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Title Power Transformer Differential Relay Protection As Affected By Magnetization Inrush Current

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The objective of this thesis investigation was the determination of the minimum time required for a differential relay to distinguish between fault current and magnetization inrush current. Inrush current can cause undesired circuit breaker operation because the ordinary differential relay may not distinguish the difference between inrush current and fault current.

Several tests of first harmonic restraint circuits indicated that at least one and one-half cycles are required after initiation of fault or inrush current before these circuits can distinguish between the two types of current.

Tests of a General Electric, HDD Harmonic Restraint Relay showed that it had a minimum operating time of approximately two and one-half cycles on symmetrical fault current.

A second harmonic restraint circuit was found to recognize the difference between fault and inrush current during the first cycle.

The investigation showed that the transient response of relay networks is a very important consideration if high-speed operation of circuit breakers is desired.

POWER TRANSFORMER DIFFERENTIAL RELAY PROTECTION AS AFFECTED BY MAGNETIZATION INRUSH CURRENT

by

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TABLE OF CONTENTS

	Page
NATURE OF PROBLEM	1
THE NATURE OF INRUSH CURRENTS	1
THE NATURE OF FAULT CURRENTS	5
TRANSFORMER DIFFERENTIAL RELAYING	6
PRESENT METHODS OF SOLVING MAGNETIZATION INRUSH PROBLEM	9
OBJECTIVE AND METHOD OF ATTACK	11
TESTS PERFORMED	16
Test of HDD Relay	31
Second Harmonic Test	38
SUMMARY OF RESULTS OBTAINED	43
CONCLUSIONS	44
BIBLIOGRAPHY	46
APPENDIX A	47

POWER TRANSFORMER DIFFERENTIAL RELAY PROTECTION AS AFFECTED BY MAGNETIZATION INRUSH CURRENT

NATURE OF PROBLEM. Transformer magnetization inrush current is a transient phenomenon which may occur when a transformer is energized, or when the voltage returns to normal after a depressed voltage condition. The magnitude of magnetization inrush current may be many times the full load current of the transformer. This thesis investigation was conducted to determine how soon a differential relay can distinguish the difference between fault current and inrush current. Relay operation should occur for fault current, but not for inrush current.

THE NATURE OF INRUSH CURRENTS. It is known that the flux linking the coils of an inductor is related to the voltage by the following equation:

$$\phi = \frac{1}{N} \int_0^t e \, dt \qquad (1)$$

Where:

ϕ = total flux

N = number of turns

e = voltage

t = time

If the voltage applied to the coil is sinuisoidal the equation becomes:

$$\phi = \frac{1}{N} \int_0^t E_m \sin(wt + \lambda)\, dt \quad (2)$$

Where:

w = angular velocity of e

λ = phase angle of e when switch is closed

Performing the integration:

$$\phi = \frac{E_m}{Nw} \left[-\cos(wt + \lambda) + \cos\lambda \right] \quad (3)$$

The preceeding equation represents a negative cosine wave offset by an amount proportional to cos λ. This is the required flux wave when a sinuisoidal impressed voltage is impressed upon a transformer. If the magnetization characteristics of a transformer are known, the waveshape and magnitude of the first cycle of inrush current may be approximated graphically.

Figure 1 shows this graphical approximation for the first cycle of applied voltage. On the left is the flux versus magnetizing current characteristic of a transformer. The fully offset cosine curve on the right is the flux required if the transformer is

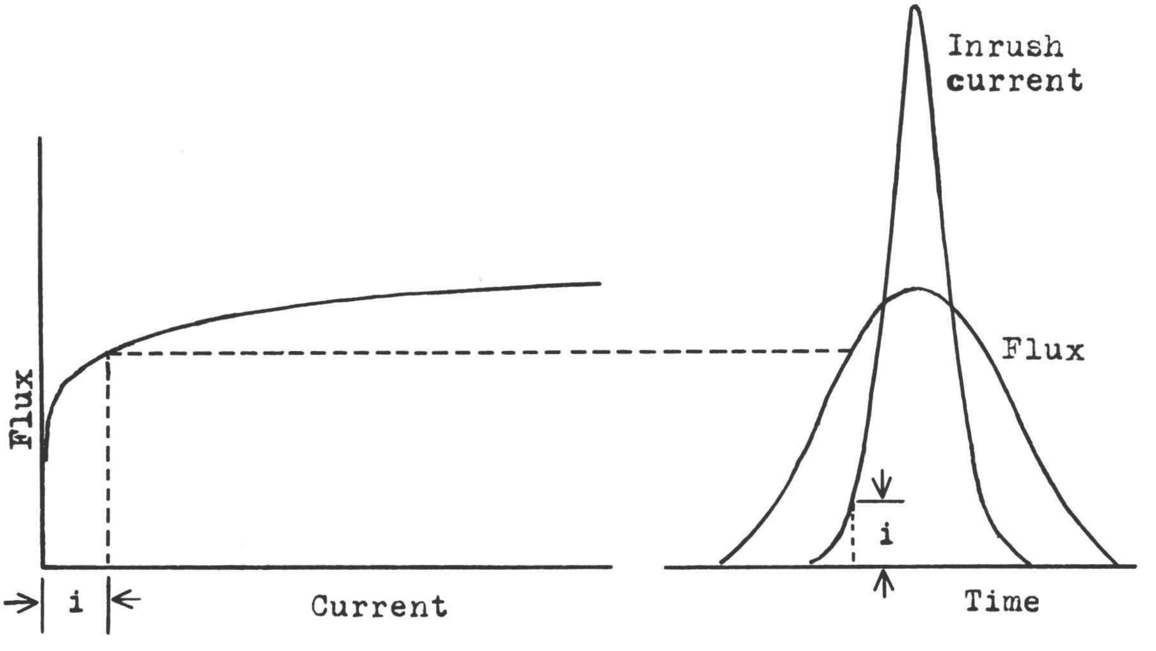


FIGURE 1

A graphical method of determining inrush current.

energized at the zero point on the voltage wave, causing cosine λ in equation 3 to be equal to unity. The current required at any point on the flux wave is found by projecting a horizontal line to the left hand curve. The current is plotted and is seen to rise to a relatively high magnitude to satisfy the peak requirements of the flux wave.

If there were residual magnetism in the positive direction, the flux wave shown would be offset still more and the peak of the inrush wave would be higher than shown. If there were residual magnetism in the negative direction, the flux wave would not be fully offset and the peak inrush current would be reduced accordingly.

Losses in the circuit cause the offset component of the flux wave to decrease with time. When the offset has decreased to zero, the magnetizing current is merely the normal, steady-state value. The time taken for the disappearance of magnetization inrush current varies between several cycles for small transformers to as much as six minutes for very large transformers. The peak magnitude of the first cycle of magnetization inrush current may be as large as 16 times the rated full load current of a transformer (1, pp. 3-4).

THE NATURE OF FAULT CURRENTS. When a power transformer is faulted the impedance seen looking into the transformer is its leakage impedance. This impedance is nearly constant, so that the problem of determining fault current becomes the determination of the current in a series resistance-inductance circuit with alternating voltage applied. The complete solution is (2, pp. 511-516):

$$i = \frac{E_m}{Z} \sin(wt + \lambda - \theta) - \frac{E_m}{Z} \sin(\lambda - \theta)\, e^{-Rt/L} \qquad (4)$$

Where:

i = instantaneous current

E_m = peak voltage applied

w = angular velocity of applied voltage

t = time in seconds

λ = phase angle of applied voltage when circuit is energized

$\theta = \tan^{-1} \frac{wL}{R}$

$Z = \sqrt{R^2 + (wL)^2}$ = leakage impedance

R = alternating current resistance of affected windings

L = leakage inductance

In a power transformer the angle θ will be nearly 90 degrees since the leakage impedance is highly inductive. For purposes of illustration θ will be set equal to 90 degrees. Equation (4) becomes:

$$i = -\frac{E_m}{Z} \cos(wt + \lambda) + \frac{E_m}{Z} \cos\lambda \, e^{-Rt/L} \qquad (5)$$

The second term in this equation is the transient term and will be very small when λ is near 90 degrees. This would indicate that if a transformer is faulted when the applied voltage is near its maximum value, there will be no transient current and the fault current will be symmetrical. This case is shown in Figure 7B, for which an air core inductor simulated the leakage inductance of a power transformer. In this oscillogram e_1 is the applied voltage and i_1 is the fault current.

Equation (5) also shows that if a transformer is faulted when the applied voltage is passing through a zero value, the transient current will be a maximum and the fault current will be asymmetrical. This condition is shown in Figure 5B, where e_1 is again the applied voltage and i_1 is the fault current.

