Current Distribution in Parallel Paths of the Coils of a 50 Hz Prototype Dipole Magnet

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Abstract— The prototype dipole made for TRIUMF's Kaon Factory proposal used coils with 12 parallel paths to reduce eddy current losses in the conductors. The ac current distribution in these paths was non-uniform due to different self and mutual inductances. Small differences in inductance can cause large circulating currents in the parallel windings. This paper describes the measurement of the inductances and shows an attempt to predict the current distribution for two alternative connection schemes.

I. INTRODUCTION

The prototype dipole made during the Kaon Factory PDS study had two main coils. The conductor was subdivided in order to reduce eddy current losses, so each coil consisted of ten turns each with 12 conductors in parallel. It was assumed that the currents would be equally shared between the parallel circuits. This turned out to be incorrect and was attributed to unequal flux linkages, hence inductances, between the top and bottom of the coils. A revised coil connection was suggested which might equalize the distribution but it gave a much worse current distribution. This paper details the two connections and discusses problems with parallel inductive circuits. The inductances between the parallel circuits were measured and used in an attempt to predict the current distribution for simple models of the coils.

II. ORIGINAL COIL CONNECTION

Criteria for limits on the maximum current and inductance led to a magnet design with a peak current of 4,500 A and ten turns per coil. A multi-stranded cable capable of carrying the total current, and a parallel array of conventional square hollow conductors were considered. The multi-stranded cable was not available in the time available to fabricate the magnet so the conventional conductor was used. Parallel conductors must encompass the same area per turn or it is necessary to transpose them to prevent circulating currents caused by unbalanced induced emf's as was done for the ISIS magnets at Rutherford where a 2 x 2 conductor array was used[1].

The conductor arrangement chosen was a 1 x 12 vertical array. This has the advantage that the coil can be wound from 12 ten-turn pancakes connected in parallel. The two coils were connected as shown in Fig. 1 because it can be seen that the included areas for all vertical flux components are identical for both coils, and the emf's induced by horizontal flux components will be in opposite directions for the upper and lower coils and should cancel.

Fig. 1. Original coil connection.

The magnet was operated at various dc and ac excitations and the pancake temperature rises were recorded. Assuming equal coolant flow and current distribution, the eddy current losses per pancake layer were estimated by deducting resistive losses. It was observed that the pancakes adjacent to the pole gap, indicated a 20% higher eddy current loss than anticipated[2]. The reasons for this discrepancy were not immediately obvious. The overall inductance was observed from voltage measurements to be in good agreement with the predicted value of 5.25 mH and other parameters were as expected. There was no difficulty in operating the magnet at full excitation.

III. MEASUREMENT OF CURRENT DISTRIBUTION

The current distribution in the coils was measured using a clip-on ammeter at a total current of 100 A. It was necessary to shut down the test for each reading. Tests were made at both 30 and 50 Hz. The results are shown in Fig. 2. There is a 13 to 36% variation in the currents with the highest values in the pancakes nearest the pole gap. The tests were repeated at dc and the currents shared equally as expected. The unequal currents make the loss estimate quoted above incorrect because the resistive losses depend upon the actual current in each pancake.

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Fig. 2. Variation of pancake current original connection.

The reason for the unequal current distribution was attributed to different inductances for the pancakes. A simulation using the Vector Fields code PE2D showed that the vertical flux linkages varied by 13.9% between the top and bottom of the coil[3]. This would cause the inductances to vary.

It was suggested that if the coils were reconnected so that a high inductance pancake in the top coil was connected in series with a low inductance pancake in the lower coil the currents might share more equally. The coils were reconnected as in Fig. 3, i.e., with the corresponding coil layers in the top and bottom coils connected with each other. The current distribution was remeasured and showed a much poorer distribution as shown in Fig. 4. Such a distribution can only be caused by different emf's in the various pancake layers causing circulating currents. These circulating currents do not affect the total ampere-turns in the coils because they cancel externally. They do, of course, add significantly to the coil losses.

A. Measurement of Inductance Values

If we consider a three branch parallel circuit as shown in Fig. 5 we can see that if the switches are open:

$$V_1 = I_1 (R_1 + j\omega L_1), \quad V_2 = j\omega M_{12} I_1, \quad \text{and} \quad V_3 = j\omega M_{13} I_1 \quad (1)$$

This can be extended to any number of parallel branches.

The resistance of each of the coil pancakes is 25 milliohms and the self inductance is nominally about 1.32 mH so at 60 Hz the inductance term is 0.498 ohm. If the resistance term is ignored the voltages measured with each pancake excited individually give the inductance terms directly. Mutual inductances are generally expressed as a coupling factor which is the ratio of the mutual inductance between the coils to the self inductance of the driving coil.

Measurements were made with a clip-on ammeter, a variable 60 Hz voltage source and a portable multimeter.

Fig. 3. Revised coil connection.

Fig. 4. Revised AC current distribution.

Fig. 5. Parallel circuit for measuring mutual inductances.

Each coil was excited in sequence at about 15 A and the voltages on the other coils and the magnet field in the gap were noted. It took about 15 minutes to make a set of measurements and some values were averaged between the start and finish. Only the top, central and lower pancakes

in each coil were measured. The results are summarized in Figs. 6(a)–6(d). The upper and lower coils show reverse symmetry due to the numbering sequences chosen for the pancakes in the two coils, e.g., the number 1 pancake in the top coil is equivalent to the number 12 pancake in the lower coil. The plots of mutual inductance are labelled with pancake numbers 1 to 30, for plotting purposes only.

Fig. 6(a) Self Inductances.

Fig. 6(b)-(d) Mutual Inductances.

