FAULT DETECTION IN SYNCHROTRON MAGNET COILS*

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Summary

Curves have been developed which show the currents in the shorted turns, the voltages across a faulted coil, and the heat losses developed, all as a function of the fault resistance. These show that with decreasing fault resistance, all faults will damage the conductor by melting the copper at the point of fault. Existing relays cannot prevent the damage. Impedance measurements, which can detect turn faults at an incipient stage, have been suggested.

Problem

With increased beam intensity and continued exposure of the main coil of the Zero Gradient Synchrotron (ZGS) to radiation, the possibility of an insulation failure and turn-to-turn short may be real. It becomes very desirable to calculate what damage can be caused by this type of fault and how successful the present protection is in preventing this. It should also be investigated whether this danger can be reduced by adding protective equipment, by conducting additional periodic tests, or by monitoring during operation certain values which give evidence of an impending or existing fault.

Current in Faulted Turns or Layers During the Rectification Period

A coil consists of 30 active turns arranged in four layers. The equivalent circuit of a faulted coil is given in Fig. 1. To simplify the calculation, constant inductance values have been used. The current I_2 can be obtained by solving the equation:

$$(n-k)kL_o \frac{dI_1}{dt} = k^2 L_o \frac{dI_2}{dt} + I_2 kR_o + R\left(I_1 + I_2\right) . \quad (1)$$

Since the faulted coil is in series with seven sound coils, the current I_1 is an impressed current and is assumed to rise from zero to 10,000A within one second. The solution of Eq. (1) for the rectification period is then

$$I_2 = -\frac{R\,10^{-4}}{R+kR_o}\,t + \frac{\left(R+kR_o\right)(n-k)\,k + Rk^2}{\left(R+kR_o\right)^2}\left(1 - e^{-\frac{t}{T}}\right) \quad (2)$$

for

$$T = \frac{10^{-4}k}{R+kR_o} . \quad (3)$$

A turn-to-turn fault will involve one turn and a layer-to-layer fault eight turns. Figures 2 and 3 show the currents I_2 and the fault currents $(I_1 + I_2)$ as a function of the fault resistance for turn-to-turn and layer-to-layer faults. The leakage inductance, which has been neglected, would have slightly increased the factor k^2 in Eqs. (1) and (2). This would have had only a very small influence on the results.

Voltage Across a Faulted Coil During the Rectification Period

The voltage is given as:

$$E = (n-k)R_o I_1 + (n-k)nL_o \frac{dI_1}{dt} - kR_o I_2 - nkL_o \frac{dI_2}{dt} . \quad (4)$$

The normal voltage E_{norm} is assumed to be 900V at the beginning of rectification and 1200V at the end of rectification. This agrees with the assumed rise of I_1 from 0 to 10,000A during rectication. Using the results of Eq. (2), the difference between the voltage across a sound and a faulted coil during rectification becomes

$$E - E_{norm} = \Delta E = -\frac{k^2 R_o^2}{R+kR_o}\,10^4 t - n^2 e^{-\frac{t}{T}} - \frac{2nRR_o k^2 + 2nR_o^2 k^3 - R_o^2 k^4}{\left(R+kR_o\right)^2}\left(1 - e^{-\frac{t}{T}}\right) . \quad (5)$$

The difference voltages and the voltages across the faulted coil are shown in Figs. 4 and 5. The difference voltages ΔE are only for layer-to-layer faults large enough to be easily observable.

Current and Voltage During Flat-Topping

Equations (1) and (4) also apply here except that I_1 is constant and the current I_2 at the start of the period is given by the current $I_2(t=1)$ from Eq. 2. The solutions of Eqs. (1) and (4) are:

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$$I_2 = -\frac{R\,10^4}{R+kR_o} + \frac{\left(R+kR_o\right)(n-k)\,k+Rk^2}{\left(R+kR_o\right)^2}\left(1-e^{-\frac{1}{T}}\right)e^{-\frac{t-1}{T}} \quad . \tag{6}$$

$$\Delta E = -\frac{k^2R_o^{\ 2}}{R+kR_o}\,10^4 + \left(n^2 + \frac{-2nRR_ok^2 - 2nk^3R_o^{\ 2} + R_o^{\ 2}k^4}{\left(R+kR_o\right)^2}\right)\left(1-e^{-\frac{1}{T}}\right)e^{-\frac{t-1}{T}} \quad . \tag{7}$$

Figure 6 shows typical curves for a turn-to-turn fault and a fault resistance of $R = 5 \times 10^{-3}\,\Omega$. The curves during inversion and the rest period are similar to those for the rectification and the flat-topping period, respectively.