TRANSFORMER DIFFERENTIAL RELAYING. The common differential relay scheme for transformer protection is shown in Figure 2. The arrows show the direction

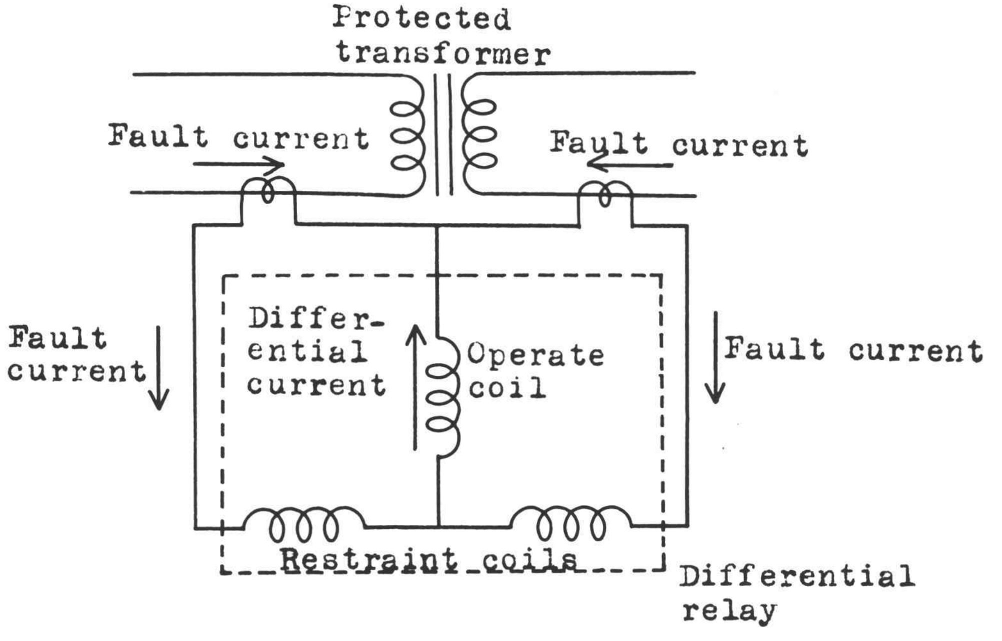


Figure 2

Simplified diagram of defferential relay transformer protection.

of current flow if the transformer is faulted. Current flows through the operate element during an internal fault and the relay operates to open the transformer circuit breaker. The restraint elements ordinarily have not more than 50% as much torque as the operate element so they do not necessarily restrain relay operation in case of internal fault.

In case of faults outside the differential protection zone, the direction of one of the currents is reversed. Theoretically, no current will flow in the operate element and there will be no operation. Due to minor unbalances some current will flow in the operate element, but a great deal more current will flow in the restraint elements to prevent operation of the relay.

The magnetization inrush current which occurs when the transformer is energized flows only in one winding of the transformer and therefore appears as differential current flowing in the operate element of the relay. Magnetization inrush current thus appears to the differential relay as a fault current, and the tendency of the relay is to operate and cause undesired circuit breaker operation.

PRESENT METHODS OF SOLVING MAGNETIZATION INRUSH PROBLEM. The most obvious method of solution is to increase the operating time of a differential relay so as to make the total operating time of the relay exceed the duration of the inrush current. This will prevent operation on most inrush currents but, of course, means decreased sensitivity and increased operating time for a fault condition.

Desensitizing methods are also used to solve the problem. Some of these are based on the assumption that transformer short circuits produce a greater voltage dip than is experienced during inrush conditions. One type of relay utilizing these methods employs an auxiliary voltage sensitive relay in addition to the differential relay. Tripping is permitted whenever the voltage relay is dropped out, as it would be on an internal fault. Upon energizing a sound transformer the voltage relay picks up because the transformer voltage is maintained near its rated value. A timer allows enough time to permit the magnetization inrush current to disappear and the differential relay contacts to reset before completing the trip circuit. One disadvantage of this type of relay is the expense of the potential transformers required.

Another method of protection is to utilize a differential relay which recognizes the difference between the waveshapes of fault current and inrush current. Some of these methods utilize the fact that inrush currents have a large direct current offset. The chief disadvantage of these methods lies in the fact that fault waves can also be completely offset. In such a case, the relay might see a fault in the transformer as an inrush current and fail to operate as promptly as desired.

The General Electric, Type HDD, Harmonic Restraint Relay is a differential relay which uses a more highly developed recognition circuit. It has two paths for differential current. One of these is a parallel circuit, tuned to a frequency of 60 cycles per second; the other is a series circuit tuned to the same frequency. A restraint coil is placed in series with the parallel tuned circuit and an operate coil is placed in series with the series tuned circuit. Current in the operate coil exerts a magnetic force on the contactor reed in opposition to that of current in the restraint coil. Since inrush current has a large percentage of harmonic components, considerable current flows in the restraint coil during inrush current conditions, and operation of the relay is restrained. Fault currents do not generally contain a large percentage of harmonics; therefore, under fault conditions, the current in the restraint coil is not sufficient to restrain the operate action of the fundamental component of current in the series tuned circuit.

OBJECTIVE AND METHOD OF ATTACK. The main objective of this thesis investigation was to determine the minimum time taken by various circuits to distinguish between inrush currents and fault currents. Since inrush current is a highly complex wave made up of a d-c component plus several harmonics, the calculation of the response of even a simple network to the inrush current wave is not simple. A differential analyzer might be used for such a study, but, since such a machine was not available, this investigation was carried out by actual test of various networks. Tests were performed using a General Electric transformer, 60 cycle 3Kva, 220/440 volts to 110/220 volts, as the transformer undergoing inrush. The power supply was the single phase, 240 volt, 60 cycle, laboratory supply. The recording instrument was a General Electric Oscillograph, Type PM-10-A1. The time of energization, λ in equations (2) and (4), was controlled by a synchronous switch. Such a switch was available, but was not at once suitable for the use intended in the investigation. It was adapted for use by methods shown in Appendix A. The elements of the various networks tested were made up of laboratory inductors, resistors and capacitors, and the magnitude of these components was determined before each test by use of a General Radio Impedance Bridge, Type 650A.

The general test circuit used for a typical test network is shown in Figure 3. T_1 in Figure 3 was a transformer modified in the laboratory in such a way as to be suitable for use as a high-burden current transformer. T_2 was a General Electric transformer, 3Kva, 60 cycle, 220/440 volts to 110/220 volts. It was connected in the 110:440 ratio to reduce the current applied to the test networks.

The response of some of the test networks to fault currents as well as to inrush currents was desired. To simulate a fault, low impedance laboratory inductors were substituted for the test transformer.

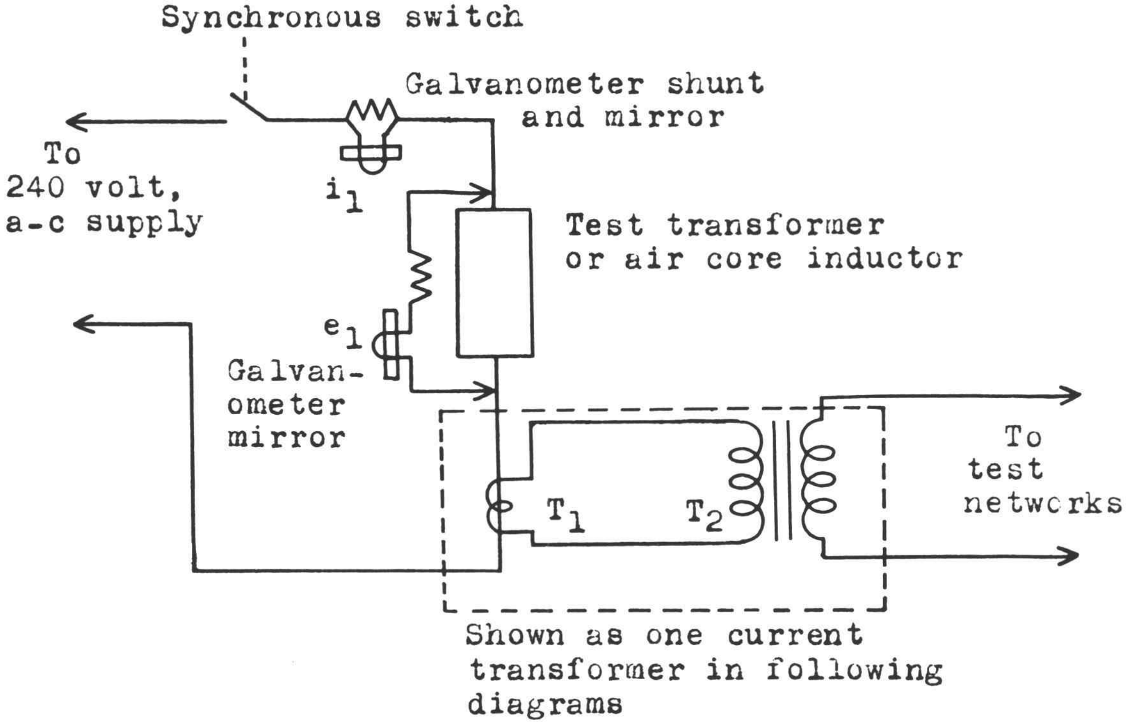


FIGURE 3

Transformer connection used for current transformation.

As previously stated, the magnitude of the residual magnetism and its polarity have a profound effect on the magnitude of the inrush current. The method used to set the residual magnetism in this investigation was first to find the maximum value of the steady state magnetization current in the test transformer. Before each test a direct current equal in magnitude to this value was allowed to flow in the transformer winding. This current was reversed several times so that flux corresponding to the normal hysterisis loop would be obtained. After several reversals, the flux remaining each time the circuit was broken was assumed to be the same as the normal residual flux.

There remained the problem of determining the proper polarity for the residual magnetism. This determination was accomplished by establishing a residual flux as described above and energizing the transformer with the synchronous switch, having previously set the switch to close at a voltage zero point. The inrush current was observed qualitatively with a Radio Corporation of America Oscilloscope, WO 27A. This oscilloscope is equipped with a single sweep circuit which made it possible to view the transient inrush current. Because of the short duration of the transient, not all of the detail of the wave form could be observed, but it was very easy to distinguish the difference between the inrush current with positive and negative residual flux, due to the extreme differences in magnitude. The determination of the correct direction for residual flux had to be performed each time the synchronous motor driving the synchronous switch was started because the relative position of the motor rotor and the voltage wave often varied in steps of 180 electrical degrees.

