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WANL-TME-1743
18 APRIL 1968

Westinghouse Astronuclear Laboratory

THE MEASUREMENT OF THE IMPEDANCES
OF THE INDUCTOTHERM ELEMENT
COATING FURNACES

MASTER

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ABSTRACT

A test and analysis program was performed to determine a method for obtaining large temperature gradients necessary in the preparation of fuel elements for nuclear reactors. The impedances of one Inductotherm element coating furnace were measured as a necessary step toward understanding the theory of operation of the furnace. The detailed procedures for running the furnace tests and the detailed calculations used to reduce the data are given in this report. The problems with instrumentation are discussed and recommendations are given for improvements for future similar tests. The self and mutual impedances for all three furnace zones for both hot and cold furnaces are provided along with the impedances of the 75 and 360 kVA saturable reactors used for furnace control.

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1.0 INTRODUCTION

New processes for the coating of fuel elements require a larger temperature gradient between the ends of the elements than can be obtained with the present furnace coils and furnace controls. A test and analysis program was carried out to determine how these large temperature gradients might be obtained with a minimum of modifications to the furnace coils, furnace fixtures, and furnace controls.

This report presents the development of rigorous equations for the analysis of the furnace and its control system and describes the tests used to measure the impedances which appear in these equations. The impedance values which were measured should apply to all Inductotherm furnaces with 42-inch diameter shells. This work is given in sufficient detail to permit the same measurements to be made on other furnace installations without redeveloping the procedures and resolving the practical problems.

The objective of this work was not to obtain precise values for furnace impedances but to obtain sufficient information on impedances to point the way to the attainment of steep temperature profiles. There are many cases where repeated calculations of the same impedance do not give the same result. This is caused by errors in the data. When this occurred during actual operations, the tests were not rerun because the results were adequate to indicate what had to be done to attain a steep profile. Suggestions are given for improvements in accuracy of future testing.

This report is written for engineers who are familiar with AC circuit calculations. It also assumes that the reader has a fundamental understanding of the theory of operation of the Inductotherm induction furnaces such as presented in a companion report, TME-1742, "The Theory and Operation of Inductotherm Element Coating Furnaces."

The greatest use of the impedances of the furnace is the calculation of the kilowatts going into each zone of the furnace when the zone voltages are known. They also permit the calculation of the size of a series air core coil for obtaining a unity power factor with available capacitors. In addition, the furnace impedances make possible the calculation of the minimum impedance required of the saturable reactors to obtain a given steepness of profile.

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2.0 DEVELOPMENT OF THE CIRCUIT EQUATIONS

Figure 1 is a simplified schematic diagram of the generator-furnace system. To obtain an understanding of the power distributions in the furnace which determine the temperature profile, it is only necessary to analyze the portion of this circuit consisting of the tapped furnace coil and the shunting saturable reactors. Figure 2 shows the circuit labeled with all the currents, voltages, resistances, and inductances used in the analysis. Since all zone and leakage fluxes are in the same direction, the mutual inductances will have the same sign as the self inductances. And since the permeability of the flux path is constant in an air core coil, the mutual inductance $M_{21} = M_{12} = MV$, and calculations can be made using RMS current values.

The voltage equations for the mesh circuits shown in Figure 2 are:

$$(R_4 + j\omega L_4) I_1 + (R_1 + j\omega L_1) I_1 + j\omega M_{21} I_1 - (R_4 + j\omega L_4) I_4 = 0 \quad (1)$$

$$(R_5 + j\omega L_5) I_2 + (R_2 + j\omega L_2) I_2 + j\omega M_{12} I_1 + j\omega M_{32} I_3 - (R_5 + j\omega L_5) I_4 = 0 \quad (2)$$

$$(R_6 + j\omega L_6) I_3 + (R_3 + j\omega L_3) I_3 + j\omega M_{23} I_2 - (R_6 + j\omega L_6) I_4 = 0 \quad (3)$$

$$(R_4 + j\omega L_4) I_4 + (R_5 + j\omega L_5) I_4 + (R_6 + j\omega L_6) I_4 - (R_4 + j\omega L_4) I_1 - (R_5 + j\omega L_5) I_2 - (R_6 + j\omega L_6) I_3 = V \quad (4)$$

where

M_{21} = coefficient of mutual inductance by which voltage is induced in the circuit of Figure 1 by current in the circuit of Figure 2.

M_{12} = coefficient of mutual inductance by which voltage is induced in the circuit of Figure 2 by current in the circuit of Figure 1.

M_{23} and M_{32} are defined similarly.

Note, it is assumed that there is negligible inductive coupling between the end sections of the coils; i. e., $M_{31} = M_{13} = 0$

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Figure 1. Simplified Diagram of Furnace System.

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Figure 2. Circuit of Tapped Furnace Coil and Shunting Saturable Reactors.

These four equations can be simplified by making the following substitutions:

$$(R_1 + j\omega L_1) = Z_1$$

$$(R_4 + j\omega L_4) = Z_4$$

$$(0 + j\omega M_{21}) = Z_{M21}$$

$$(R_2 + j\omega L_2) = Z_2$$

$$(R_5 + j\omega L_5) = Z_5$$

$$(0 + j\omega M_{12}) = Z_{M12}$$

$$(0 + j\omega M_{32}) = Z_{M32}$$

$$(R_3 + j\omega L_3) = Z_3$$

$$(R_6 + j\omega L_6) = Z_6$$

$$(0 + j\omega L_{23}) = Z_{M23}$$

Rewriting the four mesh circuit equations gives:

$$(Z_1 + Z_4) I_1 + Z_{M21} I_2 - Z_4 I_4 = 0 \quad (5)$$

$$Z_{M21} I_1 + (Z_2 + Z_5) I_2 + Z_{M32} I_3 - Z_5 I_4 = 0 \quad (6)$$

$$+ Z_{M32} I_2 + (Z_3 + Z_6) I_3 - Z_6 I_4 = 0 \quad (7)$$

$$- Z_4 I_1 - Z_5 I_2 - Z_6 I_3 + (Z_4 + Z_5 + Z_6) I_4 = V \quad (8)$$

These four simultaneous equations are the general solution of the furnace problem. In actual practice it is not necessary to solve the equations because the furnace is never operated with three partially-saturated reactors.

When a reactor is unsaturated, its impedance is so high that it may be considered to be out of the circuit. An inspection of Figure 2 shows that removing a saturable reactor will eliminate one mesh current and therefore one of the simultaneous equations.

The objective of calculations on the furnace circuit is to predict the range of control of the kilowatts going into each coil zone. In order to do this, the resistance and the self and mutual inductances of each furnace zone must be determined, and the minimum impedance, i. e. saturated impedance, of each saturable reactor must be determined.

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3.0 INSTRUMENTATION AND PROCEDURES FOR IMPEDANCE MEASUREMENT TESTS

3.1 THE FURNACE CIRCUIT

Figure 3 is a simplified circuit diagram of the Inductotherm generator, control console, and furnace system. This diagram locates the control panel instruments, the currents, and the voltage measurement points which are referred to in the following sections.

3.2 THE SELECTION OF COIL IMPEDANCE MEASURING INSTRUMENTS

The usual method for measuring an AC impedance at power frequencies is to use a voltmeter, ammeter, and wattmeter. There were no spare control panel instruments at WNCO, and instruments calibrated for 960 Hz were not readily available from other local Westinghouse plants. The expediency of obtaining information quickly made it undesirable to wait for the purchase of special instruments; so the decision was made to proceed with tests using whatever instrumentation was on hand.

One 500/5 current transformer of undocumented characteristics, but reported to be suitable for use to 1000 Hz, was available from WANL along with a Polaroid oscilloscope camera. A Tektronic 502 Dual Beam Oscilloscope was borrowed from WNCO Quality Control. With this equipment it was possible to measure both the phase angle and magnitude of the currents and voltages in the furnace coil assuming sinusoidal waveshapes. The current transformer secondary was loaded with a 0.1 ohm 1 percent precision resistor to generate a current signal for the oscilloscope.

An alternate set of measuring equipment was available and could have been used; this included a Simpson multimeter and a phase angle meter. This equipment was not used because the phase angle meter could not accept input voltages over forty volts and required voltage transformers or attenuation resistance networks which were not immediately available. The oscilloscope needed no modifications or additional accessories and was therefore used.

Better results might be attained by using the Simpson Meter and the phase angle meter because the RMS values of the voltages would be obtained from average instead of peak values of the wave shape. The direct readings presented by these instruments would have saved the time required to obtain numerical information from the oscilloscope photographs.

Figure 3. Simplified Diagram of the Furnace Power Circuit and the Control Console Instrumentation

3.3 SOURCES OF INSTRUMENT ERROR

Furnace runs which were made at several day intervals with reconnected instrumentation showed different phase shifts for the same furnace impedance. Since this inconsistency was not recognized at the time the data was being taken, the cause has not been determined. It may have been caused by stray magnetic fields in the vicinity of the current transformer. In some cases, the scope-photo data could be made consistent with the control panel instrument data by putting a fixed correction on the current phase angle. This was done in test No. 7.

The Tektronic 502 oscilloscope voltage calibration was taken at face value for all values of the attenuator setting. The scope should be calibrated for accurate results.

