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TITLE: TRANSIENT VOLTAGE OSCILLATIONS IN COILS

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TRANSIENT VOLTAGE OSCILLATIONS IN COILS*

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ABSTRACT

Magnet coils may be excited into internal voltage oscillations by transient voltages. Such oscillations may electrically stress the magnet's dielectric components to many times its normal stress. This may precipitate a dielectric failure, and the attendant prolonged loss of service and costly repair work. Therefore, it is important to know the natural frequencies of oscillations of a magnet during the design stage, and to determine whether the expected switching transient voltages can excite the magnet into high-voltage internal oscillations. The series capacitance of a winding significantly affects its natural frequencies. However, the series capacitance is difficult to calculate, because it may comprise complex capacitance network, consisting of intra- and inter-coil turn-to-turn capacitances of the coil sections. A method of calculating the series capacitance of a winding is proposed. This method is rigorous but simple to execute. The time-varying transient voltages along the winding are also calculated.

1. INTRODUCTION

Large magnets which are being used in fusion and accelerator experiments must withstand high transient voltages during switching operations. These transient voltages would produce voltage oscillations inside the winding. The magnitudes of these internal voltage oscillations may be many times higher than the magnitude of the externally applied transient voltage. Therefore, even if the external terminals of a magnet are protected by surge divertors, the magnet may fail internally caused by excessive internal voltage oscillations.

The capacitances between various parts of a winding, e.g. turn-to-turn, turn-to-ground capacitances, play a significant role under transient conditions. The initial transient voltage distribution is non-uniform, being higher at the input end. This non-uniformity will be higher for shorter wavefront of the applied transient voltage, and for larger value

of $\alpha = \sqrt{(C_g/C_s)}$ where C_g = capacitance of the winding to ground and C_s = winding series capacitance.¹ Furthermore, the various capacitances of the winding, together with its inductances, will form a resonant circuit with multiple resonant (natural) frequencies.

The equivalent series capacitances of a winding are complex capacitance network, consisting of intra- and inter-coil turn-to-turn capacitances of the coil sections. Knowledge of the series capacitance of a winding, however, is essential in order to analyze its transient behavior.² A rigorous method was developed to calculate the equivalent series capacitances of a winding.³

For the application of a magnet in a switching circuit, it is important to know the magnet's natural frequencies and the expected oscillations under a given transient voltage during the design stage.⁴ If the analysis shows that the dielectric components of the magnet will be stressed by high-voltage internal oscillations, then such an abnormal condition can be corrected either by design change or by coordinated transient-voltage protection schemes. The state variable method was used previously to determine the natural frequencies of magnets.³ In the present paper, the state variable method has been extended to determine the internal voltage oscillations at various nodes of a magnet.

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

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II. METHOD OF ANALYSIS

The natural frequencies of a winding depend upon the self and mutual inductances, the capacitances to the return lead and the equivalent series capacitances of its coil sections (Fig. 1). The inductances, L_i and M_{ij} , can be computed by any of the computer codes developed in magnet technology. The capacitances to the return lead, C_{gi} , can be computed by assuming either equivalent parallel-plate or cylindrical-symmetry configuration. Sometimes, for air-core magnets, the capacitances to return lead are significantly smaller than the equivalent series capacitances. Therefore, they can be entirely neglected. However, the equivalent series capacitances of a winding, C_{e1} , are complex capacitance networks, consisting of intra- and inter-coil turn-to-turn capacitances of the coil sections (Fig. 2).

A. Series Capacitance

Many researchers have proposed methods of computing the equivalent series capacitance of a winding.⁵⁻⁹ As each method is quite different from the others, the computation of natural frequencies of windings becomes uncertain.

A method of computing the series capacitance of a winding was devised which is mathematically rigorous but simple to execute. With reference to Fig. 2, it can be shown that,

$$C'_e = (C_{at})[1 + \{\coth(m-1)\theta'\}\coth(\theta'/2)] , \quad (1)$$

$$C_e = (C_{at}) [1 + \{\coth(m-1)\theta\}\coth(\theta/2)] , \quad (2)$$

$$\theta' = \operatorname{arccosh} (1 + C_{at}/C_t) , \quad (3)$$

$$\theta = \operatorname{arccosh} (1 + 2C_{at}/C_t) , \quad (4)$$

where C_{at} = capacitance between turns of adjacent coils,
 C_t = inter-turn capacitance within a coil,
 m = number of turns in a coil, and
 n = number of coils.

The galvanic connection between points 1 and 2 in Fig. 2a, is justified because the length of this connection will generally be short. Therefore, current will flow through this connection. However, the series capacitance is defined as that capacitance which one sees when the connection between each adjacent turn is opened. The analysis can be extended to that case by replacing the short between the points 1 and 2 in Fig. 2a, by a capacitance C_{at} . Under this condition, it can be shown that

$$C'_e = \frac{2C_{at}}{1 - \sinh(m-1)\theta' / \sinh(m\theta')} , \quad (5)$$

Fig. 2. Series-capacitance network of a winding.