1 to 12 apply to the driven coil and 15 to 26 apply to the non-driven coil. Also to show the symmetry some points are plotted with their inverse number.

The self inductances vary linearly from 2.1 to 1.55 mH with the higher value being for the pancakes closest to the return yokes. These values are all higher than the value of 1.32 mH cited earlier which is scaled from the number of turns and the observed overall inductance of 5.25 mH.

Mutual inductances depend upon the position of the pancake in the coil. In general the mutual inductance between any one pancake and others between it and the yoke is approximately constant, but for pancakes closer to the magnet gap the mutual inductance decreases linearly. The values vary from 2.03 to 1.46 mH. Mutual inductances between a pancake in one coil and any pancake in the other coil tend to be constant at about 1.1 mH.

The variation of mutual inductances between the pancakes can be explained by considering the flux paths in the magnet. Each pancake generates a portion of flux across the magnet gap and some leakage flux, which crosses the coil slot. Fig. 7 shows a pancake in the upper coil. The pancakes between it and the return yoke are tightly coupled and have the same flux coupling because there is very little leakage flux above the coil as the return yoke provides a low reluctance path. Below the pancake the coil slot and magnet gap form parallel flux paths and so the flux coupling falls off. The most efficient pancakes are those adjacent to the pole gap because they have the lowest leakage flux. The flux which crosses the magnet pole gap encircles the lower coil through the return yoke and there is no leakage flux across the lower coil, thus the mutual inductance between a driven pancake in the top coil and one in the bottom is independent of the lower pancake position.

B. Connection Simulation

The self and mutual inductances for all the pancakes can be estimated from the data and it should be possible

Fig. 7. Flux paths with one pancake only excited.

to calculate the current distribution for the two connections but this would involve 12 equations each with 24 terms. A simpler approach was considered.

It was decided to simulate the two connections by calculating the current distribution for two coils, each consisting of only the top, a central, and a bottom pancake in parallel. For the original connection the central pancake in the bottom coil is #7 and for the revised connection it is #6. The circuit for the original connection is shown in Fig. 8. The equations for the three currents are:

$$\begin{aligned} & j\omega i_{1u} [L_{1u} + M_{11-1u} + M_{1u-12l} + M_{11-12l}] \\ & + j\omega i_{6u} [M_{6u-1u} + M_{7l-1u} + M_{6u-12l} + M_{7l-12l}] \\ & + j\omega i_{12u} [M_{12u-1u} + M_{12l-1u} + M_{12u-12l} + L_{12l}] \\ & = V \end{aligned} \quad (2)$$

$$\begin{aligned} & j\omega i_{1u} [M_{1u-6u} + M_{11-6u} + M_{1u-7l} + M_{11-7l}] \\ & + j\omega i_{6u} [L_{6u} + M_{7l-6u} + M_{6u-7l} + L_{7l}] \\ & + j\omega i_{12u} [M_{12u-6u} + M_{12l-6u} + M_{12u-7l} + M_{12l-7l}] \\ & = V \end{aligned} \quad (3)$$

$$\begin{aligned} & j\omega i_{1u} [M_{1u-12u} + M_{11-12u} + M_{1u-1l} + L_{1l}] \\ & + j\omega i_{6u} [M_{6u-12u} + M_{7l-12u} + M_{6u-1l} + M_{7l-1l}] \\ & + j\omega i_{12u} [L_{12u} + M_{12l-12u} + M_{12u-1l} + M_{12l-1l}] \\ & = V \end{aligned} \quad (4)$$

these resolve to

$$\begin{vmatrix} 2.172 & 2.213 & 2.209 \\ 2.055 & 2.236 & 2.081 \\ 1.979 & 1.991 & 2.009 \end{vmatrix} \begin{vmatrix} i_1 \\ i_6 \\ i_{12} \end{vmatrix} = \begin{vmatrix} V \\ V \\ V \end{vmatrix} \quad (5)$$

and if the voltage is set to 15 V the currents are found to be:

$$i_1 = -46.7 \text{ A} \quad i_6 = 7.18 \text{ A} \quad \text{and} \quad i_{12} = 51.42 \text{ A}$$

The current distribution is not close to that shown in Fig. 2 although they it does increase with the pancake

Fig. 8. Simplified coil simulation circuit.

number. The equations have similar coefficients and the solution depends on differences between these coefficients. The measured values are not better than a few percent and a test showed that changes of 0.5% in the coefficients caused changes in the values of the calculated currents of 14 to 44%.

A similar calculation for the revised connection gives:

$$i_1 = 4.20 \text{ A} \quad i_6 = -0.34 \text{ A} \quad \text{and} \quad i_{12} = 3.33 \text{ A}$$

These are similar to the current distribution shown in Fig. 4 and are more reasonable. They indicate higher emf's at the top and bottom of the coils drive a reverse current through the centre pancake as observed.

IV. DISCUSSION AND CONCLUSION

The original coil interconnection turned out to be the correct one but it was not perfect.

The measurements allowed the problem to be discussed and understood but not to make accurate calculations of the current distribution in simple models. Small errors in the measurements can have a large effect on the calculated current distribution.

Better measurements would require a data measurement system that allowed the voltages to be measured over a much shorter time interval and with a higher relative accuracy.

A coil of this type should have a conservative cooling design so that any circulating currents causing excessive heating can be accommodated.

The variation of the inductances in a coil of this type should be considered more carefully at the design stage. This could be done by simulating each pancake separately and noting the stored energy variation with position to obtain the self inductances.

The mutual inductances could be estimated for a coil with similar distribution to the ones described here.

A multi-stranded conductor design, with one turn capable of carrying the whole current, would not have the problem of parallel conductors.

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