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INDUCTIVE VOLTAGE COMPENSATION IN SUPERCONDUCTING MAGNET SYSTEMS*

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Summary

This paper details several techniques of inductive voltage compensation developed for quench detection in superconducting magnet systems with multiple coils and power supplies, with particular application for the Large Coil Test Facility (LCTF). Sources of noise, their magnitudes, and the sensitivity required for normal zone detection to avoid damage to the magnets are discussed.

Two passive compensation schemes (second difference and central difference) are introduced and illustrated by parameters of LCTF; these take advantage of coil symmetries and other system characteristics.

An active compensation scheme based on current rate input from pickup coils and utilizing theory on ac loss voltage for calibration was tested, and the experimental setup and test results are discussed.

Introduction

As is well known, the stored energy in toroidal field (TF) magnets of large tokamak machines is very large. In the event of a quench, the stored energy must be removed quickly if these TF magnets are also superconducting. Severe damage to a magnet may result if a quench goes undetected. Thus, quench detection plays a crucial role in the protection of these expensive superconducting magnets. Furthermore, since the location of quench initiation is not known beforehand, global monitoring is required. Variables such as temperature, which measures only local changes, cannot be relied on as the sole input for quench detection.

Acoustic emission, pressure rise (or helium boiloff rate), and voltage are all global variables that transmit information on a quench event. Preliminary results on acoustic emission[1] look very promising, but not enough is known at present on the acoustic signature of different events to allow confident use of the technique for quench detection. The pressure rise may be adequate under certain circumstances, but the response time required seems too long to be useful for coils of LCTF.[2] Thus, we focus mainly on voltage as the primary signal for quench detection.

The primary drawback of the voltage signal is that, because a tokamak is a pulsed machine, inductive voltage is likely to present. Because a quench signal is very small (for typical LCTF pool-boiling coils of 1 m normal zone at 10 kA and 8 T, the signal is ∼20 mV), it can easily be masked by inductive components. Thus, central to the signal conditioning for quench detection is the removal of inductive and other undesirable components, such as noise from power supplies, electromagnetic interference, plasma disruption, eddy currents, etc.

For a single magnet, three voltage taps could be used for quench detection — one placed at the center and two at the ends. The difference between the voltage of each half of the magnet would give the quench signal, and most of the noise mentioned above would be eliminated. This scheme would also work for several magnets if each half of the magnet had identical inductive coupling to the rest of the system. The sensitivity of detection would be reduced in this scheme if two normal zones should occur simultaneously in the two halves.

For LCTF, however, the case is different. To allow full freedom in coil design, the coil currents are different in coils designed for LCTF, and each of the six coils has its own power supplies. The above scheme would not work here because the neighbors on two sides of each coil are different, meaning that each half of the magnet a different inductive coupling to the rest of the system.

In short superconductor sample experiments, voltage taps are usually bifilar-wound to remove the inductive component. A suggestion to cowind bifilar continuous voltage sensors with the conductor has previously been made,[3] but such a scheme is not equally applicable to the six different coil designs of LCTF. There is also the uncertainty of how to maintain good thermal contact between the sensor and the conductor, yet still provide between them good electrical insulation that survives the fabrication process.

Quench detection is easier for force-flow coils than for the pool-boiling coils in LCTF. This is due to the higher current density used in force-flow coils. For normal zones of the same size, the quench signal from force-flow coils is usually several factors larger than the corresponding signal from pool-boiling coils.

For LCTF pool-boiling conductors, our estimate indicates that a normal zone shorter than about 50 cm is likely to recover from a quench by cold end thermal conduction. Eariler work by others leads to similar results.[4] Thus, 50 cm may be the range below which a hot spot cannot exist. Unfortunately, that still requires a sensitivity of better than 1 in 1000 (i.e., detecting a ±10 mV signal out of, say, a ±15 V inductive component).

Inductive Voltage, Noise Magnitude, and AC Loss Voltage Effect

Before the proposed quench detection scheme is detailed, some clarification is in order, as are the estimates of various voltage signals.