The control console instruments, with the exception of the power factor meter, were assumed to be accurate for all the calculations since the Inductotherm Company stated that these instruments were all calibrated for use at 960 Hz.

It became apparent very early that the reading on the power factor meter did not agree with the power factor calculated from the generator kilowattmeter, voltmeter, and ammeter located on the control console. Figure 4 shows the results of a test on the "M" furnace console in which the number of capacitor sections was varied while the furnace voltage was held constant at 258 volts. The kW reading varied from 55 to 58 kW. The curves show that the power factor meter agrees with the calculated power factor only at unity power factor. Consultation with the Westinghouse Meter Division indicated that poor waveshape was the probable source of the trouble. This supposition was supported by an attempt to calibrate the current transformer used with the scope by having it read the same current as the control console generator ammeter. The calibration failed because the current waveshape observed on the scope was very distorted. No photographs were taken and the poor waveshape was not given any further study.

3.4 TEST PROCEDURE AND TEST DATA SHEETS

Sample test procedures and data sheets such as those used for all the tests are included as Appendix A. These samples apply to tests No. 1 and No. 2.

Figure 4. Calculated Power Factor Compared to PF Meter Reading.

3.5 THE REDUCTION OF DATA FROM THE OSCILLOSCOPE PHOTOGRAPHS

Figure 5 shows the photograph for Point F of Test No. 2. The voltage waveshape is the one with the greatest intensity and the one which is obviously non-sinusoidal. It is not surprising that the voltage waveshape is non-sinusoidal since this voltage is developed across the saturated 75 kVA reactor which has an iron core.

The oscilloscope gains for this photo are given in Appendix A as 10 volts/cm for the voltage wave and 0.5 volt/cm for the current wave.

The voltage wave on the photograph has a peak value of 2.3 cm or $2.3 \times 10 = 23$ volts. The RMS value of the voltage is calculated:

$$V_1 = 23 \times 0.707 = 16.2 \text{ volts}$$

The 500/5 current transformer is loaded with 0.1 ohm so that its calibration is $\frac{500}{0.1 \times 5} = 1000$ amperes/volt.

The current wave on the photograph has a peak value of 2.9 cm or $2.9 \times 0.5 = 1.45$ volts. The RMS value of the current is calculated:

$$I_F = 1000 \times 1.45 \times 0.707 = 1020 \text{ amperes}$$

The phase shift was calculated by scaling the photograph with a rule having 0.02 inch divisions. The length of one full cycle was measured as 3.45 inch so that the angular scale is $\frac{360}{3.45} = 104$ degrees/in.

The phase shift was measured to be 0.82 inch or $0.82 \times 104 = 85.4$ degrees.

This same procedure was used for all the oscilloscope photographs. The greatest source of error in the voltage measurement is probably the peak to RMS conversion which is correct only for a sinusoidal wave. The waveshape of this sample calculation is the poorest indicated by any of the photos that were made so that the error will not be greater than it is for this case. The phase shift can probably be calculated from the photo within 1 degree. There is a high probability that the phase shift in the transformer causes a greater error than this.

Figure 5. Oscilloscope Photograph for Point F of Test No. 2.

4.0 TEST NO. 1 - THE MEASUREMENT OF THE MINIMUM CAPACITANCE AND THE UNSATURATED IMPEDANCE OF THE 75 kVA REACTOR

4.1 TEST FURNACE AND DATE

The test was run on M furnace on November 3, 1967.

4.2 TEST CIRCUIT

The basic circuit of Figure 3 was modified for this test as shown in Figure 6. The double water-cooled leads between Points F and G were replaced with non-conducting hoses. This permitted the normal flow of the coil cooling water but opened the electrical connection to the top of the coil.

This test was run with no control current in the middle and bottom zone saturable reactors. The impedance of the unsaturated reactors is so large that they are effectively out of the circuit; so they are not shown in Figure 6.

Since two water-cooled leads would not go through the hole in the toroidal current transformer, the transformer was placed on the single water-cooled lead to the upper furnace tap.

The oscilloscope common is connected to Point A. The scope common is connected to the chassis which is normally connected to the grounding pin on the line cord. In order to avoid grounding the entire furnace through the oscilloscope leads, the grounding pin was removed and the scope chassis was left to float. The scope was isolated from the floor by the rubber wheels on the scope cart. The potential between the scope and ground was measured with a Simpson multimeter at 25 volts AC, but care should be exercised because of a potential shock hazard.

4.3 TEST CONDITIONS

- 1) 0.0 amps control current in the top zone reactor, i. e. top reactor is unsaturated.
- 2) No. 7 transformer tap, turns ratio = $\frac{14}{31}$ secondary to primary.

16

3) Capacitance = minimum = 1102.5 microfarads, nominal.

5 unswitched cans at 210 mfd each = 1050.0

1 unswitched block in one of the = 52.5

five switched cans

TOTAL CAPACITY = 1102.5 mfd

4) Furnace temperature - cold, no visible red.

4.4 TEST DATA

1) Furnace control panel instrument readings

KW = 0 (Less than 10 KW cannot be detected)

$I_G = 240$

$V_G = 164$

$V_F = 82$

PF = $\leq +0.5$ (Meter pinned at +0.5 end of scale)

2) Oscilloscope photo data

$I_F = 11$ amperes

Assume that this current lags the voltage by 90 degrees. The phase shift measured on the scope was only 37.5 degrees. Probably the current transformer introduces a phase shift when operating at this low current. The transformer is rated at 500 amperes.

4.5 CALCULATION OF THE VALUE OF MINIMUM CAPACITANCE

$$I_T = I_G \times \frac{1}{\text{ratio}} = 240 \times \frac{31}{14} = 531 \text{ amperes}$$

NOTE: This assumes that the autotransformer excitation current is negligible.

$$I_C = I_T$$

NOTE: Assume that the current through the unsaturated reactor is negligible.

$$Z_C = \frac{V_F}{I_C} = \frac{82}{531} = 0.155 \angle + 90$$

NOTE: This assumes a perfect capacitor. The manufacturer states the capacitor losses to be 3.5 watts/kVAC which corresponds to a phase angle of 89.5 degree, nearly perfect.

$$C = \frac{1}{2 \pi f Z_C}$$

$$C = 1070 \text{ mfd}$$

The nameplate value of the capacitance is 1102.5 mfd. The difference is 1102 - 1070 = 32 mfd.

$$\frac{100 \times 32}{1102} = 2.9 \text{ percent low}$$

4.6 CALCULATION OF THE UNSATURATED IMPEDANCE OF THE 75 kVA REACTOR

$$Z_4 (\text{unsaturated}) = \frac{V_F}{I_F} = \frac{82}{11} = 7.5 \text{ ohm}$$

This assumes that the voltage drops across the leads and the furnace coil are insignificant compared to the drop across the unsaturated reactor.

4.7 DISCUSSION AND RECOMMENDATIONS

The tolerance limits for the capacitors are quoted in the catalog as -0, + 10 percent so the capacitors should not be 2.9 percent below nominal as calculated.

In the following calculations, the capacity of all additional blocks which are switched "in" is taken at the nominal value. It is recommended that this test be extended to measure the capacity of each one of the nineteen switch combinations.

It is also recommended that a 10/5 current transformer should be used to measure the current in the unsaturated reactor so that an accurate measurement of the impedance can be obtained.

5.0 TEST NO. 2 - DETERMINATION OF THE IMPEDANCE OF THE SATURATED 75 kVA REACTOR, THE MUTUAL IMPEDANCE, AND THE TWO LOWER FURNACE ZONE IMPEDANCES

5.1 TEST FURNACE AND DATE

This test was run in M Furnace on November 3, 1967.

5.2 TEST CIRCUIT

The circuit was as shown in Figure 6.

5.3 TEST CONDITIONS

- 1) 8.5 amperes in the top 75/kVA reactor.
- 2) No. 7 transformer tap, turns ratio = $\frac{14}{31}$ secondary to primary.
- 3) Furnace temperature: cold, no visible red at any time during the test.

5.4 TEST DATA

- 1) Furnace control panel instrument readings:

$$KW = 31$$

$$I_G = 100$$

$$V_G = 305$$

$$V_F = 139$$

$$PF = 1.00$$

Capacitors - 3 (3 sections plus the minimum)

- 2) Scope photo data:

$$I_F = 1020 \angle 0 = 1020 + j0$$

$$\text{Point F} \quad \dot{V}_1 = 16.2 \angle 85 \text{ degrees} = 1.41 + j16.1$$

$$\text{Point G} \quad \dot{V}_7 + \dot{V}_1 = 9.5 \angle 86 \text{ degrees} = 0.66 + j9.46$$

$$\text{Point H} \quad \dot{V}_7 = 5.84 \angle 82 \text{ degrees} = 0.813 + j5.78$$

$$\text{Point I} \quad \dot{V}_7 + \dot{V}_2 = 88 \angle 76 \text{ degrees} = 21.3 + j85.3$$

$$\text{Point J} \quad \dot{V}_7 + \dot{V}_2 + \dot{V}_3 = 108 \angle 77 \text{ degrees} = 24.3 + j105.2$$

NOTE: Scope measurements should also have been made at Points L, K, and E, but they were not. A dot over a symbol designates a vector quantity.