Considerable difficulty was encountered in the initial tests due to current transformer saturation. The relatively high impedance seen by the current transformer secondary caused the current transformer voltage to be large enough to result in saturation of the core whenever appreciable current appeared in the primary. This saturation produced extremely complex waveforms of current in the tuned circuits. Since no high burden commercial current transformer was available, considerable experimentation was employed to find a suitable substitute. It was found that if the test networks were fed by the combination of transformers shown in Figure 3, the current waveform applied to the test networks would be relatively undistorted.

TESTS PERFORMED. The oscillogram and its associated circuit in Figures 4A and 4B, show the voltage and current relationships set up in a particular network, when the network has impressed upon it the magnetization inrush current of the test transformer. This network consists of parallel and series circuits tuned to 60 cycles, the tuned circuits being connected in parallel. Trace e_1 shows the waveform of the voltage applied to the test transformer. Trace i_1 shows the magnetization inrush current. Trace e_2 shows the voltage across the network. Trace i_2 is the current in the series tuned circuit portion of the network. Trace i_3 shows the current in the parallel tuned circuit. Trace i_4 gives the current impressed upon the network, which should be and is very similar to i_1. The desired currents in the two tuned circuits of the network should be different in such a way as to permit a relay to recognize the transformer current as being inrush current, and the relay should then prevent operation of interrupting devices.

The currents, i_2 and i_3, in the tuned circuits are seen to be much different and are characteristic of the response of this type of network to inrush current.

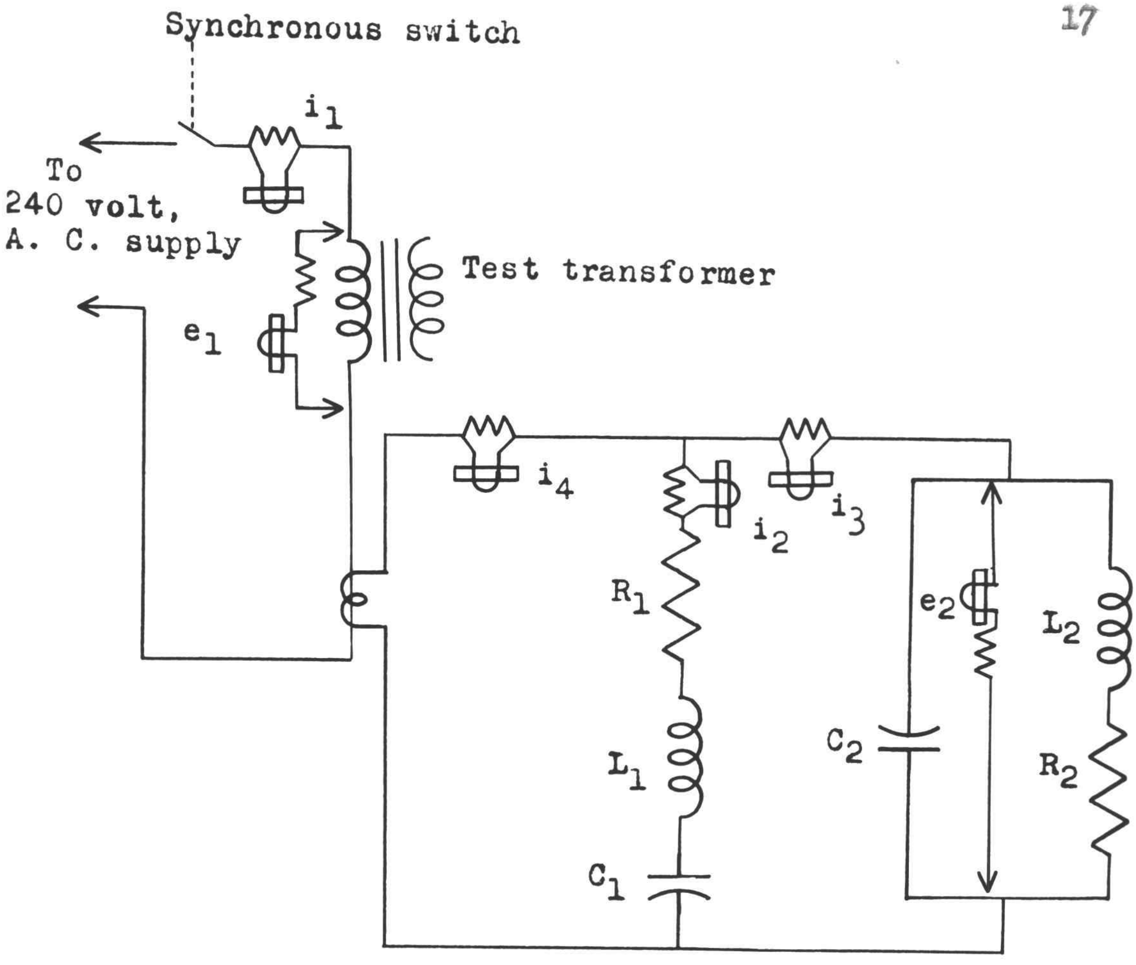


FIGURE 4A

Circuit for test of tuned circuits under magnetization inrush current.

L_1 = 2.10 henries	L_2 = 0.415 henries
C_1 = 3.36 microfarads	C_2 = 17.8 microfarads
R_1 = 29 ohms	R_2 = 11.3 ohms

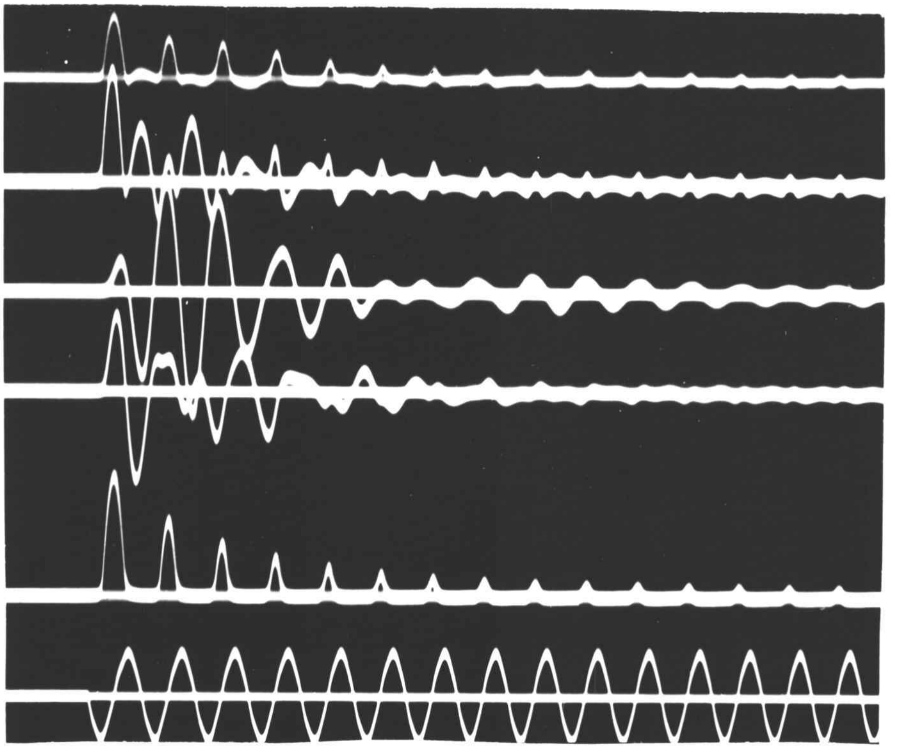


FIGURE 4B

Transient response of tuned circuits in FIGURE 4A to magnetization inrush current.

e_1 = 247 volts (rms)
i_1 (peak) = 224.5 amperes
e_2 (peak) = -180 volts

i_2 (peak) = -0.722 amperes
i_3 (peak) = 1.27 amperes
i_4 (peak) = 1.36 amperes

The initial cycle of inrush current flows in the capacitor of the parallel tuned circuit, since this is the lowest impedance path for the initial inrush of current. Each pulse of inrush current appears in the parallel tuned circuit to some extent, and the overall current waveform in the parallel tuned circuit is not symmetrical. The current in the series tuned circuit is nearly symmetrical and approaches a modulated sine wave in appearance. It can be seen from this comparison of i_2 and i_3 that the harmonic currents and the direct current tend to flow in the parallel tuned circuit, with the sixty cycle current tending to flow in the parallel tuned circuit.

