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NORMAL ZONE DETECTORS FOR A LARGE NUMBER OF INDUCTIVELY COUPLED COILS

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Abstract

In order to protect a set of inductively coupled superconducting magnets, it is necessary to locate and measure normal zone voltages that are small compared with the mutual and self-induced voltages. The method described in this paper uses two sets of voltage measurements to locate and measure one or more normal zones in any number of coupled coils. One set of voltages is the outputs of bridges that balance out the self-induced voltages. The other set of voltages can be the voltages across the coils, although alternatives are possible. The two sets of equations form a single combined set of equations. Each normal zone location or combination of normal zones has a set of these combined equations associated with it. It is demonstrated that the normal zone can be located and the correct set chosen, allowing determination of the size of the normal zone. Only a few operations take place in a working detector: multiplication of a constant, addition, and simple decision-making. In many cases the detector for each coil, although weakly linked to the other detectors, can be considered to be independent.

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Introduction

A superconducting coil can fail if part of the winding loses its superconductivity or becomes normal causing an excessive amount of heat to be produced in a localized region [1,2]. The detection of a normal zone in a single superconducting coil is a relatively simple matter. A bridge can be used to balance out the self-induced voltages, allowing the normal zone voltage to be measured [3]. Detection of a normal zone in inductively coupled coils is more difficult because, in general, it is not possible to balance out the mutually induced voltages as well as the self-induced voltages.

The MFTF-B project at the Lawrence Livermore National Laboratory contains a large number of inductively coupled coils [4]. The normal zone detector must determine the location and measure the size of one or more normal zones in the set of coils. It must function when the currents in the coils are being adjusted from one level to another as well as when the currents are constant. When the currents are changing the mutual and self-induced voltages are very large compared with the normal zone voltages that must be detected.

A method of eliminating the mutually induced voltages that first comes to mind is to directly measure the rates of change of current and calculate the mutually induced voltages [5]. The resolution required for this measurement is related to the rate of change of current caused by a normal zone. This change is minute and its measurement is difficult.

A normal zone detector for two inductively coupled coils that uses only voltage measurements has been described by one of the authors [6]. The current paper presents a reformulation that gives additional insight into the method and extends it to include any number of coupled coils.

The largest of the induced voltages, the self-induced voltages, can be cancelled out by means of bridges across the coils balanced with respect to the self-inductances. The mutual inductances, however, are not distributed in the

same way as the self-inductances. Consequently, the mutually induced voltages are only partially eliminated by the bridges, leaving a component of the mutually induced voltage. Therefore, the bridge outputs depend on the rate of change of currents as well as on the normal zone voltages. Since the rates of change of current as well as the normal zone voltages are unknown, the bridge outputs in themselves, do not contain sufficient information to determine the normal zone. In addition, the form of the bridge equation depends on the location of the normal zones. Consequently there are many sets of bridge equations, one for every normal zone location or combination of locations.

In order to determine the normal zones, additional voltage measurements are needed. The number depends on the number of normal zones—a fact that is not known a priori. An empirical approach is used to investigate this problem.

An additional set of voltages, the supplementary voltages, equal in number to the bridge voltages is assumed to be available. The bridge and supplementary voltages can be combined into a single equation with all of the normal zone terms on the left side. The left side coefficients of the normal zone voltages depend on the location of the normal zones. However, the right side does not depend on the location of the normal zones. There are two ways of combining the bridge and supplementary equations, each having this property.

The usefulness of this formulation is investigated, using the voltages across the coils as the supplementary voltages. For a single normal zone the equations are redundant, any one could be used to solve for the normal zone. However, for one of the ways of combining the bridge and supplementary equations, the equation associated with the coil containing the normal zone is much more sensitive to the presence of the normal zone than the other equations. This fact suggests a method of locating a single normal zone. It is also found that the effect of more than one normal zone is a simple linear superposition of the effects of single normal zones. Therefore, any number of normal zones can be located by examining the combined bridge and coil voltage equations.

The detector consists of both logic and arithmetic elements. The arithmetic part, the detector equations, consists of two equations for each coil, one for a normal zone in the top of the coil, the other for a normal zone in the bottom. The equations are drawn from the combined set of equations. For example, the detector equation for a normal zone in the top of coil i is the i^{th} equation of the combined equations that apply to this location of normal zone. In the detector a weighted sum of the bridge and supplementary voltages, which constitute the right side of both of the detector equations for the coil, is tested for sign to determine whether the normal zone is in the top or bottom of the coil. The correct left side factor is then applied to calculate the magnitude of the normal zone. If a threshold is exceeded a normal zone is reported, if not it is decided that there is no normal zone.