5.5 CALCULATION OF THE POWER FACTOR FROM THE CONTROL PANEL DATA

$$PF = \frac{\text{kW}}{I_G \times V_G} = \frac{31}{100 \times 305} = 1.02$$

This is about as close to 1.0 as can be expected from the accuracy of the panel meter readings. This value proves the PF meter to be in good agreement with Figure 4.

5.6 CALCULATION OF THE FURNACE CURRENT FROM CONTROL PANEL DATA

$$I_T = I_G \times \frac{31}{14} = 100 \times \frac{31}{14} = 221 \text{ amperes}$$

$$\text{Define } \dot{V}_F = 139 \angle 0$$

$$\text{Since } PF = 1.0 \text{ from 5.5, } I_T = 221 \angle 0$$

$$\dot{I}_T = 221 + j0$$

$$\dot{I}_c = \frac{\dot{V}_F}{X_c}$$

The total capacitance in the circuit is the minimum capacitance plus three sections at 52.5 mfd each.

Minimum C from 4.5	1070
3 sections at 52.5 mfd	<u>159</u>
TOTAL CAPACITY	1229 mfd

$$X_c = \frac{1}{2\pi fC} = \frac{1}{6.28 \times 960 \times 1229} = 0.147 \text{ ohm}$$

$$I_c = \frac{139 \angle 0}{0.147 \angle -90} = 947 \angle +90 = 0 + j947$$

$$\dot{I}_F + \dot{I}_T = \dot{I}_c$$

$$\begin{aligned}\dot{I}_F &= (221 + j0) - (0 + j947) \\ &= 221 - j947 \\ &= 975 \angle 76.9\end{aligned}$$

The value of I_F measured on the oscilloscope was 1020 amperes.

$$1020 - 975 = 45 \text{ amperes}$$

$$\text{percent difference} = \frac{45}{1020} = 4.42 \text{ percent}$$

This is an acceptable agreement considering the high possibility for error in the data. The value of current measured on the oscilloscope will be used in the impedance calculations because the calculated value of the minimum capacitance is probably low. This would account for the calculated value of I_F being low.

5.7 CALCULATION OF THE IMPEDANCE OF THE SATURATED 75 kVA REACTOR

$$Z_{4S} = \frac{V_1}{I_F} = \frac{16.2 \angle +85}{1020 \angle 0} = 0.0157 \angle +85 \text{ ohms} \\ = 0.00128 + j0.0158$$

5.8 CALCULATION OF THE IMPEDANCE OF THE UPPER TAP LEAD FROM THE CONTROL CONSOLE TO THE FURNACE FLANGE

$$Z_7 = \frac{V_7}{I_F} = \frac{5.84 \angle +82}{1020 \angle 0} = 0.0057 \angle +82 \text{ ohms} \\ = 0.0008 + j0.00563$$

5.9 CALCULATION OF THE MUTUAL IMPEDANCE OF THE TOP THREE TURNS OF THE FURNACE COIL

$$\begin{aligned}\dot{V}_1 &= (\dot{V}_7 + \dot{V}_1) - \dot{V}_7 \\ \dot{V}_1 &= (0.66 + j9.46) - (0.813 + j5.78) \\ &= -0.25 + j3.68 \\ &= 3.68 \angle 93.9\end{aligned}$$

This is very close to correct. $\dot{V}_1$ must be exactly 90 degrees leading $\dot{I}_F$ because no current is flowing in these three turns of the furnace coil.

$$\begin{aligned} Z_{M21} &= \frac{\dot{V}_1}{\dot{I}_F} = \frac{3.68 \angle 90}{1020 \angle 0} = 0.0036 \angle +90 \text{ ohms} \\ &= 0 + j0.0036 \text{ ohms} \end{aligned}$$

5.10 CALCULATION OF THE IMPEDANCE OF THE CENTER ZONE

$$\begin{aligned} \dot{V}_2 &= (\dot{V}_7 + \dot{V}_2) - \dot{V}_7 \\ \dot{V}_2 &= (21.3 + j85.3) - (0.813 + j5.8) \\ &= 20.5 + j79.5 \\ &= 82 \angle 75.5 \end{aligned}$$

$$\begin{aligned} (Z_2 + Z_{M32}) &= \frac{\dot{V}_2}{\dot{I}_F} = \frac{82 \angle 75.5}{1020 \angle 0} \\ &= 0.0804 \angle 75.5 \\ &= 0.0201 + j0.0778 \end{aligned}$$

Assume $M_{32} = M_{21}$ since the furnace coil is symmetrical.

$$\begin{aligned} Z_2 &= (Z_2 + Z_{M32}) - Z_{M32} \\ &= (0.0201 + j0.0778) - (0 + j0.0036) \\ &= 0.0201 + j0.0742 \\ Z_2 &= 0.077 \angle 74.5 \end{aligned}$$

5.11 CALCULATE THE IMPEDANCE OF THE BOTTOM ZONE

$$\begin{aligned}\dot{V}_3 &= (\dot{V}_7 + \dot{V}_2 + \dot{V}_3) - (\dot{V}_7 + \dot{V}_2) \\ &= (24.3 + j105.2) - (21.3 + j85.3) \\ &= 3.0 + j19.9\end{aligned}$$

$$V_3 = 20 \angle + 81.4$$

$$\begin{aligned}Z_3 + Z_{M23} &= \frac{20 \angle + 81.4}{1020 \angle 0} = 0.0196 \angle 81.4 \\ &= 0.00292 + j0.0194\end{aligned}$$

$$Z_3 = (Z_3 + Z_{M23}) - Z_{M23}$$

Assume $M_{23} = M_{21}$. This is reasonable because of the symmetry of the furnace coil.

$$\begin{aligned}Z_3 &= (0.0029 + j0.0194) - (0 + j0.0036) \\ &= 0.029 + j0.0158 \\ &= 0.016 \angle 79.6 \text{ ohms}\end{aligned}$$

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6.0 TEST NO. 3 - DETERMINATION OF THE IMPEDANCE OF THE 360 kVA REACTOR WITH 6 AMPERES CONTROL CURRENT

6.1 TEST FURNACE AND DATE

This test was run on M furnace on November 3, 1968.

6.2 TEST CIRCUIT

The circuit for this test is shown in Figure 7. It differs from Figure 6 in that the top reactor is shorted out and the center reactor is no longer unsaturated.

6.3 TEST CONDITIONS

- 1) The top zone reactor is shorted out with four 250,000 cmil cables in parallel connected at the reactor terminals.
- 2) The transformer tap is at No. 7 so that the turns ratio is $\frac{14}{31}$ secondary to primary.
- 3) The middle reactor has 6 amperes control current.
- 4) The bottom reactor has 0 amperes control current.
- 5) The furnace temperature was cold, no visible red.

6.4 TEST DATA

- 1) Furnace control panel instrument readings:

kW	=	30
I_G	=	239
V_G	=	265
V_F	=	110
PF	=	-0.73

Capacitors = 19 blocks plus minimum capacitance.

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Figure 7. Circuit for Test No. 3 and No. 4.

6.5 OSCILLOSCOPE PHOTO DATA

$$I_F = 654 \angle 0 = 654 + j0 \text{ (Angle by definition)}$$

$$\text{Point G} \quad \dot{V}_7 + \dot{V}_1 = 5.25 \angle 74.9 = 1.37 + j5.07$$

$$\text{Point H} \quad \dot{V}_7 = 3.45 \angle 68.5 = 1.26 + j3.21$$

$$\text{Point I} \quad \dot{V}_7 = \dot{V}_2 = 57.8 \angle 63.5 = 25.8 + j51.7$$

$$\text{Point J} \quad \dot{V}_7 = \dot{V}_2 + \dot{V}_3 = 89.2 \angle 61.4 = 42.7 + j78.3$$

Note: There is reason to suspect the accuracy of the phase angle measurements because $\dot{V}_7$ in test No. 2 (5.4) showed a phase angle of 82 degrees.