If the time constant T is of the magnitude of any of the four time intervals of one pulse, the current I_2 would no longer start at zero at the beginning of rectification or inversion. A steady state condition would be established only after a few pulses and the steady state curves would be slightly different from those shown.

Heat Losses and Damage Caused by Heating

Heat losses may cause damage in two different ways. The total loss consisting of the heat loss in the shorted conductors $I_2^{\ 2}R_o$ and the heat loss in the fault $(I_1 + I_2)^2R$ may increase the temperature of the cooling water and damage the insulation covering the shorted conductors. The concentrated heat loss in the fault $(I_1 \text{ and } I_2)^2\,R$ might also melt the copper of the conductor at the point of fault. Figure 7 shows these losses as a function of the fault resistance for turn-to-turn faults and Fig. 8 shows the losses for layer-to-layer faults. The calculations were based on a typical pulse form.

Damage to Insulation

Each half turn is cooled by one cooling water circuit with a flow of 13 gal/min. This amounts to 13,000 lb/hr per turn. It is assumed that the insulation may be damaged if the temperature of the cooling water reaches 300°F. With an inlet temperature of 80°, a temperature drop of 220°F is permissible and the maximum losses are given as

$$q = 13{,}000 \times 220 = 286{,}000 \text{ Btu/hr} = 835 \text{ kW} \quad . \tag{8}$$

Figure 7 shows that for turn-to-turn faults damage to insulation, except at the point of fault, does not occur. Figure 8 shows that for layer-to-layer faults, damage to insulation is extremely unlikely.

Damage to Copper Conductor

The copper conductor will be excessively heated only at the fault location. The heat transferred from the conductor surface to the cooling water will cause a temperature drop $(t_2 - t_3)$ across the water film and a drop $(t_1 - t_2)$ across the copper. See Fig. 9

The film coefficient of heat transfer $({}_2h_3)$ at the water side is a function of water temperature and diameter of the water hole. It has been calculated to:

$${}_2h_3 = 5180 \text{ Btu/hr ft}^2\text{F} \quad , \tag{9}$$

based on the area A_2 of the 0.5 diameter surface 2.

The coefficient of heat transfer ${}_1U_2$ across the copper conductor is:

$${}_1U_2 = \frac{{}_1k_2}{{}_1X_2} = \frac{219}{{}_1X_2} \text{ Btu/hr ft}^2\text{F} \quad . \tag{10}$$

${}_1k_2 = 219$ Btu/hr ft F = thermal conductivity of OFHC copper.

The area of heat transfer in copper is A_1. To arrive at an overall coefficient of heat transfer, the coefficients ${}_2h_3$ and ${}_1U_2$ have to be based on the same area. If A_2 is selected as the reference area, the coefficient of heat transfer ${}_1U_2'$ based on A_2 will be:

$${}_1U_2' = {}_1U_2\,\frac{A_1}{A_2} = \frac{{}_1k_2}{{}_1X_2}\,\frac{A_1}{A_2} \quad . \tag{11}$$

The overall coefficient of heat transfer ${}_1U_3$ is given by:

$$\frac{1}{{}_1U_3} = \frac{1}{{}_1U_2'} + \frac{1}{{}_2h_3} \quad . \tag{12}$$

For a turn-to-turn fault and a fault length L, the values of ${}_1X_2$, A_1, and A_2 are:

$${}_1X_2 = L_{tt} = 0.35 \text{ in} = \frac{0.35}{12} = 0.029 \text{ ft}$$

$$A_2 = \frac{0.5}{12} \times \frac{\pi}{2}\,L = 0.0656\,L \text{ ft}^2$$

$$A_1 = A_{tt}L = \frac{1.1}{12}\,L = 0.0915\,L \text{ ft}^2$$

$$\frac{1}{{}_1U_2'} = \frac{0.029}{219} \times \frac{0.0656}{0.0915} = 9.50 \times 10^{-5}$$