Normal zones that are symmetrical to the self-inductance bridges are nearly invisible to the detector. The probability of missing a normal zone is reduced if additional bridges are placed across part of the coil. When this is done it is possible to use the voltage across the coils for all of the detectors.

There are two kinds of error in the detector (7): scale factor error and error due to the changing currents. Improving the balance of the self-inductance bridges reduces both kinds of error. When the bridges are perfectly balanced, the scale factor error is zero. Obviously the largest source of error is the error due to changing currents when the bridges are unbalanced. Fortunately, the bridge balance can be fine-tuned after the coils and detector are in place.

The Bridge Equations

Figure 1 shows n coils each with a bridge connected across the entire coil. The bridges are balanced with respect to the self-inductances of each coil.

The coils are coupled with each other by mutual inductance. Figure 2 defines the nomenclature used for the mutual inductance between two arbitrarily chosen coils j and k . The mutual inductance between one entire coil and the other entire coil is M_{jk} . A property of coils is that

$$M_{jk} = M_{kj}.$$

Figure 1. The Coils and Their Bridges

Figure 2. Nomenclature for the Inductances

The mutual inductance between part of one coil and whole of the other coil also enters into the bridge equations. The mutual inductance of the bottom part of coil j to the whole of coil k is called M_{bjk} . In general

$$M_{bjk} \neq M_{kbj}.$$

The voltage across the first coil v_{c1} is

$$v_{c1} = L_1 \frac{di_1}{dt} + M_{12} \frac{di_2}{dt} + M_{13} \frac{di_3}{dt} + \dots + M_{1n} \frac{di_n}{dt} + r_1 i_1. \quad (1)$$

The last term $r_1 i_1$, the normal zone voltage, is due to a normal zone which is assumed to be present in coil 1. The normal zone voltage and the position of the normal zone are functions of time.

If the normal zone is in the lower part of the coil, the voltage across the bridge associated with the first coil is

$$v_1 = L_{b1} \frac{di_1}{dt} + M_{b12} \frac{di_2}{dt} + M_{b13} \frac{di_3}{dt} + \dots + M_{bin} \frac{di_n}{dt} + r_1 i_1 - \frac{R_{b1}}{R_{B1}} v_{c1}. \quad (2)$$

If the normal zone is in the upper part of the coil, the normal zone voltage $r_1 i_1$, the next to last term of Equation 2, is missing from the equation. However, since the normal zone voltage is a term in the expression for v_{c1} it remains represented in v_1 .

When v_{c1} is replaced by the right side of Equation 1, there is a term

$$\left(L_{b1} - \frac{R_{b1}}{R_{B1}} L_1 \right) \frac{di_1}{dt}$$

This term is eliminated by balancing the bridge so that

$$\frac{L_{b1}}{L_1} = \frac{R_{b1}}{R_{B1}} = p_1.$$

When this is done only the mutually induced and normal zone voltages remain.

For a normal zone in the lower part of the bridge the resultant equation, after collecting terms, is

$$v_1 = (M_{b12} - p_1 M_{12}) \frac{di_2}{dt} + (M_{b13} - p_1 M_{13}) \frac{di_3}{dt} + \dots + (M_{b1n} - p_1 M_{1n}) + (1 - p_1) r_1 i_1.$$

For a normal zone in the upper part of the bridge the equation is the same except for the normal zone term which is $-p_1 r_1 i_1$ instead of $(1-p_1) r_1 i_1$

$$v_1 = (M_{b12} - p_1 M_{12}) \frac{di_2}{dt} + (M_{b13} - p_1 M_{13}) \frac{di_3}{dt} + \dots + (M_{b1n} - p_1 M_{1n}) - p_1 r_1 i_1.$$

A similar equation can be written for each of the coils. Combining results in the matrix equation, Equation 3.