6.6 CALCULATION OF THE CURRENT I_T FROM CONTROL PANEL DATA

Assume all losses in the furnace and reactor and no losses in the transformer or capacitor.

$$(I_T) = I_G \times \frac{31}{14} = 239 \times \frac{31}{14} = 528 \text{ amperes}$$

$$\text{PF} = \frac{\text{KW} \times 10^3}{V_F \times I_T} = \frac{30 \times 10^3}{110 \times 528} = 0.517$$

$$\cos^{-1} 0.517 = 58.8 \text{ degrees}$$

$$\text{Define } V_F = 110 \angle 0$$

$$I_T = 528 \angle -58.8 \text{ degrees} = 273 - j452$$

6.7 CALCULATION OF THE CURRENT $(\dot{I}_R + \dot{I}_F)$

$$\dot{I}_T = \dot{I}_c + (\dot{I}_R + \dot{I}_F)$$

$$\text{Minimum capacitance from 4.5} = 1070$$

$$19 \text{ sections at } 52.5 \text{ each} = \underline{1000}$$

$$\text{Total capacitance} = 2070 \text{ mfd}$$

$$X_c = \frac{1}{2\pi f c} = \frac{1}{6.28 \times 960 \times 2070} = 0.0802 \text{ ohm}$$

$$\dot{I}_c = \frac{110 \angle 0}{0.0802 \angle -90} = 1370 \angle +90$$

$$\begin{aligned} (\dot{I}_R + \dot{I}_F) &= \dot{I}_T - \dot{I}_c \\ &= (273 - j452) - (0 + j1370) \end{aligned}$$

$$\begin{aligned} (\dot{I}_R + \dot{I}_F) &= 273 - j1822 \\ &= 1840 \angle -81.5 \text{ ampere} \\ &= 283 - j1820 \end{aligned}$$

6.8 CALCULATION OF THE MUTUAL IMPEDANCE OF THE TOP THREE TURNS OF THE FURNACE COIL

$$\begin{aligned} \dot{V}_1 &= (\dot{V}_7 + \dot{V}_1) - \dot{V}_7 \\ &= (1.37 + j5.07) - (1.26 + j3.21) \\ &= 0.11 + j1.86 \\ &= 1.86 \angle 86.6 \end{aligned}$$

Note that this measured angle is very close to the 90 degrees which it must be for a pure mutual inductance.

$$Z_{M21} = \frac{\dot{V}_1}{\dot{I}_F} = \frac{1.86}{654} = 0.00285 \text{ ohm}$$

There is no obvious reason why this result is different from the value of 0.0036 ohm calculated in 5.9.

6.9 CALCULATION OF THE CURRENT $\dot{I}_R$

This calculation is only necessary because the current transformer was placed on the upper tap lead instead of on the lower tap lead where it would have measured $\dot{I}_R$ directly.

Unfortunately, photos were not taken for points L, K, and E so voltages V_3 , V_9 , and V_{10} were not measured. It will be sufficiently accurate to assume that these lead impedances have a phase angle of +85 degrees. Referring to Figures 7 and 8:

$$\dot{V} + (\dot{V}_8 + \dot{V}_9 + \dot{V}_{10}) + (V_7 + V_2 + V_3)$$

$$\text{Let } \dot{V} = 110 \angle 0 \text{ (angle by definition)}$$

$(\dot{V}_8 + \dot{V}_9 + \dot{V}_{10})$ is the voltage drop resulting from the flow of $(\dot{I}_R + \dot{I}_F)$ in the water-cooled leads.

$$\begin{aligned} \dot{V}_8 + \dot{V}_9 + \dot{V}_{10} &= (\dot{I}_R + \dot{I}_F) \times Z_{8,9,10} \\ &= |V_8 + V_9 + V_{10}| \angle (-81.5) + (85 \text{ degrees}) \\ &= |V_8 + V_9 + V_{10}| \angle +3.5 \text{ degrees} \\ &= 0.995 |V_8 + V_9 + V_{10}| + j0.061 |V_8 + V_9 + V_{10}| \end{aligned}$$

$$(V_7 + V_2 + V_3) = 89.2 \angle \Psi \text{ from oscilloscope data}$$

$$(110 + j0) = 0.995 |V_8 + V_9 + V_{10}| + j0.061 |V_8 + V_9 + V_{10}| + 89.2 \cos \Psi + 89.2 \sin \Psi$$

$$110 = 0.995 |V_8 + V_9 + V_{10}| + 89.2 \cos \Psi$$

$$0 = 0.061 |V_8 + V_9 + V_{10}| + 89.2 \sin \Psi$$

Solving graphically

$$\left| V_8 + V_9 + V_{10} \right| = 21$$

$$\angle = -0.82 \text{ degree}$$

$$\text{Thus } \begin{cases} \dot{V}_7 + \dot{V}_2 + \dot{V}_3 = 89.2 \angle -0.82 \\ V_8 + V_9 + V_{10} = 21. \angle +3.5 \end{cases} \left\{ \begin{array}{l} \text{with respect to } \dot{V}_F = 0. \end{array} \right.$$

From the photo data we see that $\dot{V}_7 + \dot{V}_2 + \dot{V}_3$ leads I_F by 61.4 degrees. With respect to $V_F \angle 0$,

$$\begin{aligned} I_F &= 654 \angle - (61.4 - 0.8) \\ &= 654 \angle - 62.2 \\ &= 305 - j579 \end{aligned}$$

The photo data can be converted to this new base with $V_F \angle 0$ instead of $I_F \angle 0$ by subtracting 62.2 degrees from the angles. Note that this step eliminates any error caused by a phase shift in the current transformer.

$$\begin{aligned} \text{Point G } \dot{V}_2 + \dot{V}_1 &= 5.25 \angle 12.7 = \\ \text{Point H } \dot{V}_7 &= 3.45 \angle 6.3 = 3.42 + j0.4 \\ \text{Point I } \dot{V}_7 + \dot{V}_2 &= 57.8 \angle 1.3 = 57.8 + j0.6 \\ \text{Point J } \dot{V}_2 + \dot{V}_3 &= 89.2 = \angle -0.8 = 89.2 + j1.2 \end{aligned}$$

$$\begin{aligned} IR &= (\dot{I}_F + \dot{I}_R) - I_F \\ &= (283 - j1820) - (305 - j579) \\ &= -22 - j1241 \\ &= 1240 \angle -90 \end{aligned}$$

6.10 CALCULATION OF IMPEDANCE OF THE SATURATED 360 kVA REACTOR

Referring to Figure 7, it is seen that

$$Z_5 = \frac{\dot{V}_7 + \dot{V}_2}{\dot{I}_R} - Z_7$$

where Z_7 is the impedance of the lower tap lead calculated in 5.8

$$\begin{aligned} Z_5 &= \frac{57.8 \angle 1.3}{1240 \angle 90} - 0.057 \angle 82 \\ Z_5 &= 0.0466 \angle 88.7 - 0.0057 \angle 82 \\ &= (0.001 + j0.047) - (0.0008 + j0.00563) \\ &= 0.0002 + j0.041 \\ &= 0.041 \angle 90 \text{ ohms} \end{aligned}$$

Note that the saturated reactor is still highly reactive, i.e., the losses are very low. Certainly the phase angle is not 90 degrees. The probable source of error in this calculation is the phase angle of 61.4 degrees between $\dot{I}_F$ and $(\dot{V}_7 + \dot{V}_2 + \dot{V}_3)$ which was measured by using the current transformer.

6.11 CALCULATION OF THE IMPEDANCE OF THE CENTER ZONE

$$\begin{aligned} \dot{V}_2 &= (\dot{V}_7 + \dot{V}_2) - V_7 \\ &= (57.8 + j0.6) - (3.42 + j0.4) \\ &= 54.4 - j0.2 \\ \dot{V}_2 &= (\dot{I}_F + \dot{I}_R) M_{32} + I_F Z_2 \end{aligned}$$

$$54.4 - j0.2 = 1840 \angle -81.5 \times 0.0036 \angle +90 + 654 \angle -62.2 \times Z_2$$

$$= 6.53 \angle 8.5 + 654 \angle -62.2 \times Z_2$$

$$654 \angle -62.2 \times Z_2 = (54.4 - j0.2) - (6.4 + j1.0) = 48 - j1.2$$

$$Z_2 \times 654 \angle -62.2 = 48 \angle -1.4$$

$$Z_2 = \frac{48 \angle -1.4}{654 \angle -62.2}$$

$$= 0.074 \angle 60.8$$

Note that the mutual impedance voltage is 12 percent of V_2 and is not negligible.

6.12 CALCULATION OF THE IMPEDANCE OF THE UPPER TAP LEAD

$$Z_7 = \frac{\dot{V}_7}{\dot{I}_F} = \frac{3.45 \angle 6.3}{654 \angle -62.2}$$

$$= 0.00528 \angle 68.5$$

Note that the phase angle does not agree with the value calculated in 5.8. Again, the error is probably due to a phase shift in the current transformer.

6.13 CALCULATION OF THE IMPEDANCE OF THE BOTTOM ZONE

$$V_3 = (\dot{V}_7 + \dot{V}_2 + \dot{V}_3) - (\dot{V}_2 + \dot{V}_7)$$

$$V_3 = (89.2 + j0) - (57.8 + j0.6)$$

$$= 31.4 - j0.6$$

$$= 31.4 \angle 1.1 \text{ degree}$$

$$Z_3 = \frac{\dot{V}_3 - I_F Z_{M32}}{(\dot{I}_F + \dot{I}_R)}$$

$$= \frac{(31.4 - j0.6) - 654 \angle -62.2 \times 0.0036 \angle 90}{1840 \angle -81.5}$$

$$= 0.0159 \angle 78.2$$

This is very good agreement with the previously calculated value of $0.016 \angle 79.6$ considering all of the opportunities for inaccuracies. Note that the voltage due to the mutual impedance is 7.6 percent of V_3 .

6.14 DISCUSSION OF THE RESULTS OF TEST NO. 3

The vector diagram of Figure 8 is of interest because it shows the relative magnitude of the voltages that add up to V_F . Note that the drop in the leads is about 23 percent of the available furnace voltage.

The diagram also emphasizes that the reactor current is 1.9 times the coil current showing that the shunt reactor is effective in reducing the kW dissipated in the center zone.