Since the stated purpose of this investigation is to determine how soon a relay can distinguish the difference between inrush and fault current, a test was performed with an offset sine wave impressed upon the same test network. The oscillograph mirrors were placed in the same positions in the networks as for the previous oscillogram with the exception of one mirror, which was reconnected as indicated to measure the current in one branch of the parallel tuned circuit. The circuit and oscillogram are shown in Figures 5A and 5B. In this test the current in the series tuned circuit is again

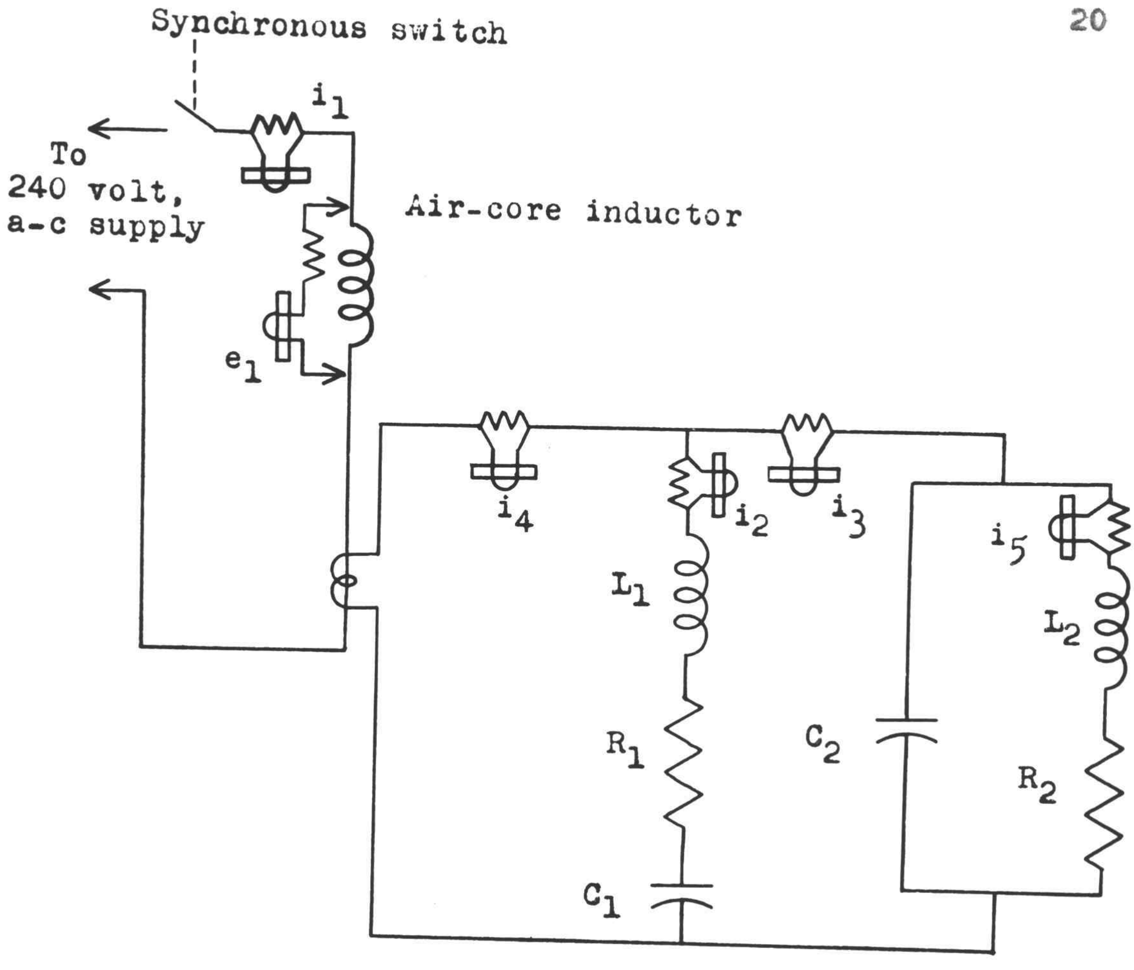


FIGURE 5A

Circuit for test of tuned circuits under fault current.

L_1 = 2.10 henries
C_1 = 3.3 microfarads
R_1 = 29 ohms

L_2 = 0.415 henries
C_2 = 17.8 microfarads
R_2 = 11.3 ohms

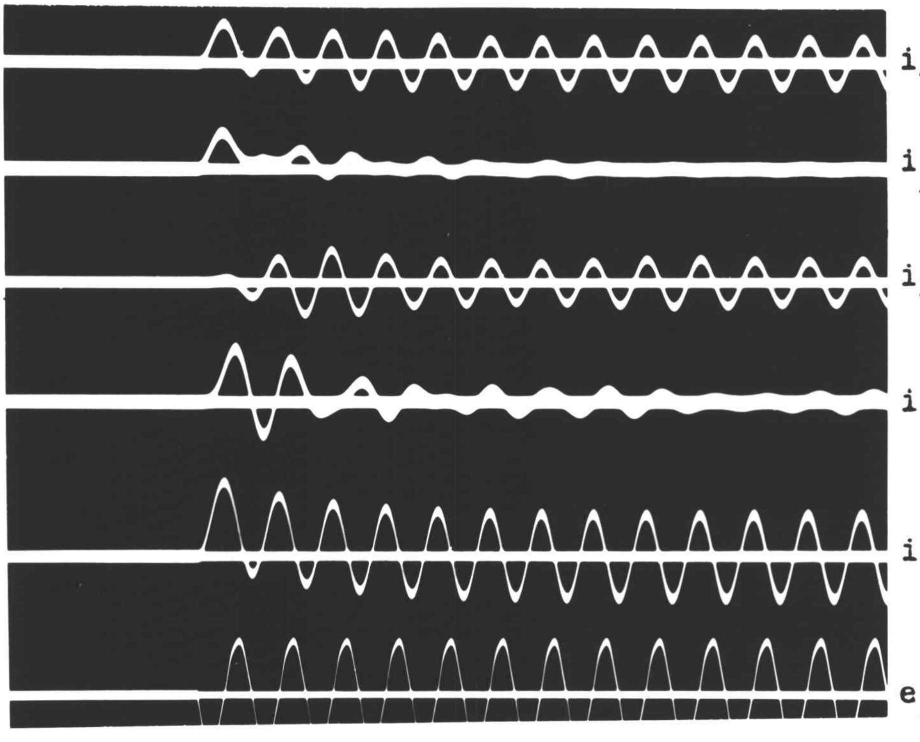


FIGURE 5B

Transient response of resonant circuits
in FIGURE 5A to asymmetrical fault current.

e_1 = 247 volts (rms)
i_1 (peak) = 148 amperes
i_5 (peak) = 1.26 amperes

i_2 (peak) = 0.232 amperes
i_3 (peak) = 0.783 amperes
i_4 (peak) = 0.801 amperes

very much smaller than the current in the parallel tuned circuit during the first cycle of impressed current. However, after the transient currents have decayed, nearly all the current flows in the series tuned circuit because it offers low impedance to the 60 cycle current.

A comparison of oscillograms 4A and 5A shows that the relative magnitudes of the currents in the parallel and series tuned circuits are very nearly the same for either inrush or fault currents during the first cycle of the input current. This would indicate that if the current in the series tuned circuit were to be used as an "operate current" in a relay circuit and the current in the parallel tuned circuit were to be used as a "restraint current", the relay could not operate reliably in less than approximately one and one-half cycles, due to the fact that little current would flow in the operate circuit during the first cycle of either inrush or fault current.

Since the reason for the greater flow of initial current into the parallel tuned circuit was due to the low impedance of C_2, the 17.8 microfarad capacitor, it was thought advisable to repeat the tests with C_2 decreased and L_2 increased to maintain 60 cycle resonance. The results of this test are shown in oscillogram 6B.

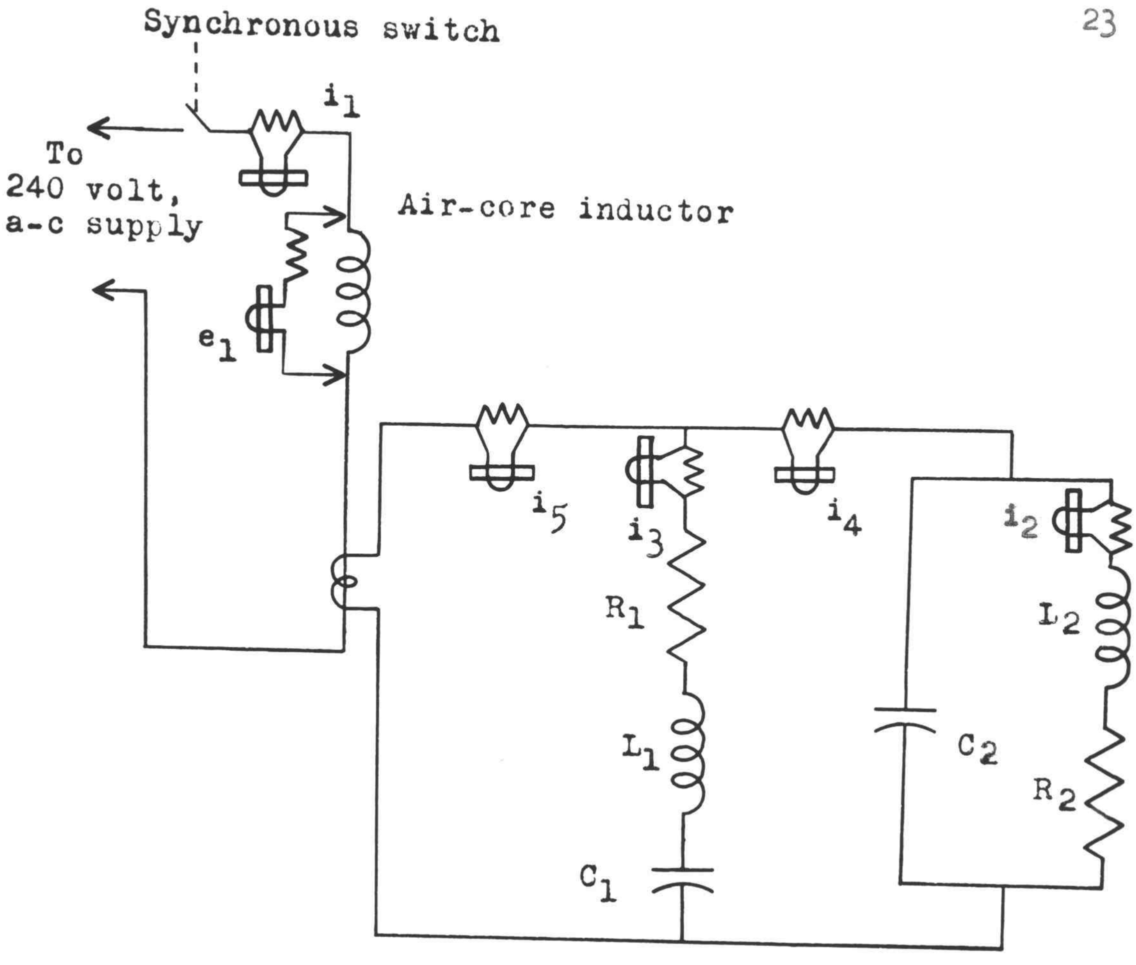


FIGURE 6A

Circuit for test of tuned circuits under fault current, with shunt capacitance increased.