Required Sensitivity

The scheme should be able to detect a signal of 10 mV at 10 Hz for a 50-cm normal zone. All signals will be preconditioned by a 2-kHz filter and postconditioned after compensation by a 10-Hz filter.

Inductive Voltage Components

Self-Inductive Voltage. The self-inductive voltage range for the proposed power supply is ±15 V.

Mutual Inductive Voltage. The mutual inductive voltage for the proposed power supply is 2.4 V from each nearest neighbor.

Inductive Voltage of the Plasma or Pulse Coils. The inductive voltage from the plasma or the pulse coils should be nearly zero if the plasma or pulse current is symmetrical about the torus midplane. Otherwise, it could be large (e.g., in one pulse field test for LCTF, only one of a pair of pulse coils is energized and the inductive voltage across one TF coil due to pulsing can reach ∼60 V).

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Inductive Voltage of the Eddy Currents. Eddy currents are induced in the coil case, the conductor, and other structural members during the charging and discharging of the TF and pulse coils. The effect during the charging of the TF coils is expected to be small because of the low charging rate (∿10 kA/hr). The effect of the discharging TF coil need not concern quench detection because, if one coil is quenched, all LCTF coils will be discharged. The effect of the pulse field is mostly limited to the 1-sec rise or the 1-sec discharge interval of the pulse current, except for the eddy currents in the conductor, which may linger longer because of the shielding effect.

Noise Magnitude

Power Supply Ripple. The ripple from the power supply is expected to approach 250 mV peak-to-peak for values of ∿300 Hz and 500 mV for values >300 Hz.

Input Line Voltage Variation. The 3% variation of the input line voltage is estimated to be ∿30 mV.

Pickup Noise. For a typical LCTF coil, the pickup noise should be several hundred millivolts (mV) at 60 Hz or higher.

AC Loss Voltage

AC Loss Voltage During the Charging of a Magnet. Turning to the ac loss voltage during the charging of a magnet, we see that, besides inductive voltage, loss voltage resulting from the flux diffusion into the conductor can appear as terminal voltage during the current ramp. In a typical superconducting magnet, assuming a linear current ramp, the compensated loss voltage can be divided into two distinct regions, namely, the shielding region and the flux-flow region. We have applied a previously published theory[5] to a coil of the size used in the Large Coil Program (LCP) to estimate the magnitude of these voltages. In the shielding region, it is estimated that ΔV_s has a negative value of 200 mV from 0-1000 A. As the current increases, the flux begins to penetrate and thus changes the voltage to a positive value. For current greater than 2000 A, it is believed that flux-flow starts to take place. Based on the magnetic data available for a NbTi composite strand similar to that used in LCTF coils, we have estimated that in this region, ΔV_F is less than 1 mV (Fig. 1). Because the charging time is much larger than the skin time of the conductor, the ac loss voltage resulting from the eddy currents induced in the conductor during charging is expected to be negligible.

AC Loss Voltage During the Pulse Test. For a pulse test of 1-sec ramp-up and 1-sec ramp-down, the ac loss voltage is estimated to be ∿100 mV for a monolithic LCTF conductor. It has a complex waveform and is time-dependent. For this reason, direct compensation seems impractical and a 1-sec disabling feature is proposed for quench detection in LCTF.

Passive Compensation Schemes

The Second Difference Scheme

From Table 1, we see that the two Japanese and Swiss coils have a large even number of pancakes. If the traditional quench detection scheme is used, i.e., if the voltage across two symmetrically placed pancakes is measured and the difference is determined, the self-inductive voltage is eliminated. The same symmetry also eliminates noise and ac loss voltage due to the pulse coil (assuming the pulse coil is symmetrically placed across the coil midplane).