It should be noted that the voltage due to mutual inductance is considerable.

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Figure 8. Vector Diagram for the Calculations of Test No. 3

7.0 TEST NO. 4 - DETERMINATION OF IMPEDANCE OF THE MIDDLE AND BOTTOM FURNACE ZONES WHEN HOT

7.1 TEST FURNACE AND DATE

This test was run on M furnace on November 3, 1967.

7.2 TEST CIRCUIT

The circuit for this test was the same as Figure 7 except that Z_5 is out of the circuit because the reactor is unsaturated.

7.3 TEST CONDITIONS

- 1) Top reactor shorted with four 250,000 cmil cables.
- 2) Center reactor with 0.0 amperes control current.
- 3) Bottom reactor with 0.0 amperes control current.
- 4) No. 7 transformer tap turns ratio $\frac{14}{31}$ primary to second.
- 5) Furnace temperature

Sight Port No. 2 1355°C

Sight Port No. 3 1800°C

Sight Port No. 4 1690°C

7.4 TEST DATA

- 1) Furnace control panel instrument readings:

kW = 65

I_G = 175

V_G = 400

V_F = 175

P_F = -0.99

Capacitors = 6 seconds at 52.5 mfd each.

2) Oscilloscope Photo Data

The current transformer was placed around the upper tap lead.

$$\dot{I}_F = 1480 \angle 0 \text{ (Angle by definition)}$$

$$\text{Point G} \quad \dot{V}_7 + \dot{V}_1 \quad 13.4 \angle 83.2$$

$$\text{Point H} \quad \dot{V}_7 \quad 8.48 \angle 81$$

$$\text{Point I} \quad V_7 + V_2 \quad 122 \angle 70.7$$

$$\text{Point J} \quad V_7 + V_2 + V_3 \quad 148 \angle 70.7$$

7.5 CALCULATION OF THE FURNACE CURRENT FROM PANEL DATA

$$|I_T| = I_G \times \frac{31}{14} = 175 \times \frac{31}{14} = 388 \text{ amperes}$$

$$PF = \frac{kW \times 10^3}{V_F \times I_T} = \frac{65 \times 10^3}{175 \times 388} = 0.958$$

$$\theta = \cos^{-1} 0.958 = 16.5 \text{ degree}$$

$$\text{Define } \dot{V}_F = 175 \angle 0$$

$$\dot{I}_T = 388 \angle -16.5 = 372 - j110$$

Minimum capacitance from 3, 3.4 1070 mfd

6 sections at 52.5 mfd each 315 mfd

Total capacitance 1385 mfd

$$X_c = \frac{1}{2\pi f} \quad C = \frac{1}{6.28 \times 960 \times 1385} = 0.1197 \text{ ohm}$$

$$\dot{I}_c = \frac{\dot{V}_F}{X_c} = \frac{175 \angle 0}{0.1197 \angle -90} = 1463 \angle 90 = 0 + j1463$$

$$\begin{aligned}
 \dot{I}_F &= \dot{I}_T - \dot{I}_C \\
 &= (372 - j110) - (0 + j1463) \\
 &= 372 - j1573 = 1610 \angle -76.7
 \end{aligned}$$

$$\text{Error} = 1610 - 1480 = 130 \text{ amperes}$$

$$\frac{130}{1480} = 8.78 \text{ percent error}$$

Assume that the photo measurement of I_F is correct.

7.6 CALCULATION OF THE MUTUAL IMPEDANCE OF TOP THREE TURNS OF THE FURNACE COIL

$$\begin{aligned}
 \dot{V}_1 &= (\dot{V}_7 + \dot{V}_1) - \dot{V}_7 \\
 &= 13.4 \angle 83.2 - 8.5 \angle 81 \\
 &= (1.58 + j13.3) - (1.33 + j8.38) \\
 &= 0.25 + j4.9 \\
 \dot{V}_1 &= 4.9 \angle 87.1 \\
 Z_{M21} &= \frac{\dot{V}_1}{I_c} = \frac{4.9}{1480} = 0.00331 \angle 90
 \end{aligned}$$

7.7 CALCULATION OF THE IMPEDANCE OF THE UPPER TAP LEAD

$$Z_7 = \frac{\dot{V}_7}{\dot{I}_F} = \frac{8.48 \angle 81}{1480 \angle 0} = 0.00573 \angle 81$$

7.8 CALCULATION OF THE IMPEDANCE OF THE CENTER ZONE

$$\dot{V}_2 = (V_7 + V_2) - \dot{V}_7$$

$$\dot{V}_2 = (40.3 + j114) - (1.3 + j8.4)$$

$$= 39 + j106$$

$$= 113 \angle 69.9$$

$$(Z_2 + Z_{M32}) = \frac{\dot{V}_2}{i_F} = \frac{113 \angle 69.9}{1480 \angle 0} = 0.0771 \angle 69.9$$

$$= 0.0265 + j0.0724$$

Assume $M_{32} = M_{21}$ since the furnace is symmetrical

$$Z_2 = (Z_2 + Z_{M32}) - Z_{M32}$$

$$= (0.0265 + j0.0724) - (0 + j0.0033)$$

$$= 0.0265 + j0.0691$$

$$Z_2 = 0.074 \angle 69$$

7.9 CALCULATION OF THE IMPEDANCE OF THE BOTTOM ZONE

$$\dot{V}_3 = (\dot{V}_7 + \dot{V}_2 + \dot{V}_3) - (V_7 + V_2)$$

$$= (48.8 + j139) - (40.3 + j114)$$

$$= 8.5 + j25$$

$$\dot{V}_3 = 26.6 \angle 71.3$$

$$Z_3 + Z_M^{32} = \frac{26.6 \angle 71.3}{1480} = 0.0180 \angle 71.3$$

$$= 0.00577 + j0.0168$$

$$Z_3 = (0.00577 + j0.0168) - (0 + j0.0033)$$

$$= 0.0058 + j0.0135$$

$$= 0.0147 \angle 66.8$$

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8.0 TEST NO. 5 - DETERMINATION OF IMPEDANCE OF TOP AND BOTTOM ZONES OF FURNACE

8.1 TEST FURNACE AND DATE

This test was run on M furnace on November 11, 1967.

8.2 TEST CIRCUIT

The circuit for this test is shown in Figure 9.

The current transformer was placed on one of the two water-cooled leads to the bottom of the furnace. The magnitude of the current waveshape is only approximately correct since there is no guarantee that the furnace current is dividing equally between the two parallel leads. The current trace should be an accurate phase reference. The voltages are measured with respect to Point K of Figure 9 so that the measurement of Z_3 should be accurate.

8.3 TEST CONDITIONS

- 1) Top reactor with 0 amps control current.
- 2) Center reactor shorted with four 250,000 cmil cables.
- 3) Bottom reactor with 0 amps control current
- 4) No. 7 transformer tap, turns ratio = $\frac{14}{31}$ primary to second.
- 5) Furnace cold: no visible red at any time during the test.

8.4 TEST DATA

- 1) Furnace control panel instrument readings:

kW = 50 kilowatts

I_G = 142 amperes

V_G = 380 volts

V_F = 170 volts

PF = -0.99

Capacitors = 19 sections of 52.5 mfd each

Figure 9. Circuit for Test No. 5

2) Oscilloscope Photo Data

$$I = |I_F| \angle 0$$

$$\text{Point E} \quad 7.6 \angle 84.7 = \dot{V}_{10}$$

$$\text{Point J} \quad 8.5 \angle 88.8 = \dot{V}_9$$

$$\text{Point I} \quad 45.9 \angle 80.5 = \dot{V}_9 + \dot{V}_3$$

$$\text{Point H} \quad 77.8 \angle 80.5 = \dot{V}_9 + \dot{V}_3 + V_2$$

$$\text{Point G} \quad 134 \angle 80.5 = \dot{V}_4 + \dot{V}_3 + \dot{V}_2 + \dot{V}_1$$

$$\text{Point L} \quad 155 \angle 80.5$$

8.5 CALCULATE THE FURNACE CURRENT FROM PANEL DATA

Assume no losses in the transformer or capacitor.

$$|I_T| = I_G \times \frac{31}{14} = 142 \times \frac{31}{14} = 314 \text{ amperes}$$

$$\text{PF} = \frac{\text{kW}}{V_F \times I_T} \times \frac{10^3}{1} = \frac{50}{170 \times 314} \times \frac{10^3}{1} = 0.937 = \cos \theta$$

$$\theta = \cos^{-1} 0.937 = 20.5 \text{ degrees}$$

$$\text{Define } \dot{V}_F = 170 \angle 0$$

$$\dot{I}_T = 314 \angle -20.5 \text{ degrees} = 294 - j110$$

Minimum capacitance from 3, 3.4

1070 mfd

19 sections at 52.5 mfd each

1000

Total capacitance

2070 mfd

$$X_c = \frac{1}{2\pi fc} = \frac{1}{6.28 \times 960 \times 2070} = 0.0802 \text{ ohm}$$

$$\dot{I}_c = \frac{\dot{V}_F}{X_c} = \frac{170 \angle 0}{0.0802 \angle -90}$$

$$\dot{I}_c = 2120 \angle -90 = 0 + j2120$$

$$\dot{I}_F = \dot{I}_T - \dot{I}_c$$

$$= (294 - j110) - (0 + j2120)$$

$$= 294 - j2230$$

$$= 2250 \angle -82.5$$

8.6 CALCULATION OF IMPEDANCE OF BOTTOM ZONE, Z_3 .

Note that Z_{M32} is neglected because the current in Zone 2 is low.

$$\dot{V}_3 = (\dot{V}_3 + \dot{V}_9) - \dot{V}_9$$

$$= (7.58 + j45.2) - (0.18 + j8.5)$$

$$= 7.4 + j39.7$$

$$\dot{V}_3 = 40.3 \angle +79.4 \quad \text{referred to } I_F \angle 0$$

$$Z_3 = \frac{\dot{V}_3}{\dot{I}_F} = \frac{40.3 \angle 79.4}{2250 \angle 0} = 0.0179 \angle 79.4$$

This value compares favorably with $0.016 \angle 79.6$ calculated in 3.4.11 and is probably the more accurate of the two because it was not obtained by subtracting two large voltages.