$$\frac{1}{{}_1U_3} = 0.50 \times 10^{-5} + \frac{1}{5180} = 28.8 \times 10^{-5}$$

$${}_1U_3 = 3470 \text{ Btu/hr ft}^2\text{F} \quad .$$

For a layer-to-layer fault, the values:

$${}_1X_2 = L_{\ell\ell} = 0.54 \text{ in} = \frac{0.54}{12} = 0.045 \text{ ft}$$

$$A_1 = A_{\ell\ell} L = \frac{0.8}{12} \; L = 0.066 \, L \text{ ft}^2$$

$$\frac{1}{{}_1U_2'} = \frac{0.045}{219} \times \frac{0.0656}{0.066} = 20.4 \times 10^{-5}$$

$$\frac{1}{{}_1U_3} = 20.4 \times 10^{-5} + \frac{1}{5180} = 39.84 \times 10^{-5}$$

$${}_1U_3 = 2500 \text{ Btu/hr ft}^2\text{F} \quad .$$

The heat loss is:

$$q = {}_1U_3 A_2 \quad t_1 - t_3 \quad \times 2 \quad . \tag{13}$$

The factor 2 occurs because the heat flows through two conductors to the cooling water. With $t_1 = 1982^\circ$F (melting point of copper) $t_3 = 86^\circ$F (cooling water temperature) and assuming the length of fault L to be 1 in, the heat loss required to melt the copper is then for turn-to-turn faults:

$$q_{tt} = 3470 \times \frac{0.0656}{12} \times 1896 \times 2 = 72,000 \text{ Btu/hr}$$

$$q_{tt} = 21 \text{ kW} .$$

For layer-to-layer faults,

$$q_{\ell\ell} = 2500 \times \frac{0.0656}{12} \times 1896 \times 2 = 52,000 \text{ Btu/hr}$$

$$q_{\ell\ell} = 15.2 \text{ kW}.$$

The losses are shown as straight lines in Figs. 7 and 8. All faults, except those with very high fault resistance, will cause melting of copper. If the fault covers more than 1-in length of the conductor, correspondingly higher heat losses are required to reach the melting point. Faults covering a length of less than 1-in are believed to cause no higher temperature than faults of 1-in length. The heat conduction along the conductor has been neglected in the calculations and it is assumed that this additional path will keep the total resistance of the heat transfer to that calculated for the 1-in length.

Protective Relaying and Monitoring

On the cooling water return manifold, thermal switches (Klixons) are arranged on each cooling water return circuit. They disconnect the ring magnet power supply if the cooling water return temperature has reached 105°F. The heat losses required to trip a Klixon switch are therefore

$$q = 13,000 \times 25 = 325,000 \text{ Btu/hr} = 95 \text{ kW} \quad .$$

This line is also shown in Figs. 7 and 8.

Obviously the Klixon switches cannot disconnect the coil before the fault current has melted the copper.

In Figs. 7 and 8 the voltage change $\Delta E/E$ in percent as seen by a search coil ($\dot{B}$ coil) at the end of the rectification is given. Manual or automatic monitoring of the search coils can give no improved protection. If the voltage change ΔE can be reliably observed, the heat losses have already melted the copper.

Preventive Testing

Equations (1) and (4) permit the calculation of the impedance of the faulted coil as a function of the fault resistance for sine wave magnetization. The impedance Z_o of an unfaulted coil is:

$$Z_o = j\omega n^2 L_o \quad . \tag{14}$$

If Z is the impedance of the faulted coil and

$$Z_o - Z = \Delta Z \quad , \tag{15}$$

the ratio $\Delta Z/Z_o$ is obtained from Eqs. (1) and (4) as:

$$\frac{\Delta Z}{Z_o} = \frac{j\omega k^2 L_o}{R + j\omega k^2 L_o} \tag{16}$$

if contributions of smaller magnitude are neglected.