The bridges are balanced so as to eliminate the self-induced voltages

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} 0 & M_{12} & \dots & M_{1n} \\ M_{21} & 0 & \dots & M_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ M_{n1} & M_{n2} & \dots & 0 \end{bmatrix} \begin{bmatrix} \frac{dI_1}{dt} \\ \frac{dI_2}{dt} \\ \vdots \\ \frac{dI_n}{dt} \end{bmatrix} + \begin{bmatrix} V_{s1} & 0 & \dots & 0 \\ 0 & V_{s2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & V_{sn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix}$$

THE MATRIX EQUATION: $V = A \frac{dI}{dt} + B I_n$, V_n = THE NORMAL ZONE VOLTAGES

V = THE BRIDGE VOLTAGES

WHERE V , V_n , B & I ARE COLUMN MATRICES

A IS A SQUARE MATRIX SUCH THAT

$$a_{ij} = \begin{cases} 0, & i = j \\ M_{ij} - p_i M_{ji}, & i \neq j \end{cases}$$

B IS A DIAGONAL MATRIX SUCH THAT

$$b_{ii} = \begin{cases} 0, & \text{IF THERE IS NO NORMAL ZONE} \\ 1 - p_i, & \text{IF THE NORMAL ZONE IS IN THE BOTTOM OF THE COIL} \\ -p_i, & \text{IF THE NORMAL ZONE IS IN THE TOP OF THE COIL} \end{cases}$$

The A matrix, which is a square matrix, with a zero diagonal, contains the mutual inductances and the bridge ratios. The diagonal is zero, because the self-inductance terms have been cancelled out by balancing the bridges. In forming the matrix, advantage has been taken of the fact that $M_{jk} = M_{kj}$. However, as is pointed out earlier, the partial mutual inductances are all unique.

The B matrix is a diagonal matrix with diagonal elements that depend on the existence and location of a normal zone. If a coil has no normal zone the diagonal element is zero. If the normal zone is in the top portion of the coil the element is $-p_i$, if it is in the bottom the element is $1 - p_i$. Since p is a ratio less than one, $-p$ is negative and $1 - p$ is positive. Therefore, the location of the normal zone determines the sign of the element.

The Combined Equations

The bridge equations alone are not sufficient to solve for the normal zone voltages. The rates of change of current are unknown, making more than n unknowns for the set of n equations.

Additional information in the form of a set of voltage measurements is needed. It is not immediately clear what voltages should be used, but there are several candidates: the voltages across the coils, part of the voltages across the coils, the output of a second bridge balanced with respect to mutual inductance, or possibly voltages between coils.

Whatever the choice, the set of voltages, which will designate the supplementary voltages, can be written as a matrix equation with one term due to the mutual and self-induced voltages and the other due to the normal zone voltages.

$$V_s = C \frac{dI}{dt} + D V_n \quad (4)$$

where

V_s = the supplementary voltages

V_s , I , and V_n are column matrices.

C is a square matrix with elements that depend on the mutual and self-inductances.

D is a square matrix.

The supplemental voltage equation and the bridge equation comprise a set of $2n$ equations. There are n unknown rates of change of current and anywhere from zero to n normal zones if there is only one normal zone per coil.

An expression for the normal zone voltage can be derived in two different ways. In the first method an expression for the derivatives of the current is obtained from the supplemental equations and this is substituted into the bridge equation.

From Equation 4,

$$\frac{dI}{dt} = C^{-1} V_s - C^{-1} D V_n$$

Eliminating the derivatives from Equation 3 yields

$$V = (A C^{-1} V_s - C^{-1} D V_n) + B V_n$$

Collecting the normal zone terms on the left side,

$$(B - A C^{-1} D) V_n = V - A C^{-1} V_s \quad (5)$$

Solving for the normal zones is not a simple matter of multiplying both sides of the combined equations by the inverse of $B - A C^{-1} D$. The B matrix is a diagonal matrix with elements that depend not only on the existence of a normal zone in a coil, but also whether it is in the top or bottom. The exact form of the D matrix depends on the choice of supplementary voltages, but it also has elements that depend on the location of the normal zones. Therefore, instead of being a single set of n equations, the combined equations are actually a large number of sets of n equations, one set for each normal zone location or combination of normal zone locations.

The existence and location of the normal zones are not known at the onset of the measurement, but are unknowns to be determined. Therefore, determination of which set of equations is valid is part of the initial problem.