8.7 CALCULATION OF IMPEDANCE OF TOP ZONE Z_1

$$\dot{V}_1 = (\dot{V}_9 + \dot{V}_3 + \dot{V}_2 + \dot{V}_1) - (\dot{V}_9 + \dot{V}_3 + \dot{V}_2)$$

$$= 134 \angle 80.5 - 77.8 \angle 80.5$$

$$\dot{V}_1 = 56 \angle 80.5$$

$$Z_1 = \frac{\dot{V}_1}{I_F} = \frac{56 \angle 80.5}{2250 \angle 0} = 0.0249 \angle 80.5$$

8.8 CALCULATION OF IMPEDANCE OF BOTTOM FURNACE LEADS

$$Z_9 = \frac{\dot{V}_9}{I_F} = \frac{8.5 \angle 88.8}{2250} = 0.00378 \angle 88.8$$

8.9 CALCULATION OF IMPEDANCE OF WATER-COOLED CAPACITOR LEADS AND THE KNIFE SWITCH IN THE CONTROL CONSOLE

$$Z_{10} = \frac{\dot{V}_{10}}{I_F} = \frac{7.6 \angle 84.7}{2250} = 0.00338 \angle 84.7$$

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9.0 TEST NO. 6 - DETERMINATION OF THE IMPEDANCE OF THE SERIES AIR CORE INDUCTANCE

9.1 TEST FURNACE AND DATE

This test was run on M furnace on November 28, 1967.

9.2 TEST CIRCUIT

The circuit used for this test is shown in Figure 10. The series air core coil was made by wrapping two parallel 18 foot number 16 water-cooled leads into four turns with no spacing between the turns.

9.3 TEST CONDITIONS

- 1) Top reactor with 0 amperes control current.
- 2) Center reactor shorted with four 250,000 cmil cables.
- 3) Bottom reactor with 0 amperes control current.
- 4) No. 7 transformer tap, turns ratio = $\frac{14}{31}$ primary to secondary.
- 5) Furnace cold: no visible red at any time during the test.

9.4 TEST DATA

- 1) Furnace control panel instrument readings:

kW = 50 kilowatts

I_G = 107 amperes

V_G = 500 volts

V_F = 220 volts

PF = -0.99

Capacitors = 8 sections of 52.5 mfd each

- 2) Oscilloscope Photo Data

The current transformer was placed on one of the two water-cooled leads to the top of the furnace. The magnitude of the current oscilloscope trace is only approximately

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Figure 10. Circuit for Test No. 6.

correct since there is no guarantee that the furnace current is dividing equally between the two parallel leads. The current trace should be an accurate phase reference. All voltages are measured with respect to point L as a reference.

Point F	$\dot{V}_8$	$= 74.3 \angle 67.8 \text{ (87.2)}$	$1/2 \dot{I}_F$ $1200 \angle 0$
Point G	$\dot{V}_8 + \dot{V}_7$	$= 83.0 \angle 67.8 \text{ (87.2)}$	$1200 \angle 0$
Point H	$\dot{V}_8 + \dot{V}_7 + \dot{V}_1$	$= 136.0 \angle 64.7 \text{ (84.1)}$	$1220 \angle 0$
Point I	$\dot{V}_8 + \dot{V}_7 + \dot{V}_1 + \dot{V}_2$	$= 166.0 \angle 64.7 \text{ (84.1)}$	$1220 \angle 0$
Point J	$\dot{V}_8 + \dot{V}_7 + \dot{V}_1 + \dot{V}_2 + \dot{V}_3$	$= 205.0 \angle 64.7 \text{ (84.1)}$	$1220 \angle 0$
Point K	$V_8 + V_7 + V_1 + V_2 + V_3 + V_9$	$= 212.0 \angle 66.8 \text{ (86.2)}$	$1220 \angle 0$
Point E	$V_8 + V_7 + V_1 + V_2 + V_3 + V_9 + V_{10}$	$= 216.0 \angle 64.3 \text{ (83.7)}$	$1200 \angle 0$

9.5 CALCULATE THE FURNACE CURRENT FROM PANEL DATA

$$|I_T| = I_G \times \frac{31}{14} = 107 \times \frac{31}{14} = 237 \text{ amperes}$$

$$PF = \frac{kW}{V_F \times \frac{10^3}{I_T}} = \frac{50}{220 \times \frac{10^3}{237}} = 0.960$$

$$\theta = \cos^{-1} 0.960 = 16.2 \text{ degree}$$

$$\text{Define } \dot{V}_F = 220 \angle 0$$

$$\dot{I}_T = 237 \angle -16.2 = 228 - j66.0$$

Minimum capacitance from 3.3.4 1070 mfd

8 sections at 52.5 mfd each 420

Total capacitance 1490 mfd

$$X_c = \frac{1}{2\pi fc} = \frac{1}{6.28 \times 960 \times 1490} = 0.1090 \text{ ohm}$$

$$\dot{I}_c = \frac{\dot{V}_F}{X_c} = \frac{220 \angle 0}{0.1090 \angle -90} = 2020 \angle 90 = 0 + j2020$$

$$\begin{aligned} \dot{I}_F &= \dot{I}_T - \dot{I}_c \\ &= (228 - j66.0) - (0 + j2020) \\ &= 228 - j2086 \\ &= 2100 \angle -83.7 \end{aligned}$$

The current measured with the oscilloscope is approximately $2 \times 1200 = 2400 \angle -64.3$. This difference may be due to damage to the current transformer during the high temperature run immediately preceding this run.

Assume a constant correction of the current phase angle of $83.7 - 64.3 = 19.4$ degree. Also assume that the calculated value of $\dot{I}_F$ is correct. The corrected phase angles for the oscilloscope voltage measurements are shown in parenthesis with the oscilloscope data.

9.6 CALCULATION OF THE IMPEDANCE OF THE SERIES AIR CORE INDUCTANCE, THE LEADS TO THE FURNACE SWITCH, AND THE SWITCH

$$Z_{8'} = \frac{\dot{V}_8}{\dot{I}_F} = \frac{74.3 \angle 87.2}{1200 \angle 0} = \frac{0.062 \angle 87.2}{0.003 + j0.062} \text{ ohms}$$

9.7 CALCULATION OF THE INDUCTANCE OF THE AIR CORE COIL

$$\begin{aligned} X_L &= 2\pi fL = \frac{62}{6.2} \times 10^{-3} \times 10^{-3} = 10 \\ L &= \frac{X_L}{2\pi f} = \frac{0.062}{6.28 \times 960} = 10.3^{-6} = 10.3 \text{ microhenries} \end{aligned}$$

9.8 CALCULATION OF THE IMPEDANCE OF THE TOP FURNACE LEADS

$$\begin{aligned}
 \dot{V}_7' &= (V_8 + V_7') - \dot{V}_8 \\
 &= 83.0 \angle 87.2 - 74.3 \angle 87.2 \\
 &= (4.0 + j83.0) - (3.5 + j74.3) \\
 &= 0.5 + j8.7 = 8.7 \angle 86.7
 \end{aligned}$$

Note that the angle is likely to be very much in error.

$$Z_7' = \frac{V_7'}{I_F} = \frac{8.7 \angle 86.7}{2100 \angle 0} = 0.0041 \angle 86.7 \text{ ohm}$$

This compares very well with 0.00378 for the bottom furnace leads as calculated in

3.6.7.

9.9 CALCULATION OF THE IMPEDANCE OF THE TOP ZONE

$$\begin{aligned}
 \dot{V}_1 &= (\dot{V}_8' + \dot{V}_7' + \dot{V}_1') - (V_8' + V_7') \\
 &= (14.1 + j136) - (4.0 + j83.0) \\
 &= 10.1 + j53 \\
 &= 54.0 \angle 79.2 \\
 Z_1 &= \frac{\dot{V}_1}{I_F} = \frac{54.0 \angle 79.2}{2100 \angle 0} = 0.0257 \angle 79.2
 \end{aligned}$$

This compares very well with the value of 0.0249 $\angle$ 80.5 which was calculated in

3.6.6.