L_1 = 2.10 henries
C_1 = 3.3 microfarads
R_1 = 29 ohms

L_2 = 0.745 henries
C_2 = 9.65 microfarads
R_2 = 11.3 ohms

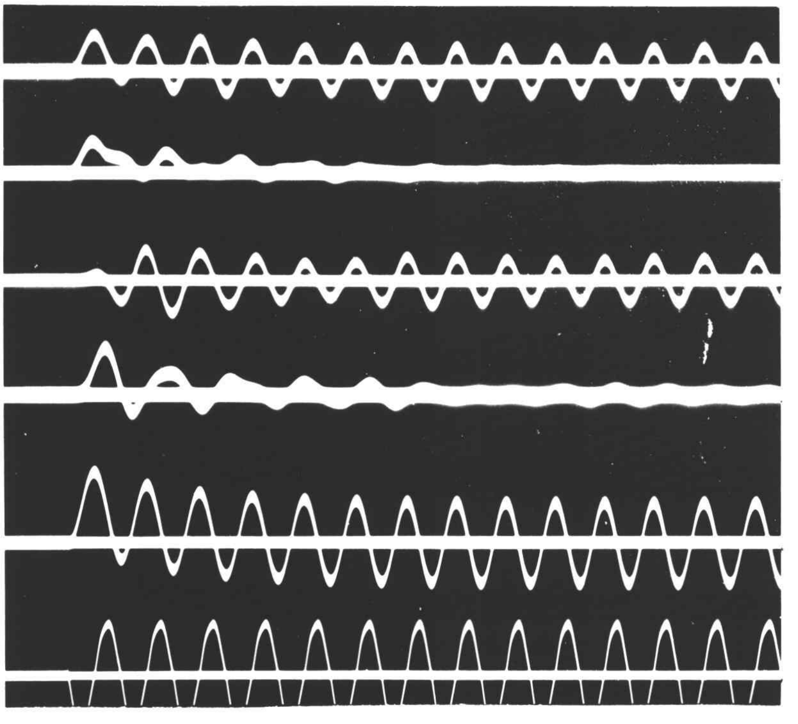


FIGURE 6B

Transient response of resonant circuits in FIGURE 6A to fault current.

e_1 = 245 volts (rms)
i_1 (peak) = 138 amperes
i_2 (peak) = 0.74 amperes
i_3 (peak) = -0.91 amperes
i_4 (peak) = 0.45 amperes
i_5 (peak) = 0.99 amperes

There is no appreciable reduction in the proportionate amount of current drawn by the parallel tuned circuits during the first cycle of fault current.

From the preceeding oscillograms it would seem reasonable to conclude that use of a network consisting of a parallel tuned circuit and a series tuned circuit will give currents in relay coils which will be different in magnitude and waveshape for a fault current and for an inrush current. It seems equally reasonable to conclude that these differences are clearly apparent only after the first cycle of inrush or fault current.

The next three oscillograms, Figures 7B, 7C, and 8B, show the result of adding resistance in the series tuned circuit. This was done to attempt to reduce the magnitude of current in this part of the circuit for inrush current conditions after the first cycle. The results are rather satisfactory in this respect. Figure 7B shows the currents obtained when a symmetrical fault wave is impressed upon the network. After the first cycle much more current flows in the series tuned circuit, or operate circuit, than in the parallel or restraint circuit. Figure 7C shows that much more current flows in the parallel tuned circuit for an offset fault than for a symmetrical fault. However, by the

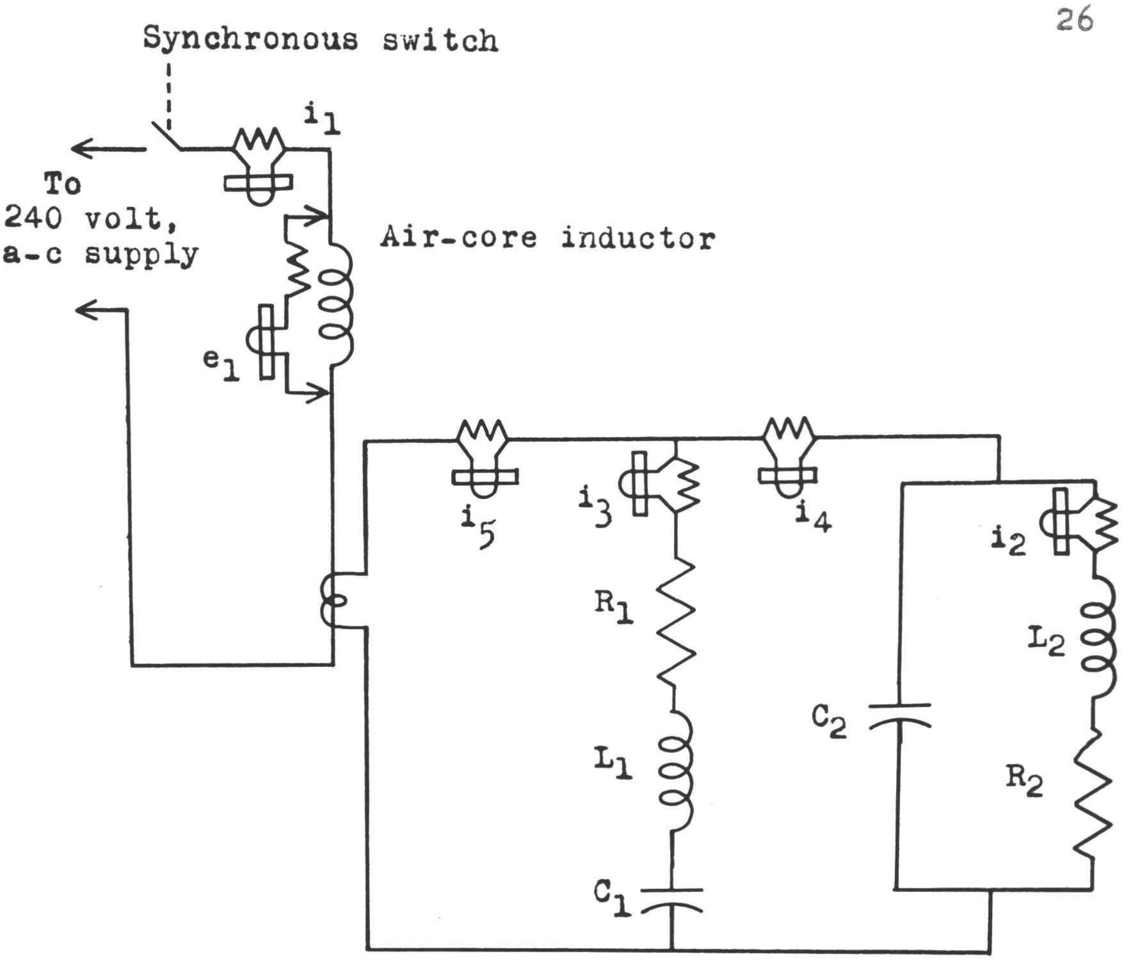


FIGURE 7A

Circuit for test of tuned circuits under fault current, with increased resistance in series tuned circuit.

L_1 = 1.82 henries
C_1 = 3.36 microfarads
R_1 = 140 ohms

L_2 = 0.83 henries
C_2 = 8.48 microfarads
R_2 = 15.3 ohms

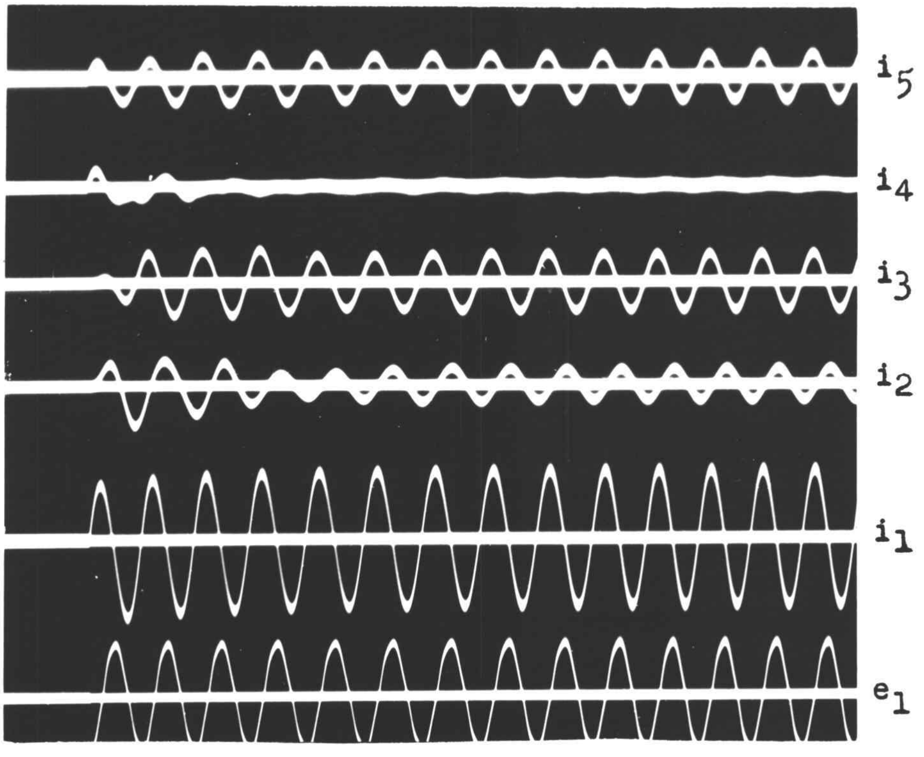


FIGURE 7B

Transient response of tuned circuits in FIGURE 7A to symmetrical fault current.