As long as $R << j\omega k^2 L_o$, the impedance $Z \cong 0$ and $\Delta Z/Z_o \cong 1$. If the impedance of the faulted coil becomes larger than 90% of the normal impedance, the detection of faulted coils becomes less reliable and this is the limit of the sensitivity of this fault detection method. If the voltage in the impedance measurement is measured by a search coil, the leakage impedance is eliminated and the accuracy improved. Table 1 gives the maximum fault resistances in ohms where faults can be detected.

ω = 60 Cycles	0.375 (tt) - 24.0 ($\ell\ell$)
ω = 400 Cycles	2.50 (tt) - 160.0 ($\ell\ell$)

Table 1. Maximum Fault Resistances for Detection

A 400-cycle power supply is available which permits the application of up to 1600V ac to one coil, which is almost twice the peak value during normal operation. Such tests may detect faults in the incipient stage and prevent extensive damage. The disadvantage of these tests are that they are time-consuming and require the separation of all coils.

A faster test will be to open up the ring at one point only and apply the 400-cycle voltage to all the coils in series. The capacitors of the ripple filters close the ring and bypass the rectifiers. This will put only about 200V across each coil, but this could still be sufficient to detect faults. If one of the coils would be faulted, the voltage induced into the $\dot{B}$ coil (search coil) associated with this octant would be reduced.

Conclusion

Turn shorts will cause damage only at the point of fault and melt the copper conductor if the fault resistance becomes low enough. Only audio frequency impedance tests can detect shorts at an incipient stage. The melting will start at the conductor surface and it is believed that the fault resistance will become very low after a conducting bridge between conductors has been formed. This would reduce the losses and stop the melting before the conductor is destroyed. Klixons would not detect these permanent shorts but monitoring of search coils and impedance tests would.

It is intended to make simulated tests to verify these assumptions.

Loss and heat transfer calculations have been greatly simplified and the pulse form and nature of faults may change the results considerably. The general conclusions will, nevertheless, remain valid.

Acknowledgment

I am indebted to Mr. W. A. Siljander who guided me on the heat transfer problem. In particular, he pointed out that turn shorts might develop into low loss, low resistance faults without being detected by the Klixons and without destroying the conductors.

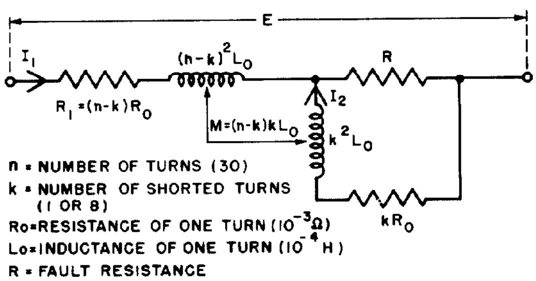

Fig. 1 Equivalent Circuit of Shorted Turn or Layer

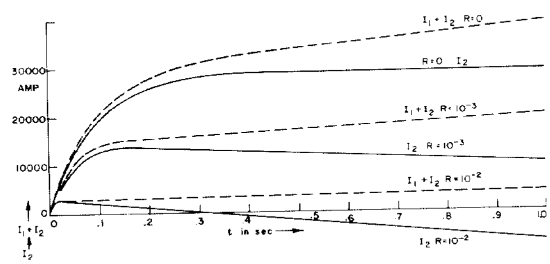

Fig. 2 $I_2(t)$ and $(I_1 + I_2)(t)$ for Turn-to-Turn Fault during Rectification

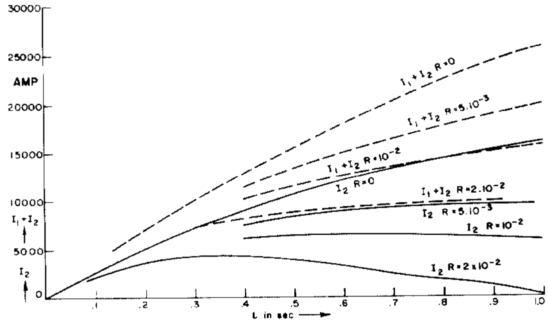

Fig. 3 $I_2(t)$ and $(I_1 + I_2)(t)$ for Layer-to-Layer Faults during Rectification