9.10 CALCULATION OF IMPEDANCE OF CENTER ZONE SHUNTED BY SHORTED 360 kVA REACTOR

$$\dot{V}_2 = (\dot{V}_8' + \dot{V}_7' + \dot{V}_1' + \dot{V}_2') - (\dot{V}_8' + \dot{V}_7' + \dot{V}_1')$$

$$\begin{aligned}
 &= (17.2 + j165) - (14.1 + j136) \\
 &= (17.2 + j165) - (14.1 + j136) \\
 &= 3.1 + j29 = 29.2 \angle 83.9 \\
 Z_2' &= \frac{29.2 \angle 83.9}{2100 \angle 0} = 0.0139 \angle 83.1
 \end{aligned}$$

This impedance of the center zone shunted by the two tap leads and the shorting cable across the 360 kVA reactor is to be compared with the impedance Z_2 of the center zone which was calculated in 3.4.10 at $0.077 \angle 74.5$ ohm.

9.11 CALCULATION OF THE DIVISION OF CURRENT BETWEEN THE FURNACE CENTER ZONE AND THE SHUNT

$$\frac{1}{Z_2} = \frac{1}{Z_2} + \frac{1}{Z_5}$$

$$\frac{1}{0.0139 \angle 83.9} = \frac{1}{0.077 \angle 74.5} + \frac{1}{Z_5}$$

$$71.9 \angle -83.9 = 13.0 \angle -74.5 + \frac{1}{Z_5}$$

$$7.6 - j71.5 = 3.5 - j12.5 + \frac{1}{Z_5}$$

$$4.1 - j59 = \frac{1}{Z_5} = 59 \angle -86.0$$

$$\dot{I}_5 = \dot{V}_2 \times \frac{1}{Z_5} = 29.2 \angle 83.9 \times 59 \angle -86.0 = 1720 \angle -2.1$$

$$\dot{I}_2 = \dot{V}_2 \times \frac{1}{Z_2} = 29.2 \angle 83.9 \times 13.0 \angle -74.5 = 380 \angle +9.4$$

$$\dot{I}_F = \dot{I}_5 + \dot{I}_2 = 1720 \angle -2.1 + 380 \angle +9.4$$

$$\begin{aligned}
 &= (1720 - j63) + (374 + j62.1) \\
 &= 2094 - j0.9 \\
 &= 2100 \angle 0
 \end{aligned}$$

This is a good check.

Thus only 380 amperes out of 2100 amperes or 18 percent of the current flows in the center zone.

9.12 CALCULATION OF THE IMPEDANCE OF THE BOTTOM ZONE

$$\begin{aligned}
 \dot{V}_3 &= (\dot{V}_8 + \dot{V}_7 + \dot{V}_1 + \dot{V}_2 + \dot{V}_3) - (V_8 + V_7 + V_1 + V_2) \\
 &= (21.4 + j204) - (17.2 + j165) \\
 &= 4.2 + j39 = 39 \angle 83.9 \\
 Z_3 &= \frac{\dot{V}_3}{I_F} = \frac{39 \angle 83.9}{2100 \angle 0} = 0.0186 \angle 83.9
 \end{aligned}$$

This compares favorably with $0.0179 \angle 79.4$ calculated in 3.6.5 but is not as accurate because it was obtained from the difference of two large voltages.

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10.0 TEST NO. 7 - DETERMINATION OF THE HOT IMPEDANCE OF THE TOP AND BOTTOM ZONES

10.1 TEST FURNACE AND DATE

This test was run on M furnace on September 28, 1967.

10.2 TEST CIRCUIT

The circuit for this test was the same as Figure 10 except that Point G was used as the oscilloscope reference.

10.3 TEST CONDITIONS

- 1) Top reactor with 0 amperes control current.
- 2) Center reactor shorted with four 250,000 cmil cables.
- 3) Bottom reactor with 0 amperes control current.
- 4) No. 7 transformer tap, turns ratio $\frac{14}{31}$ primary to second.
- 5) Furnace hot: No. 2 sight port 1500°F
No. 3 sight port 1600°F
No. 4 sight port 1800°F

10.4 TEST DATA

- 1) Furnace control panel instrument readings:

kW = 50 kilowatts

I_G = 112 amperes

V_G = 470 volts

V_F = 208 volts

PF = -0.99

Capacitors = 8 sections of 52.5 mfd each.

2) Oscilloscope Photo Data

The current transformer was placed on one of the two water-cooled leads to the top of the furnace. The magnitude of the current trace is only approximately correct because there is no guarantee that the furnace current is dividing equally between the two parallel leads. All voltages are measured with respect to Point G as a reference.

$$I_F = |I_F| \angle 0$$

Point H	$\dot{V}_1$	$48.8 \angle 52.5$	(79.0)
Point I	$\dot{V}_1 + \dot{V}_2$	$77.6 \angle 51.5$	(78.0)
Point J	$\dot{V}_1 + \dot{V}_2 + \dot{V}_3$	$109.5 \angle 56.5$	(83.0)

10.5 CALCULATION OF THE FURNACE CURRENT FROM PANEL DATA

$$|I_T| = I_G \times \frac{31}{14} = 112 \times \frac{31}{14} = 248 \text{ amperes}$$

$$P. F. = \frac{KW}{V_F \times \frac{10^3}{I_T}} = \frac{50}{208 \times \frac{10^3}{248}} = 0.970$$

$$\theta = \cos^{-1} 0.970 = 14.0 \text{ degrees}$$

$$\text{Define } \dot{V}_F = 208 \angle 0$$

$$\dot{I}_T = 248 \angle -14 = 240 - j60$$

$$X_c = 0.1090 \text{ from 3.7.4}$$

$$\dot{I}_c = \frac{\dot{V}_F}{X_c} = \frac{208 \angle 0}{0.1090 \angle -90} = 1910 \angle 90 = 0 + j1910$$

$$\begin{aligned}
 &= (240 - j60) - (0 + j1910) \\
 &= 240 - j1970 \\
 &= 1980 \angle 83.0
 \end{aligned}$$

Assume that the true phase angle at Point J is the phase angle calculated from control panel data, i. e. 83 degrees. The oscilloscope phase angle measured with the bad current transformer was 56.5 degree. The correction is $83.0 - 56.5 = 26.5$ degree. Also assume that the calculated value of I_F is correct. The corrected phase angles for the oscilloscope voltage measurements are shown in parenthesis with the oscilloscope data.

10.6 CALCULATION OF THE IMPEDANCE OF THE TOP ZONE HOT

$$Z_1 = \frac{\dot{V}_1}{\dot{I}_F} = \frac{48.8 \angle 79}{1980} = 0.0247 \angle 79 \text{ degrees}$$

10.7 CALCULATION OF THE IMPEDANCE OF THE BOTTOM ZONE HOT

$$\begin{aligned}
 \dot{V}_3 &= (\dot{V}_1 + \dot{V}_2 + \dot{V}_3) - (\dot{V}_1 + \dot{V}_2) \\
 &= (13.3 + j108.6) - (16.1 + j75.7) \\
 &= -2.8 + 32.9 = 33.0 \angle 94.9 \\
 Z_3 &= \frac{\dot{V}_3}{\dot{I}_F} = \frac{33.0 \angle 94.9}{1980 \angle 0} = 0.0166 \angle ?
 \end{aligned}$$

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11.0 TEST NO. 8 - STUDY OF THE VARIATION OF ZONE VOLTAGE AS A FUNCTION OF REACTOR CONTROL CURRENT

11.1 TEST FURNACE, DATE, AND PURPOSE

This test was run on M furnace on September 15, 1967. The purpose of the test was to determine if the reactors continued to cause the zone voltage to drop as the control current was increased.

It is known that the saturable reactors are two-core units. Such a reactor when operated in its linear region draws an average AC current which has a fixed ratio to the DC control current. It is therefore not correct to speak of these reactors as being "fully saturated." The curves of zone voltage versus control current for a constant furnace current are given just to show a typical case. If a different fixed furnace current was selected, the percentage drop in zone voltage for a given reactor control current might be different. Saturable reactors are not linear impedance devices but are waveshape choppers. Due to this characteristic, impedance changes sharply once each half cycle of applied voltage.

11.2 TEST CIRCUIT

The test circuit is shown in Figure 3. The zone voltages were measured on Simpson multimeters which are rectifier type AC instruments.

11.3 TEST CONDITIONS

The bottom reactor was left unsaturated for both test runs so that this impedance would be constant. The voltage across this fixed impedance was kept constant by adjusting the generator field so that a fixed furnace current was maintained throughout both runs.

11.4 TEST DATA

Table 1 provides all the data which was taken. The curves of zone voltage versus reactor control current for the two reactors are given in Figure 11.