The measured voltages V and V_s appear on the right side of the combined equations. The two matrices on the right side, A and C , do not depend on the location of the normal zone, but only on the bridge ratios, and the mutual and self-inductances. Therefore, the right-hand side of the matrix equation can be instrumented in an unambiguous manner, to form the first stage of the detector. This stage is used to determine the location of the normal zone.

The Detector Based on the Voltages Across the Coils

As far as can be determined, there is no simple principle that governs the optimum choice of the supplementary voltage. It is necessary to proceed by trial, choosing a supplementary voltage and then examining the properties of the resulting detector.

The voltages across the coils are a prime choice because of their ready accessibility. The voltage across coil 1 of Figure 1 is given by Equation 1. Each coil voltage can be expressed by a similar equation. Putting all of these equations together results in the matrix equation, Equation 6.

By premultiplying the matrix equation by the bridge and coil's self inductances

$$\begin{bmatrix} L_{11} & L_{12} & L_{13} & \dots & L_{1n} \\ L_{21} & L_{22} & L_{23} & \dots & L_{2n} \\ L_{31} & L_{32} & L_{33} & \dots & L_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ L_{n1} & L_{n2} & L_{n3} & \dots & L_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & \dots & C_{1n} \\ C_{21} & C_{22} & C_{23} & \dots & C_{2n} \\ C_{31} & C_{32} & C_{33} & \dots & C_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_{n1} & C_{n2} & C_{n3} & \dots & C_{nn} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_n \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{13} & \dots & D_{1n} \\ D_{21} & D_{22} & D_{23} & \dots & D_{2n} \\ D_{31} & D_{32} & D_{33} & \dots & D_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ D_{n1} & D_{n2} & D_{n3} & \dots & D_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ V_n \end{bmatrix}$$

THE MATRIX EQUATION: $V_c = C \frac{dI}{dt} + D V_c$

WHERE V_c , I , AND I ARE COLUMN MATRICES

C IS A SQUARE NONSINGULAR MATRIX SUCH THAT

$$C_{ij} = \begin{cases} L_{ij} & i = j \\ M_{ij} & i \neq j \end{cases}$$

D IS A DIAGONAL MATRIX SUCH THAT

$$d_{ii} = \begin{cases} 1 & \text{IF THERE IS A NORMAL ZONE IN THE COIL.} \\ 0 & \text{IF THERE IS NO NORMAL ZONE IN THE COIL.} \end{cases}$$

The C matrix is a symmetric square matrix with the self-inductances as the diagonal elements and whole coil mutual inductances as the off-diagonal elements. The symmetry is due to the fact that $M_{jk} = M_{kj}$.

The D matrix is a diagonal matrix with diagonal elements that depend on the presence or absence of a normal zone. If a normal zone is present in a coil, the diagonal element corresponding to the coil is a 1. If there is no normal zone the diagonal element is a 0.

The Combined Equations for a Normal Zone in the Top of Coil i

The bridge equations and the coil equations can be united to form a combined equation. There are many sets of combined equations, one set for each normal zone and combination of normal zone locations. Something of the structure of these equations can be seen by writing the equation for a single normal zone, arbitrarily located in the top of the i th coil.

Since only the left side of the combined equation depends on the normal zone location, only the left side is written in expanded form. The combined equation, Equation 5, is used.

$$B - AC^{-1}D = \begin{bmatrix} 0 & \dots & 0 & \dots & 0 \\ 0 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & -p_i & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & \dots & 0 \end{bmatrix} \begin{bmatrix} a_{12} & a_{11} & a_{1n} \\ a_{21} & a_{22} & a_{2n} \\ \vdots & \vdots & \vdots \\ a_{i1} & a_{i2} & a_{in} \\ \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & a_{nn} \end{bmatrix} \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1i} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2i} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \dots & x_{ii} & \dots & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \dots & x_{ni} & \dots & x_{nn} \end{bmatrix} \begin{bmatrix} 0 & \dots & 0 & \dots & 0 \\ 0 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & 0 & \dots & 0 \end{bmatrix}$$

where,

$$C^{-1} = [x]$$

Partitioning the A and C^{-1} matrices as useful,

$$\text{Let } AC^{-1} = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{bmatrix} \begin{bmatrix} x_1 & x_2 & \dots & x_i & \dots & x_n \end{bmatrix}$$

where the A_j 's are row matrices consisting of the rows of A and the x_j 's are column matrices consisting of the columns of C^{-1} . The left side of the combined equation can now be written,