Table 2 gives the mutual inductance between the 12-pancake coils (Swiss) with a typical first neighbor of 600 turns. Because of the large number of pancakes, mutual inductance with each pancake is relatively small, and the difference of inductance between two symmetrically placed pancakes is down to the mini-Henry (mH) range (column 3 in Table 2). Furthermore, there are not many coils in LCTF; the distance between the coil centers is large compared to the axial thickness of the coils. Thus, mutual inductance changes slowly as one moves from one pancake position to the next. This is also reflected in the numbers of column 3, which also vary slowly from one row to the next. Thus, if we take the difference between two consecutive numbers, they are all nearly the same, and the largest difference is 1.39 mH. For a maximum charging rate of 5 A/sec (i.e., 33 min to reach 10 kA), this corresponds to 7 mV.

Electrically, this scheme corresponds to the value given by first taking the differential voltage between two symmetrically placed pancakes, then the difference between two such differential outputs. Thus, for the 12-pancake coils, there will be five outputs. The first one is $(V_{12} - V_1) - (V_{11} - V_2)$, the second one is $(V_{11} - V_2) - (V_{10} - V_3)$, etc.

For this scheme at a 5-A/sec charging rate, the largest voltage resulting from the next nearest neighbor is 1 mV. Because of symmetry, there is no coupling with the third (opposite) neighbor. Thus, this scheme reduces the mutual inductive voltage to an absolute maximum of 16 mV. We have assumed here that symmetrically placed pancakes have the same number of turns. If one turn such as the heater zone is excluded on one side, then the corresponding turn on the other side is excluded, etc.

This scheme yields better results for the Japanese coil. The increased number of pancakes further reduces the inductive coupling and more than compensates for the increment in the number of turns.

An inductance code for noncircular toroidal field coils has been modified to allow for the computation required here. Coil shape fitting and inductance value convergence are checked to assure the four significant digits sufficient for the computation required here. Results reported here were checked for coil shape variation and winding cavity displacement and found to be insensitive to these changes.

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The Central Difference Scheme

The Second Difference Scheme cannot be used for the remaining toroidal coils that are either plates, or layer-wound, or that have fewer than seven and an odd number of pancakes. To eliminate the mutual inductive voltage between toroidal field coils, we use instead a "central difference scheme" as is illustrated by the last column in Table 2 for the 12-pancake case. Namely, we take the voltage across three consecutive pancakes, say numbers 1, 2, and 3. Then we take the average of voltages 1 and 3 and subtract voltage 2. Because the coils are thin relative to the distance between them, the field is changed little as we move from one pancake to the next. Thus, good compensation is expected. For layer-wound coils, this shows that the flux passing through each layer is very nearly proportional to the area enclosed. Figure 2 shows the connection scheme for a seven-pancake coil. Five channels are monitored. In order to have better sensitivity for normal zones in the end pancake or layers (numbers 1 and 7 in Fig. 1), channels 1 and 5 in Fig. 2 can be replaced by $V_1 + V_4 - V_2 - V_3$ and $V_7 + V_4 - V_5 - V_6$, respectively. Assuming a 5-A/sec maximum charging rate, the results are shown in Table 3. They are seen to be acceptable provided the number of turns changes no more than one or two from pancake to pancake. (As seen in Table 1, the number of turns is not an integer multiple to the number of pancakes or layers.) This also takes care of the effect of the exclusion of turns with heaters that are monitored separately. Self-inductive voltage is also significantly reduced by the central difference scheme, e.g., for the middle channel of the seven-pancake case, the self-inductive voltage at the 5-A/sec charging rate is about 45 mV.

Discussion

The scheme proposed above requires less hardware for quench detection in LCTF than would be required to compensate inductive voltage by employing dI/dt signals from each power supply.

If the 1-sec disabling feature is adopted, the two Japanese and Swiss coils would not require any dI/dt input. Three of the other coils (EURATOM, General Electric, and General Dynamics) require only the dI/dt from itself. Thus, quench detection can be set up on a permanent basis regardless of which is the test coil or which is being energized.

The sensitivity is comparable to or exceeds what is achievable by compensating with dI/dt input at present. It also has the advantage of canceling out a large part of the power supply noise, the pickup noise from 60 Hz, the nonbifilar winding of voltage taps, or ac loss voltage, etc.

Furthermore, this scheme would be much less sensitive to factors like inductance change (magnet expansion) during charging. The dI/dt compensation scheme, being calibrated at low current, may suffer some error due to inductance change.