e_1 = 247 volts (rms)
i_1 = 1.05 amperes (peak)
i_2 = -0.52 amperes (peak)
i_3 = 0.319 amperes (peak)
i_4 = 0.208 amperes (peak)
i_5 = 0.344 amperes (peak)

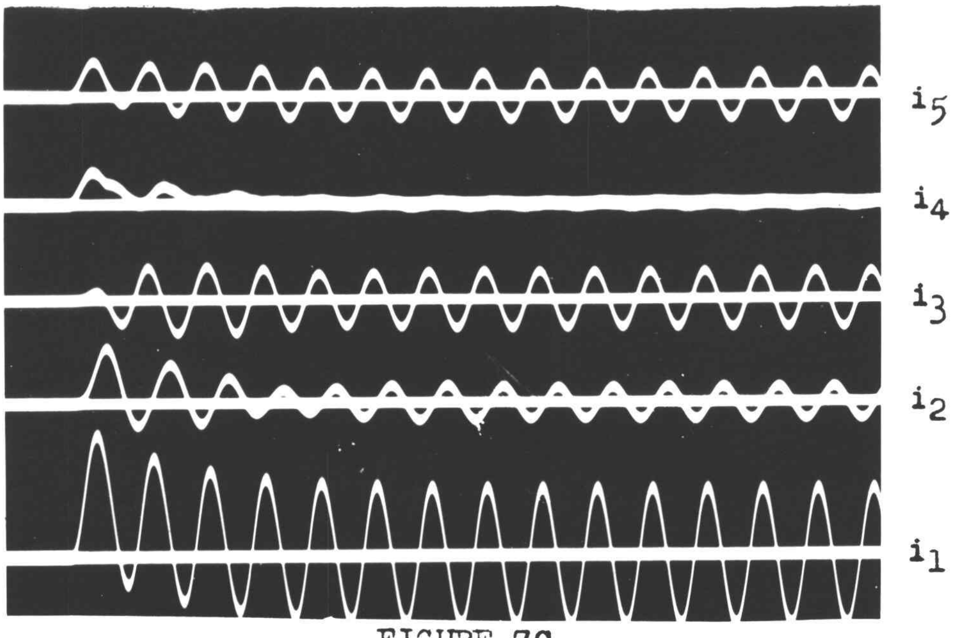


FIGURE 7C

Transient response of resonant circuits in FIGURE 7A to asymmetrical fault current.

i_1 (peak) = 210 amperes
i_2 (peak) = 0.702 amperes
i_3 (peak) = 0.386 amperes
i_4 (peak) = 0.416 amperes
i_5 (peak) = 0.500 amperes

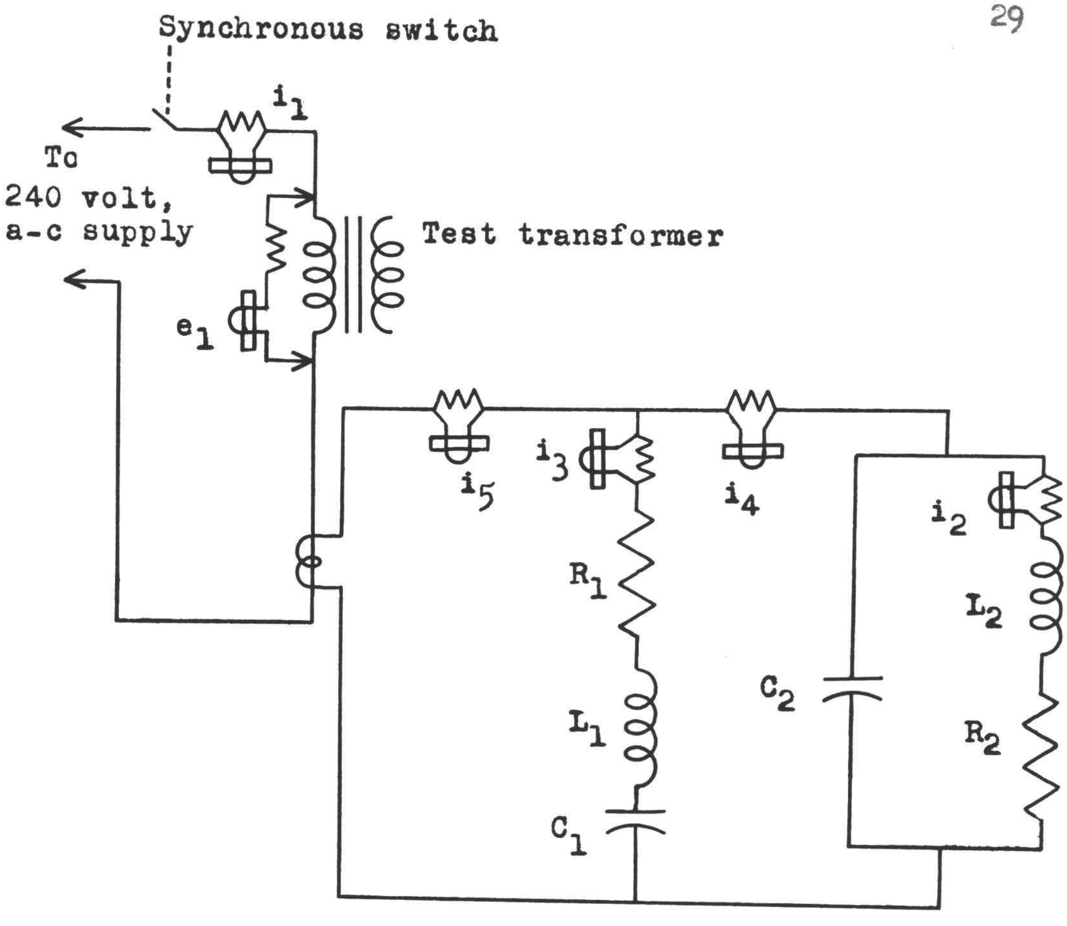


FIGURE 8A

Circuit for test of tuned circuits under magnetization inrush current with increased resistance in series tuned circuit.

L_1 = 1.82 henries	L_2 = 0.83 henries
C_1 = 3.36 microfarads	C_2 = 8.48 microfarads
R_1 = 140 ohms	R_2 = 15.3 ohms

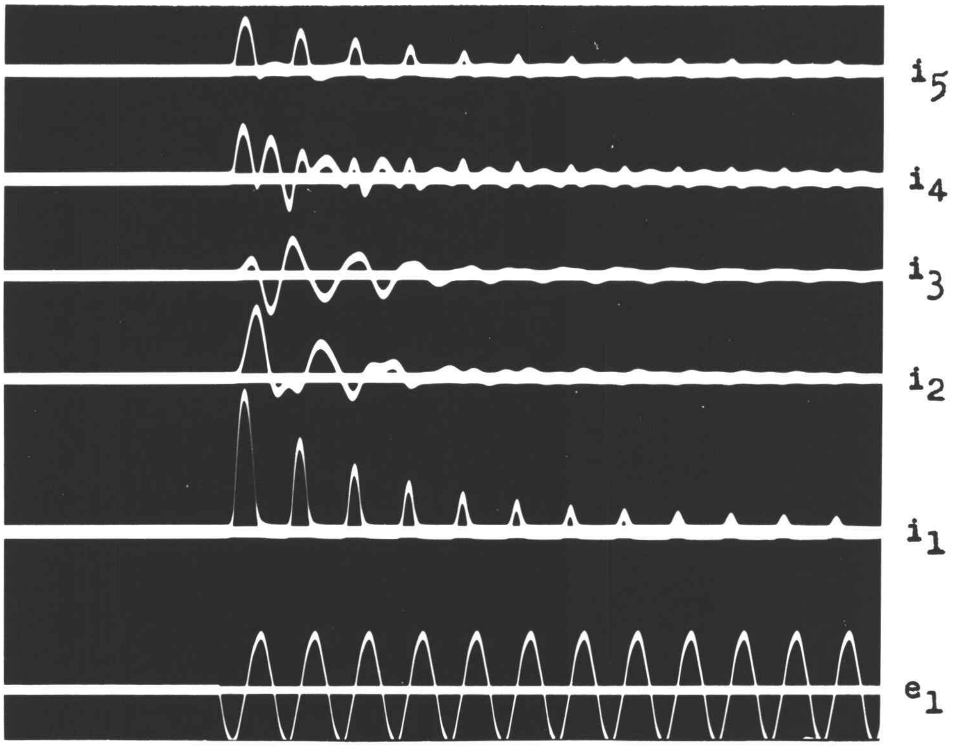


FIGURE 8B

Transient response of tuned circuits in FIGURE 8A to magnetization inrush current.

e_1 = 247 volts (rms)
i_1 (peak) = 238 amperes
i_2 (peak) = 0.885 amperes
i_3 (peak) = 0.441 amperes
i_4 (peak) = 0.624 amperes
i_5 (peak) = 0.750 amperes

beginning of the second cycle, the current in the series tuned circuit has reached a magnitude at least as great as its steady state value. In oscillogram 8B, the same circuit is subjected to a magnetization inrush current wave. Here the current in the parallel tuned circuit is maintained at a root mean square magnitude which is appreciable as compared to the current in the series tuned circuit, and this relationship is maintained for the duration of the inrush current. It would seem, that with adequate rectification and filtering, this restraint current in the parallel tuned circuit could adequately restrain operation of a relay during inrush periods, even though the relay would operate under a fault condition.