TABLE 1
DATA FROM REACTOR SATURATION TEST

	P.F.	CAP.	Control Panel Readings				Reactor Control Current				Zone Voltages		
			V _G	I _G	KW	V _F	Top*	Mid	Bot.	Gen.	V ₁	V ₂	V ₃
Run No. 1	1.0	14	501	179	82	225	0.0	8.0	0	4.3	59.0	90	39
	-0.99	15	475	173	75	210	1.0	8.0	0	4.4	47.5	90	39
	-0.99	17	440	165	67	200	2.0	8.0	0	4.05	40.5	90	39
	+1.0	19	439	168	67	195	3.0	8.0	0	3.90	35.0	90	39
	-0.99	19	421	169	65	190	4.0	8.0	0	4.3	31.0	90	39
	-0.98	19	420	179	65	187	5.0	8.0	0	4.7	28.0	90	39
	-0.96	19	401	189	62	178	6.0	8.0	0	5.0	23.5	90	39
Run No. 2	+0.99	8	610	260	129	275	4.5	1.0	0	5.4	28.0	175	39
	-0.98	8	570	239	108	250	4.5	2.0	0	6.1	28.0	151	39
	1.00	13	520	195	90	230	4.5	3.0	0	4.6	28.0	132	39
	1.00	15	472	180	80	210	4.5	4.0	0	4.4	28.0	116	39
	1.00	17	459	175	74	201	4.5	5.0	0	4.2	28.5	108	39
	-0.99	19	442	173	72	200	4.5	6.0	0	4.0	28.5	102	39
	-0.99	19	435	172	68	196	4.5	7.0	0	4.3	30.0	95	39
	-0.98	19	421	178	66	195	4.5	8.0	0	4.65	31.0	89	39
	-0.97	19	410	183	62	180	4.5	9.0	0	4.9	30.0	85	39

* Set at 0 kW. This current increased slightly as the generator was brought to full kW.

Figure 11. Typical Curves of Top and Middle Zone Voltages VS Reactor Control Currents for Constant Bottom Zone Voltage

11.5 DISCUSSION OF RESULTS

Possibly some interesting calculations could be made using the data of Table 2, but little confidence could be placed in the results of such calculations since the saturable reactor is a non-linear device. The effect of the saturable reactor cannot be calculated by linear AC circuit theory.

The curves of Figure 11 are given solely to illustrate the effect of the reactors on a typical test.

12.0 SUMMARY OF RESULTS AND CONCLUSIONS

12.1 RESULTS

The results of all the calculations in the report are collected for easy review in Table 2.

In view of the results of test No. 8, the values of the saturated impedance for the 75 and 360 kVA reactors are only approximate.

The close agreement between the values for an impedance calculated from the data from different tests enhances confidence in the result.

12.2 GENERAL CONCLUSIONS

The most important result which was obtained from these tests was the determination that the mutual inductance between the center and end zones of the coil is small enough to be neglected in practical furnace control problems. This mutual impedance is roughly one-fifth the impedance of the end zones and only one-twentieth the impedance of the center zone. This means that changes in the current in one zone will have little effect on the voltage in the adjacent zone. This permits the kW in a furnace zone to be calculated from the voltage appearing across the zone assuming a constant value for the impedance of the zone.

$$kW_2 = \frac{V_2}{Z_2} \cos \theta_2$$

θ_2 is the phase angle associated with Z_2 .

The data in Table 1 supports this conclusion. Note that in run No. 1, V_2 remained constant as the coil current decreased in zone 1. Also in run No. 2, V_1 changed only slightly as coil current changed in zone 2.

The effect of the mutual impedance, however, cannot be neglected when calculating accurate values for the furnace impedances as was shown in the calculation of Z_2 in 6.11 and Z_3 in 6.13.

TABLE 2

SUMMARY OF IMPEDANCE CALCULATIONS FOR M FURNACE

Circuit Element	Symbol	Test Number						
		1	2	3	4	5	6	7
Unsaturated 75 kVA	Z_4	7.5 $\angle -90$						
Saturated 75 kVA	Z_{45}		0.0157 $\angle 85$					
Saturated 360 kVA	Z_{55}			0.041 $\angle 90$				
Mutual Impedance	$Z_{M21},$ Z_{M32}		0.0036 $\angle 90$	0.00285 $\angle 90$	0.00331 $\angle 90$			
Top Zone Cold	Z_1					0.025 $\angle 80.5$	0.0257 $\angle 79.2$	
Top Zone Hot	Z_1							0.0247 $\angle 79$
Center Zone Cold	Z_2		0.077 $\angle 74.5$	0.074 $\angle 60.8$				
Center Zone Hot	Z_2				0.074 $\angle 69$			
Bottom Zone Cold	Z_3		0.016 $\angle 79.6$	0.0159 $\angle 78.2$		0.018 $\angle 79.4$	0.0186 $\angle 83.9$	
Bottom Zone Hot	Z_3				0.0147 $\angle 66.8$			0.0166 $\angle ?$
Top Lead	Z_7'						0.0041 $\angle 36.7$	
Upper Tap Lead	Z_7		0.0057 $\angle 82$	0.0053 $\angle 68.5$	0.0051 $\angle 81$			
Bottom Lead	Z_9					0.0038 $\angle 88.8$		
Capacitor Leads and Switch	Z_{10}					0.0034 $\angle 34.7$		
Series Air Core Coil	Z_8'						0.062 $\angle 87.2$	

APPENDIX A

PROCEDURE FOR TEST NO. 1

PURPOSE

The measurement of the minimum capacitance and the unsaturated impedance of the 75 kVA reactor.

PREPARATION FOR TEST NO. 1

- 1) Remove the water-cooled leads to the top of the furnace and replace with non-conducting hoses.
- 2) Place the current transformer with a 0.1 ohm shunt on the upper tap lead.
- 3) Remove the grounding pin from the scope line cord so that the chassis may be operated above ground.
- 4) Connect the scope common to Point E of the circuit diagram, Figure 6, and to one end of current transformer shunt.
- 5) Connect a 10:1 attenuator probe lead on the upper channel of the scope and connect this lead to Point L.
- 6) Set scope to trigger on the upper channel.
- 7) Use a 1:1 attenuator probe lead on the lower channel of the scope and connect this lead to the other end of the current transformer shunt.
- 8) Switch in minimum capacitance.
- 9) Put zero control current in all reactors.
- 10) Turn the generator field current to zero.
- 11) Mount the oscilloscope Polaroid camera and set at f 5.6 at 1/10 second.

CONDUCT OF TEST NO. 1

- 1) Turn on the furnace power.
- 2) Increase the generator field current until the generator current reaches the red line value of 240 amperes.

- 3) Record all the control panel meter readings.
- 4) Adjust the scope sensitivities to obtain reasonable signal amplitudes.
- 5) Snap the picture.
- 6) Record the scope sensitivities.
- 7) Reduce generator field to zero.
- 8) Shut off the furnace power.

PROCEDURE FOR TEST NO. 2

PURPOSE

Determination of the impedance of the saturated 75 kVA reactor, the mutual impedance, and the two lower furnace zone impedances.

PREPARATION FOR TEST NO. 2

- 1) Remove the water-cooled leads to the top of the furnace and replace with non-conducting hoses.
- 2) Place the current transformer with a 0.1 ohm shunt on the upper tap lead.
- 3) Remove the grounding pin from the oscilloscope line cord so that the chassis may be operated above ground.
- 4) Connect the scope common to Point A of the circuit diagram, Figure 6, and to one end of the current transformer shunt.
- 5) Connect a 10:1 attenuator probe lead to the upper channel of the scope and use this lead for measurement of the point voltages.
- 6) Set the scope to trigger on the lower channel.
- 7) Connect a 1:1 attenuator lead on the lower channel of the scope and connect.
- 8) Switch in minimum capacitance.
- 9) Put 8.5 amperes control current in the top reactor.
- 10) Turn the generator field current to zero.
- 11) Mount the oscilloscope Polaroid camera and set at f 5.6 at 1/10 second.

CONDUCT OF TEST NO. 2

- 1) Connect the upper channel lead to Point F.
- 2) Turn on the furnace power.
- 3) Increase the generator field until the generator current reaches 100 amperes.
- 4) Switch in capacitor blocks until a power factor of 1.0 is attained.

- 5) Adjust the scope sensitivities to obtain reasonable signal amplitudes.
- 6) Record all the control panel meter readings and the scope sensitivities as in Table 3.
- 7) Snap the picture.
- 8) Reduce the generator field to zero.
- 9) Shut off the furnace power.
- 10) Move the upper channel lead to the next voltage point.
- 11) Repeat steps 2 through 10 for each voltage point.

TABLE 3

CONTROL PANEL METER READINGS AND SCOPE SENSITIVITIES

(Furnace M, Date 11/3/67)

Test No.	Point	CAP	KW	I _G	V _G	V _F	PF	Top Reactor	Middle Reactor	Upper	Units	Atten.	Lower	Units	Atten.
1	L	0	0	240	164	82	+0.5	0	0	5.0	V/CM	X10	50.0	MV/CM	X1
2	F	3	31	100	305	139	1.0	8.5	0	1.0	V/CM	X10	0.5	V/CM	X1
	G	3	31	100	305	139	1.0	8.5	0	1.0	V/CM	X10	0.5	V/CM	X1
	H	3	31	100	305	139	1.0	8.5	0	0.5	V/CM	X10	0.5	V/CM	X1
	I	3	31	100	305	139	1.0	8.5	0	5.0	V/CM	X10	0.5	V/CM	X1
	J	3	31	100	305	139	1.0	8.5	0	5.0	V/CM	X10	0.5	V/CM	X1