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However, the passive compensation scheme is not sensitive enough to detect simultaneous multiple normal zones. Thus, if the passive scheme is used, the heaters in symmetrically placed pancakes should not be energized at the same time. Also, the winding scheme of the Westinghouse coil does not lend itself easily to the above type of analysis because it is a combination of layer and pancake winding schemes.

For test with the heater and pulse fields, on the one hand, one would like to delay dump triggering in order to allow time for the conductor to demonstrate its capability of recovering; on the other hand, delayed triggering leads to high thermal stress at the hot spot, especially for force-flow coils. In LCTF, the time threshold for dump initiation is to be recommended by coil manufacturer.

Active Compensation Scheme

Concept

The active compensation scheme utilizes a separate pickup coil near the coil current bus to obtain the time rate of the current change in the coil. For a multiple coil configuration as in LCTF, one of these pickup coils, commonly called a Rogowski coil, is used in each coil circuit. The concept used successfully here and described previously[5] has been to subtract electronically the Rogowski coil signal from the coil voltage in order to remove the inductive portion. The signal remaining after this compensation represents any ac loss voltage or any normal zone in the coil. Extending the concept to multiple coils with significant mutual inductances requires that each Rogowski coil signal be subtracted from the voltage measured across a particular superconducting coil in order to compensate for all the inductive components. Note that this scheme does not cancel any of the pickup noise in the coils.

Instrumentation

The active compensation scheme may be simple in concept, but its implementation in hardware and software presents many problems. The diagram in Fig. 3a shows the instrumentation required for each superconducting coil. For coils with inductances on the order of Henries, as is the case with LCTF, the Rogowski coil is a difficult design problem due to the small dI/dt. Commercial amplifiers were used in past experiments because common mode voltages greater than 300 V were not encountered. With LCTF and larger magnets, dump voltages on the order of 2500 V are needed, which means that the amplifiers connected to the coil must either withstand the dump voltage or be protected from it. In addition, the gain and phase responses of the amplifiers must be matched very closely to the highest frequencies of interest. For example, a differential phase shift of 0.5° at a particular frequency will cause an error of 1%. The amplifier outputs come together in the compensation stage. High resolution gain adjustments must be made in the Rogowski coil

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signals in order to provide accurate inductive voltage cancellation. The calibration of these gain adjustments has been a manual, time-consuming procedure. With multiple coils, the number of these calibrations can be considerable. In LCTF, for instance, the General Dynamics coil with 14-layer voltage measurements and with three Rogowski coil inputs requires 42 calibrations.

Calibration Procedure

To meet the calibration needs of LCTF, a computerized calibration procedure has been developed and tested. The gain adjustment is accomplished by a digitally programmable gain circuit with 12 binary bits of resolution, as indicated in Fig. 3a. One of these circuits is included in the compensation stage for each Rogowski coil signal input. Using the algorithm described below, a computer adjusts the gains until the compensation criterion is reached.

To calibrate the gains, a slow ramp of current is input to the coil, as shown in Fig. 3b. The current and the compensated voltage are measured. This compensated voltage can be represented for one coil as

$$\Delta V_m = C\, K_v \frac{dI}{dt} + K_v iR \;,$$

where C represents the cancellation error for some arbitrary gain K_C. To eliminate the resistance term, ΔV_m is integrated over two time periods in the same current ramp. The measured current is also integrated over the same two time periods. The resulting computation is

$$C = \frac{\dfrac{K_S K_I}{K_v} \displaystyle\int_{t_1}^{t_2} I_m dt \int_{t_3}^{t_4} \Delta V_m dt - \int_{t_3}^{t_4} I_m dt \int_{t_1}^{t_2} \Delta V_m dt}{I_{mt_4} - I_{mt_3} \displaystyle\int_{t_1}^{t_2} I_m dt - I_{mt_2} - I_{mt_1} \int_{t_3}^{t_4} I_d dt} \;. \tag{1}$$