<u>Test of HDD relay</u>. In order to determine the effectiveness which electrical manufacturers have obtained in transformer protection, a General Electric, type HDD, Harmonic Restraint Relay was tested under magnetization inrush current conditions and simulated fault current conditions. As previously described, this relay has a series tuned circuit and a parallel tuned circuit, both tuned circuits being connected in parallel. As a further refinement, the current in the restraint coil is rectified by means of a full wave rectifier to

smooth the restraining pull on the armature and to permit application of similarly rectified current from the secondaries of the through current transformer. This transformer supplies restraint currents on a through current fault to give the relay its percentage differential characteristics.

In order to measure the transient currents in the tuned circuits, connections inside the relay case were broken and oscillograph mirror leads inserted in series with the operate coil, the restraint coil, the parallel tuned circuit, and the secondary of the relay differential current transformer. One trace shows the time of closure of the contactor to operate a circuit breaker in normal installations. The current in the primary of the relay differential current transformer is also shown.

The relay was first adjusted according to the manufacturer's instructions (3, pp. 12-14), and was then subjected to a symmetrical fault current, an asymmetrical fault current and a magnetization inrush current wave. The results are shown in Figures 9B, 9C, and 10B. They show that the operate time on a symmetrical fault current is approximately two and one-half cycles from the beginning of fault current until the contactor is firmly established in the trip position. The operate time for

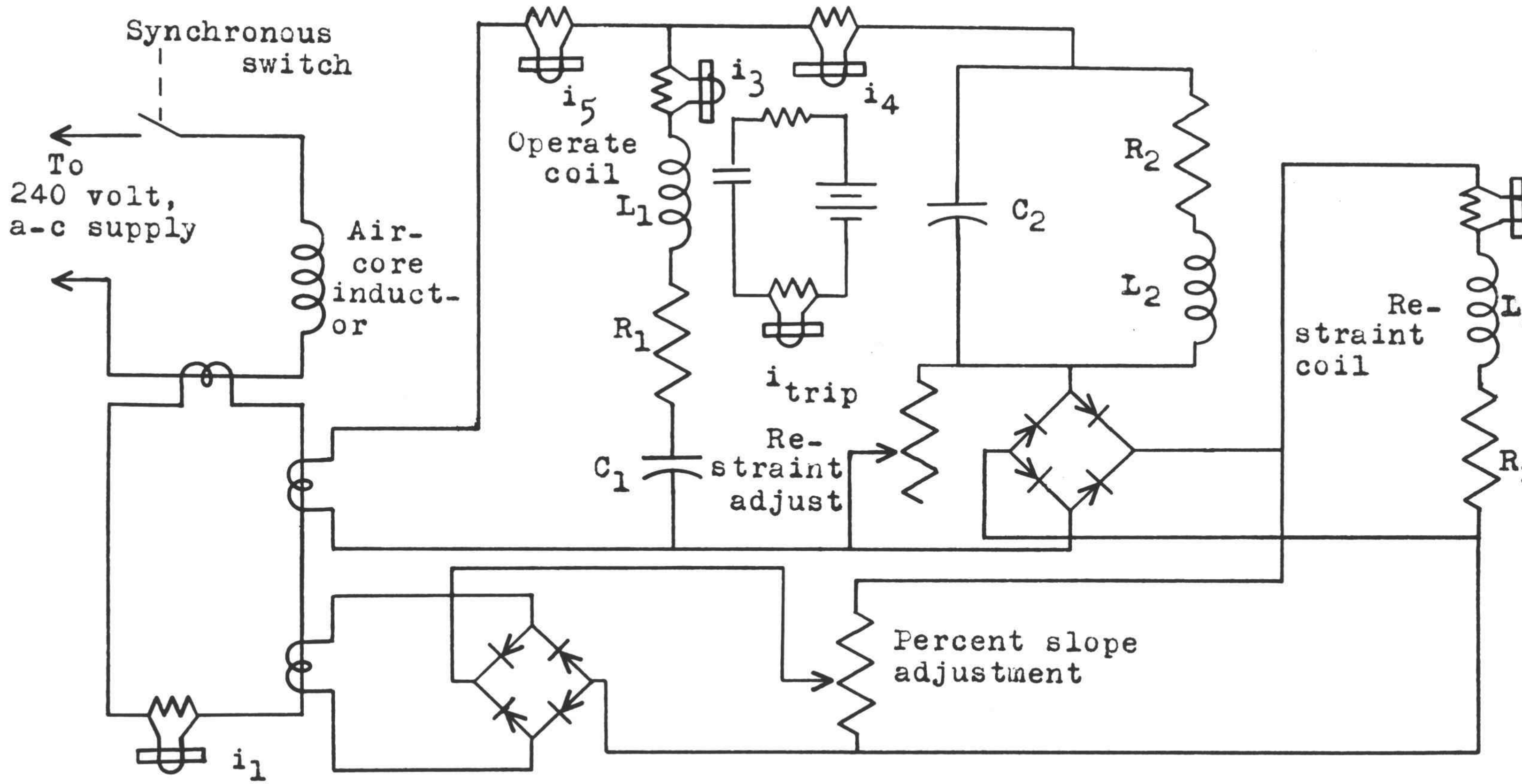


FIGURE 9A

Circuit for test of General Electric harmonic restraint relay under fault current.

L_1 = 2.15 henries	L_2 = 0.405 henries	L_r = 2.45 henries
C_1 = 2.88 microfarads	C_2 = 14.8 microfarads	R_r = 243 ohms
R_1 = 145 ohms	R_2 = 20 ohms	

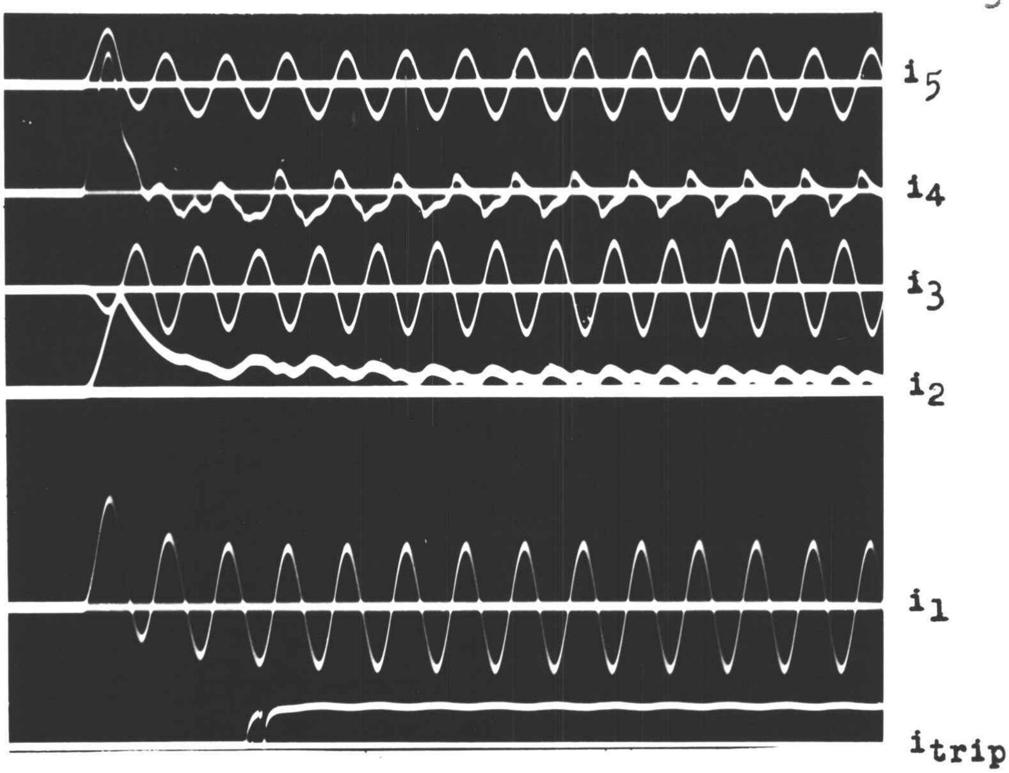


FIGURE 9B

Transient response of General Electric harmonic restraint relay circuits to asymmetrical fault current.

i_1 (peak) = 18.5 amperes
i_2 (peak) = 0.0966 amperes
i_3 (peak) = 0.166 amperes
i_4 (peak) = 0.264 amperes
i_5 (peak) = 0.373 amperes
i_{trip} (peak) = 0.5 amperes

