil elements to the walls of the metal dewar. Although the degree of non-linear voltage distribution for the insulating dewar is lesser, the danger of overvoltages caused by resonances still remains. The only difference in this case will be a shift in the resonant frequencies. In a metal dewar, the amplitudes of voltage oscillations would be damped to some extent by eddy currents induced on the dewar walls.

Although the effects of the coil resistance were neglected in our analysis, the importance of the damping caused by this resistance is emphasized. Hysteresis losses in the superconductor and eddy current losses in the cryostabilizer will cause much needed damping. The possibility of damping by proper design of the cryostabilizer should be explored.

Conclusions

These studies show that a large magnet cannot be represented simply by an inductance to evaluate its transient performance. The capacitances between various parts of the coil as well as the distributed capacitance between the coil and the metal dewar wall play significant roles in the performance of a large magnet.

The analysis of transient performance of a magnet can be performed by techniques similar to those used in transformer technology.

The possibility exists of high internal voltage either by nonlinear voltage distribution or by resonance or by both.

The transient performance of a magnet coil should be studied during its design stage, and the dielectric system of the magnet should be designed to withstand the expected transient voltages.

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