The coil and measured voltages are assumed to be linear so that C is directly proportional to K_C, or

$$C = aK_C + B$$
$$C' = aK_C' + B \;. \tag{2}$$

To obtain a particular value of C, which is the compensation criterion, two values of C must be calculated with different gains, K_C. The compensated gain is then

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$$K_C \text{ (compensated)} = \frac{C_{\text{compensated}}(K''_C - K'_C) + K'_C C'' - K''_C C'}{C'' - C'} , \tag{3}$$

where C'' is the value calculated with gain K''_C, and C' is the value calculated with gain K'_C. The compensation criterion as given in Ref. 5 is a constant, $C_{\text{compensated}}$, and is dependent upon the individual coil properties.

For multiple coils, the same procedure is applied iteratively for each compensating input. The calculated gains can be shown to converge to the correct values after several iterations, depending upon the amount of mutual coupling between the coils.

Test Results

An experimental check of the above method has been performed on a superconducting magnet (Magnet II of Ref. 5). Figure 4 shows the current waveform and the terminal voltage before compensation. The ramp rate is 1.25 A/sec and the maximum current is 5 A. The peak-to-peak induction voltage is above 300 mV. With active compensation, the voltage is reduced to 3.5 mV, as shown in Fig. 5a. The corresponding magnetization, applied external field (M-H) curve is shown in Fig. 5b. For the same compensation, the results of a 20-A peak current ramp is shown in Figs. 6a and b. The above results are obtained by using a bread-board model of the circuit. Further improvement of the sensitivity of the computation should be expected for the shop prototype model.

This method seems quite promising and will be used as the primary method for quench detection in LCTF. The passive scheme of detection is also to be tested.

Acknowledgment

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References

1. H. Nomura, K. Takahisa, K. Koyama, and T. Sakai, Cryogenics 17(8), 471 (1977).
2. Peter Walstrom (Oak Ridge National Laboratory), private communication, 1979.
3. Mike Walker (Intermagnetics General Corporation), private communication, 1978.
4. R. L. Willig, Proc. 6th Symp. on Engineering Problems of Fusion Research, p. 128 (1976).
5. S. S. Shen and H. T. Yeh, IEEE Trans. Magn., MAG-13, 1(1), 855 (1977).

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Table 1. LCTF coil parameters

Coil	Winding	Number of components	Number of turns
General dynamics	Layer	14	647
General electric	Pancake	7	670
Westinghouse	Plate	26	462
EURATOM	Pancake	7	600
Japanese	Pancake	20	662
Swiss	Pancake	12	440

Table 2. Mutual inductance for 12-pancake coil with first neighbor TF coil in LCTF

Pancake number	Mutual inductance M_n (Henry)	Difference between Symmetrical pancakes $M_{13-n} - M_n$	First difference $\Delta_{n+1} = M_{n+1} - M_n$	Central difference* $C_n = \frac{1}{2}(\Delta_{n+1} - \Delta_n)$
1	.01268	.00752	(Multiply by 10^{-4})	(Multiply by 10^{-5})
2	.01321	.00613	5.3	1
3	.01376	.00475	5.5	1.5
4	.01434	.00339	5.8	1.5
5	.01495	.00203	6.1	1.5
6	.01560	.00067	6.5	2
7	.01627		6.7	1
8	.01698		7.1	2
9	.01773		7.5	2
10	.01851		7.8	1.5
11	.01934		8.3	2.5
12	.02020		8.6	1.5

$^*C_n = \frac{M_{n+1} + M_{n-1}}{1} - M_n$

Table 3. Inductive voltage on General Electric (GE), General Dynamics (GD) and EURATOM coils

	Maximum inductive voltage (in mV) in channel due to:		
	First neighbor	Second neighbor	Third neighbor
GD			
Central difference channels	0.08	0.03	0.02
Channel associated with end layer	0.25	0.05	0.05
Voltage due to one missing turn	2.4	0.7	0.4
GE/EURATOM			
Central difference channels	0.8	0.15	0.1
Channel associated with end pancake	3.0	0.5	0.4
Voltage due to one missing turn	3.0	0.8	0.5

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