$$B - AC^{-1}D = \begin{bmatrix} 0 & 0 & \dots & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & -p_i & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 & \dots & 0 \end{bmatrix} \begin{bmatrix} A_1 x_1 & A_1 x_2 & \dots & A_1 x_i & \dots & A_1 x_n \\ A_2 x_1 & A_2 x_2 & \dots & A_2 x_i & \dots & A_2 x_n \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ A_i x_1 & A_i x_2 & \dots & A_i x_i & \dots & A_i x_n \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ A_n x_1 & A_n x_2 & \dots & A_n x_i & \dots & A_n x_n \end{bmatrix} \begin{bmatrix} 0 & 0 & \dots & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 & \dots & 0 \end{bmatrix}$$

If the normal zone voltages are zero except for coil i ,

$$(B - AC^{-1}D) V_n = \begin{bmatrix} -A_1 x_i \\ -A_2 x_i \\ \vdots \\ -p_i - A_i x_i \\ \vdots \\ -A_n x_i \end{bmatrix} \quad V_{ni} = V - AC^{-1}V_c \quad (7)$$

If the normal zone is in the bottom of coil i , the appropriate equation is obtained by substituting $(p_i - 1)$ for p_i .

As Equation 7 shows, a normal zone in coil i affects all of the combined equations. If it is known that there is only one normal zone and it is in coil i , any one of the equations could be solved for the value of the normal zone voltage V_{ni} .

However, it is not known, a priori, how many normal zones there are and where they are located. The question then is "Is there a pattern in the measured outputs, when combined in accordance with the right side of the equation $V - AC^{-1}V_c$, that shows the number and location of the normal zone?"

A key factor is the relative values of the term $-p_i - A_i x_i$ and the other terms. The size of the $A_i x_i$ terms is not at all apparent because x_i is a submatrix of the inverse of C .

The Detector

Although a normal zone in one coil affects all of the combined equations, the equation for the coil containing the normal zone is affected more than the others. This enables the coil containing the normal zone to be identified. The sign of the combined equation indicates whether the normal zone is in the top or bottom of the coil. Using this information the correct choice of D and B matrices can be made.

If the effect of a normal zone is largely confined to the equation associated with it, the structure of the detector can be simplified. The detector can consist of a number of independent detectors, one for each coil based on the equation associated with the coil.

For coil i the two equations associated with coil i are used. If the normal zone is in the top of coil i , the equation used in the detector is

$$(-p_i + A_i X_i) V_{ni} = V_i + (Y_{i1} V_{s1} + Y_{i2} V_{s2} + \dots + Y_{in} V_{sn})$$

For a normal zone in the bottom of coil i , the equation used in the detector is

$$(-p_i + 1 - A_i X_i) V_{ni} = V_i + (Y_{i1} V_{s1} + Y_{i2} V_{s2} + \dots + Y_{in} V_{sn})$$

For convenience let

$$-p_i + A_i X_i = LTI_i$$

$$-p_i + 1 - A_i X_i = LBI_i$$

Implementing the equations in a physical detector requires a combination of arithmetic and decision making. Figure 3 shows a diagram of the detector for a single coil i . The detector for a set of n coils consists of n similar detectors.

As the diagram shows, for each detector a sum is formed of the output of a single bridge, the bridge associated with the detector, and a weighted sum of the supplementary voltages. This sum is tested to determine whether it is positive or negative. If it is negative, the normal zone is in the top, and the right side sum is divided by the left side coefficient associated with the top, LTI_i . If it is positive the sum is divided by the left side coefficient associated with the bottom, LBI_i . The result in either case is the voltage across a normal zone, if one exists. The calculated normal zone voltage is tested against a threshold. If the value is less than the threshold the decision is made that no normal zone exists in the coil. If it is more than the threshold the normal zone voltage is divided by the current through the coil to yield the normal zone resistance.

Figure 3. A Combination Block Diagram and Flowchart for the Detector Associated with a Single Coil, Coil i

Although the detector associated with the coil containing the normal zone will register the largest normal zone voltage, the normal zone voltages indicated by the other

detectors are not zero. The sensitivity of a detector to a normal zone in its coil as compared with its sensitivity to a normal zone in other coils is important in determining the threshold and the smallest normal zone that can be detected.

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