(a) Complete network. (b) Reduced string. (c) Equivalent series capacitance.

C_{at} = capacitance between turns of adjacent coils, C_t = inter-turn capacitance within a coil,
 m = number of turns in a coil, and n = number of coils in a winding.

where, θ' is given by Eq. (3). The equation for C_e is similar to Eq. (5) except θ' is replaced by θ which is given by Eq. (4).

For shielded windings, C_e' does not exist,⁹ and the series-capacitance network in Fig. 2 will consist of n series-connected branches, each branch comprising two parallel-connected capacitances of value C_e .

The total equivalent series capacitance of an unshielded n -coil winding will then be given by

$$C_a = \frac{2C_e \times C_e'}{4C_e + (n-2)C_e'} \quad (6)$$

For a shielded winding,

$$C_a = \frac{2C_e}{n} \quad (6a)$$

This method of calculation of the equivalent series capacitance was verified by a simple circuit such as a double-disk winding with two turns per disk (Fig. 3). Figure 3a represents the case where the two disks are galvanically connected, whereas in Fig. 3b the galvanic connection is replaced by a capacitance. Table I shows the equivalent series capacitances of the networks of Fig. 3, computed by various methods. As shown, the proposed method is the most accurate.

B. Natural Frequencies

The natural frequencies of a complex winding can be determined by considering the winding as a lumped network as shown in Fig. 1. Once the winding has been divided into an N -section ladder network, a convenient way of solving the network is by the state variable method. Thus,¹⁰

$$dX(t)/dt = A_1 \cdot X(t) + A_2 \cdot V(t) \quad , \text{ and} \quad (7)$$

$$U(t) = A_3 \cdot X(t) + A_4 \cdot V(t) \quad , \quad (8)$$

where
 $X(t)$ = state vector,
 $U(t)$ = output vector of node voltages,
 $V(t)$ = applied voltage, and
 A_1, A_2, A_3 , and A_4 = matrices of constant coefficients.

The eigenvalues of the matrix A_1 give the natural frequencies of the winding.

C. Internal Voltage Oscillations

The voltage at each node $U(t)$ for any type of applied voltage $V(t)$ can be determined from Eq. (8) once the state vector $X(t)$ is found from Eq. (7). Recognizing that Eq. (7) is a matrix differential equation, it can be solved either by the classical methods or by Laplace transform. Assuming a unit step-function applied voltage, the solution of Eq. (7) is given by

$$X(t) = [\exp(A_1 \cdot t) - I] \cdot A_1^{-1} \cdot A_2 \quad , \quad (9)$$

where I = identity matrix. The exponential function in Eq. (9) is also a matrix function. It is evaluated in closed form by invoking Sylvester's theorem as follows,¹¹

$$\exp(A_1 \cdot t) = \sum_{r=1}^m \exp(\alpha_r t) \cdot \prod_{\substack{s=1 \\ s \neq r}}^m \frac{\alpha_s \cdot I - A_1}{\alpha_s - \alpha_r} \quad , \quad (10)$$

where $\alpha_r (r=1, m)$ are m distinct eigenvalues of A_1 , which were already evaluated to determine the natural frequencies of the magnet.

III. APPLICATION TO MAGNETS

The natural frequencies of two magnets were calculated by this method:

1. 30-MJ superconducting winding for the SMFS project,¹² and
2. Model of the poloidal winding of ZTF fusion experiment.

The SMFS winding is a pancake winding, with 40 pancakes each having 23 turns. The ZTF poloidal winding consists of eight coils, each coil having 17 or 18 turns wound in two layers. The SMFS winding was analyzed as a 10-mesh circuit, and the ZTF winding was analyzed as an 8-mesh circuit. The internal oscillations at various points of these windings, when a unit step-function voltage is impressed at the terminals, were also calculated.

Fig. 3. Equivalent series capacitance of a four-turn double-disk winding. (a) Two disks galvanically connected. (b) Two disks capacitively connected.

The natural frequencies were measured by exciting the windings with a variable-frequency, sine-wave voltage source. The first space harmonic was observed when the voltage at the midpoint of the winding reached a maximum, and the second space harmonic when the voltage across the 1/4 and 3/4 points of the winding reached a maximum. The natural frequencies were also measured when the return-lead current reached maxima as the frequency was varied. For the ZTP winding, resonances were also measured at various points along the winding. Measurements on the SMES winding were made at room temperature without any dewar. The results, computed and measured, are shown in Table II.