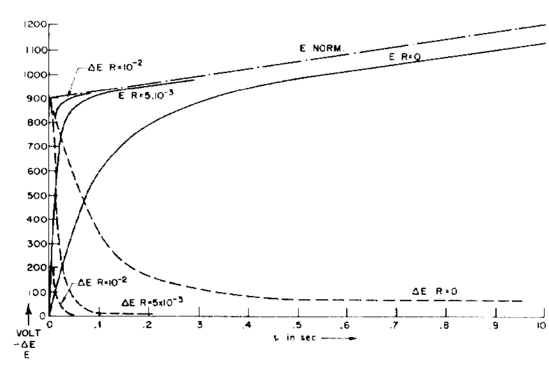

Fig. 4 Voltage E Across Faulted Coil for Turn-to-Turn Fault during Rectification

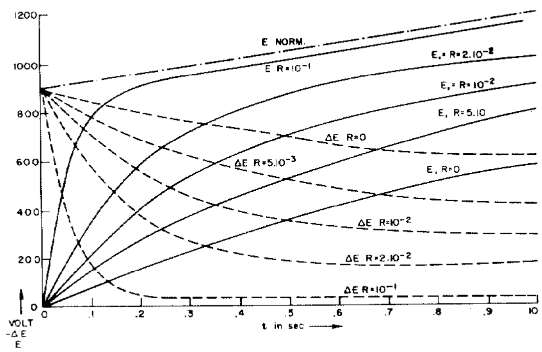

Fig. 5 Voltage Across E Faulted Coil for Layer-to-Layer Fault during Rectification

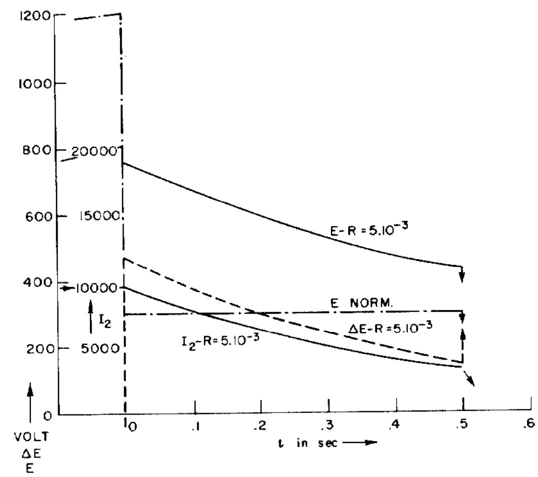

Fig. 6 $I_2(t)$ and Voltage E Across Faulted Octant for Layer-to-Layer Fault during Flat-Topping

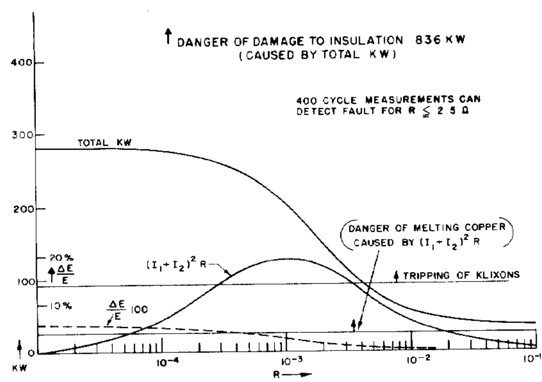

Fig. 7 Peak Power for Turn-to-Turn Faults

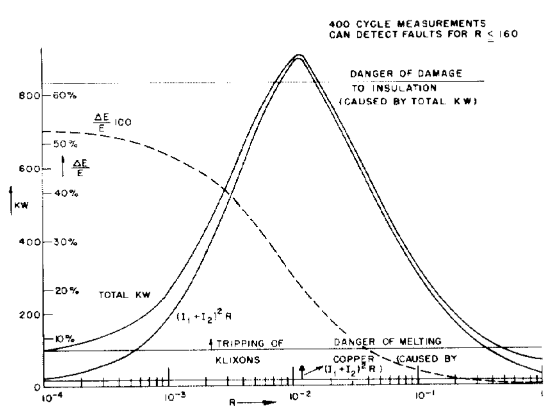

Fig. 8 Peak Power for Layer-to-Layer Faults