IV. DISCUSSION

In discussing resonances in a winding, one must distinguish between terminal resonances and internal resonances.¹³ Terminal resonances occur at frequencies when the impedance of the winding attains a minimum if it is excited by a variable-frequency voltage source, i.e., when the input current attains a maximum. Internal resonances occur at frequencies when the voltages at internal points of the winding attain maxima. For instance, the midpoint of the winding attains a maximum at the fundamental space harmonic. Similarly, the voltage across the 1/4 and 3/4 points along the winding attains a maximum at the second space harmonic. For complex windings, internal oscillations may not be detected by measuring the input current.¹³

For the ZTP poloidal winding, the computed resonant frequencies were closer to the measured terminal resonances than to the inter-

nal resonances of the winding (Table II). The natural frequencies of a winding were determined by the state variable method, Eqs. (7) and (8).¹⁰ The eigenvalues of the matrix A_1 , provide the zeros of the terminal impedance, and hence the natural frequencies of the winding as seen from its terminals.

Figures 4 and 5 show the voltage oscillations at nodes 1 and 5 of the SMES winding with an insulated and a metal dewar respectively, excited by step-function voltage. As mentioned earlier, the SMES winding was analyzed as a 10-mesh circuit. Therefore, node 1 is at 10% point from the entry, and node 5 is at the midpoint of the winding. Figure 6 shows the voltage oscillograms at nodes 1 and 4 of the ZTP poloidal winding, excited by step-function voltage. These nodes are at 1/8th point from the entry and at midpoint of the winding respectively. All three figures show clearly that the internal points of the winding are stressed more than the entry point where the voltage is applied. It should be noted from Figs. 4 and 5 that the stresses in a winding are higher for a metal dewar than those for an insulated dewar. A metal dewar produces higher capacitances to the return lead, C_g (Fig. 1), and hence higher $\alpha = \sqrt{C_g/C_s}$. This generates higher amplitudes of oscillations.¹ An iron-core magnet would, similarly, experience higher amplitudes of internal oscillations than an air-core magnet.

It is evident that reducing the factor α will reduce voltage oscillations inside a magnet. However, this may not eliminate the internal oscillations completely. For instance, the midpoint voltage of the ZTP poloidal winding was 12 times higher than the external applied voltage when the frequency of the

TABLE I

Series Capacitances Computed by Various Methods

	<u>Karasev [2]</u>	<u>Bulgakov [3]</u>	<u>Waldvogel & Rouxel [4]</u>	<u>Brechna [5]</u>	<u>Jayaram [7]</u>	<u>Proposed Method</u>
Network of Fig. 3a	0.90C	0.85C	0.67C	1.50C	1.26C	1.50C
Network of Fig. 3b	1.52C	1.50C	1.33C	2.50C	0.96C	1.33C

TABLE II

Computed and Measured Natural Frequencies of Two Magnets

	<u>Computed Natural Frequencies</u>		<u>Measured Natural Frequencies</u>	
	<u>First Harmonic kHz</u>	<u>Second Harmonic kHz</u>	<u>First Harmonic kHz</u>	<u>Second Harmonic kHz</u>
SMES Winding	8.8 ^a 4.8 ^b	15.9 ^a 13.6 ^b	7.3 --	15.3 --
ZTP Poloidal Winding Model	139.5	335.9	125.3 143.8 ^c	352.5 338.6 ^c

^a With insulated dewar^b With metal dewar^c Frequencies at which the return-lead current reached maxima

Fig. 4. Voltage oscillations at nodes 1 and 5 of SMES winding excited by step-function voltage: insulated dewar.

Fig. 5. Voltage oscillations at nodes 1 and 5 of SMES winding excited by step-function voltage: metal dewar.

applied voltage coincided with that of the fundamental space harmonic of the winding. To protect against such a situation, one should calculate the natural frequencies of a magnet during the design stage. If the expected applied voltage has frequency components which coincide with the natural frequencies

(particularly the first two space harmonics) then either the magnet should be redesigned or the applied voltage should be filtered. In the design of the magnet, the various capacitances can be varied by selecting the dielectric materials of proper permittivity and/or of proper dielectric strength to withstand the

Fig. 6. Voltage oscillations at nodes 1 and 4 of ZTP poloidal winding model excited by step-function voltage.

expected voltage oscillations. Another possible solution is to install nonlinear resistors (e.g. varistors) at the various nodes of the magnets where high-amplitude oscillations are expected.

V. CONCLUSIONS

A winding (transformer, reactor or magnet) may be excited into internal voltage oscillations during switching because of capacitances between various parts of the winding. This study shows a method to calculate the equivalent series capacitances of a winding. It also shows how to calculate the natural frequencies and internal voltage oscillations of a winding.

Transient-voltage analysis of a winding should be performed during its design stage. Then, a potential dielectric failure can be averted either by design change or by coordinated overvoltage protection scheme or by both.

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