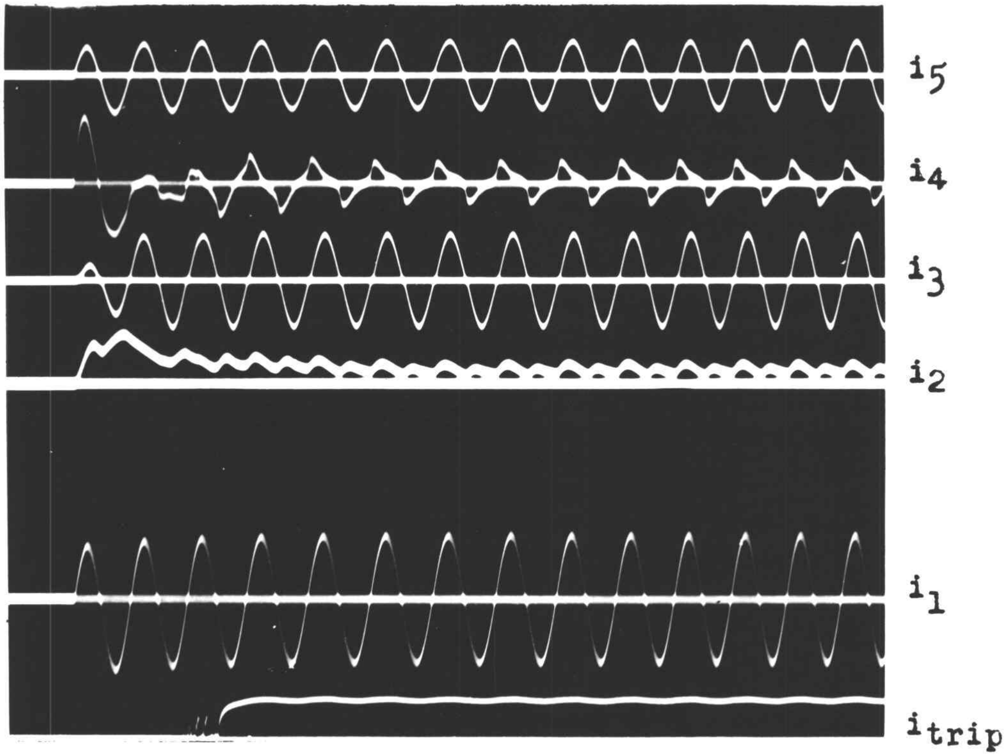


FIGURE 9C

Transient response of General Electric harmonic restraint relay circuits to symmetrical fault current.

i_1 (peak) = 10.6 amperes
i_2 (peak) = 0.0504 amperes
i_3 (peak) = 0.193 amperes
i_4 (peak) = 0.1245 amperes
i_5 (peak) = 0.2215 amperes
i_{trip} (peak) = 0.5 amperes

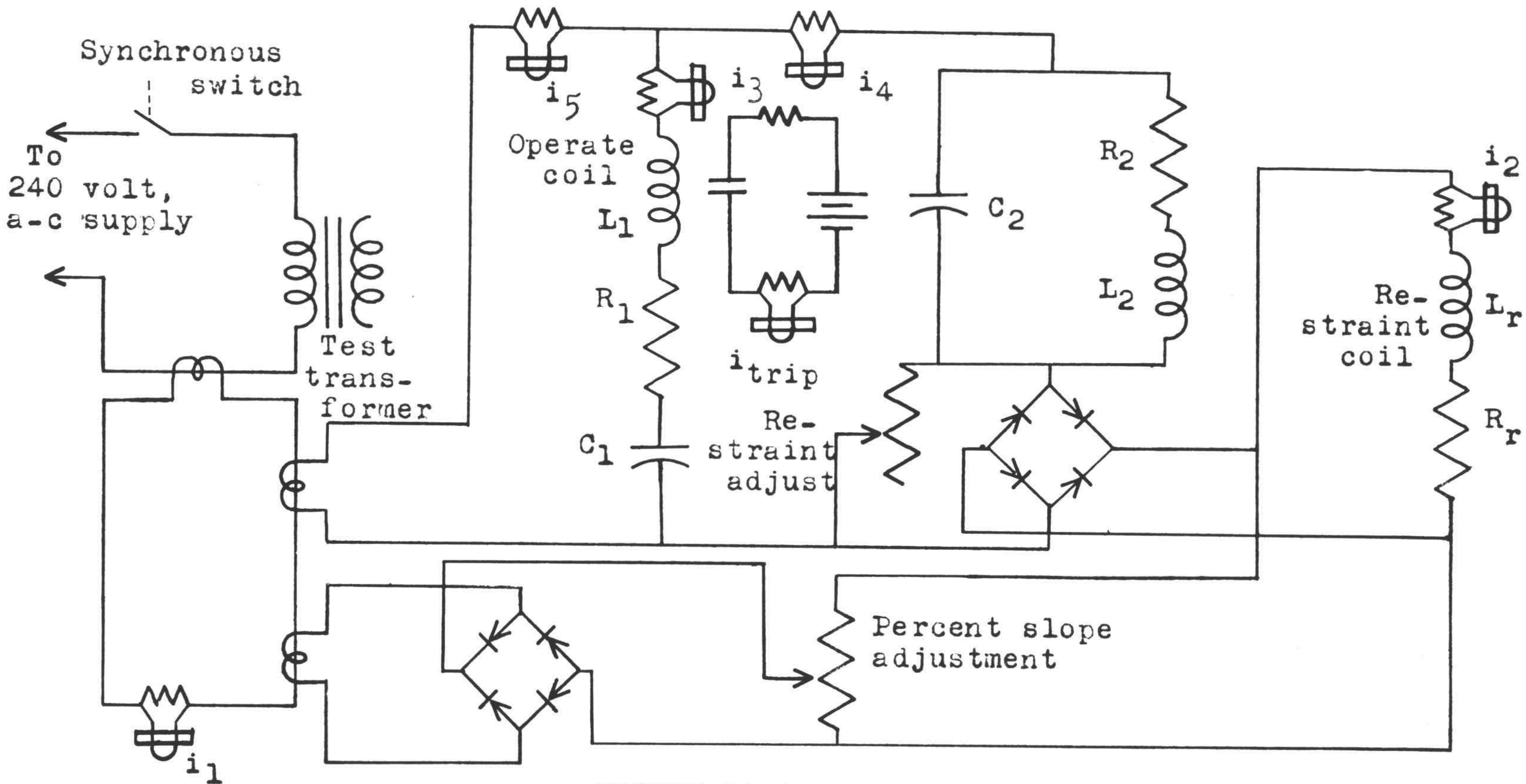


FIGURE 10 A

Circuit for test of General Electric harmonic restraint relay under magnetization inrush.

$L_1 = 2.15$ henries	$L_2 = 0.405$ henries	$L_r = 2.45$ henries
$C_1 = 2.88$ microfarads	$C_2 = 14.8$ microfarads	$R_r = 243$ ohms
$R_1 = 145$ ohms	$R_2 = 20$ ohms	

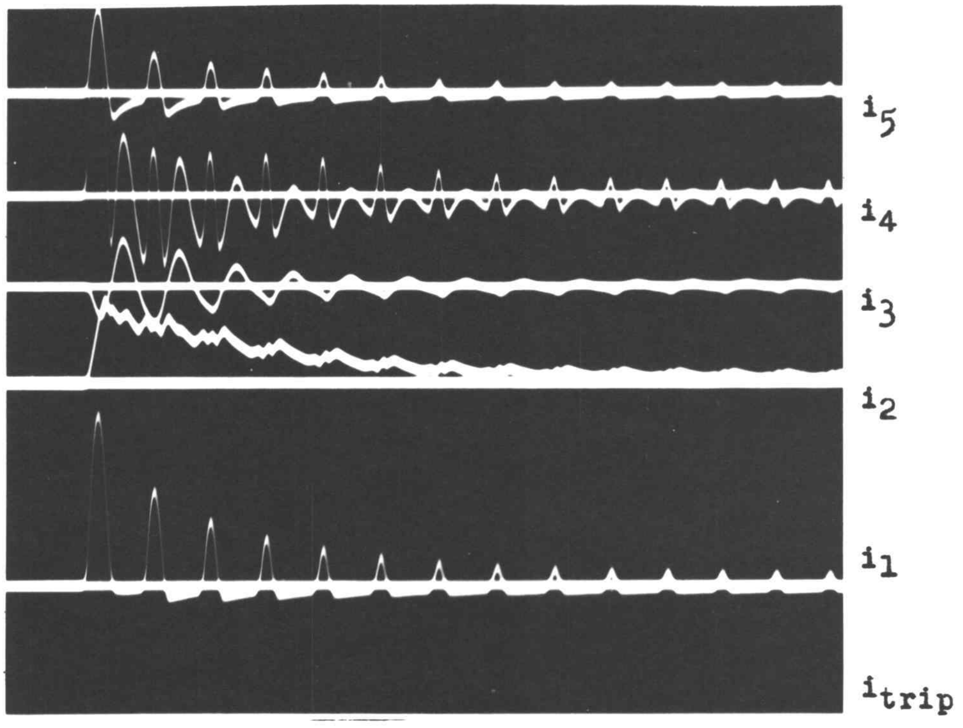


FIGURE 10B

Transient response of General Electric harmonic restraint relay circuits to magnetization inrush current.

i_1 (peak) = 32 amperes
i_2 (peak) = 0.092 amperes
i_3 (peak) = 0.212 amperes

i_4 (peak) = 0.574 amperes (approximately)
i_5 (peak) = 0.607 amperes
i_6 = 0 amperes

an asymmetrical fault is approximately three cycles. Relay operation was restrained for magnetization inrush current. There is some contact bounce before final closure on fault currents.

It is noteworthy that the relative magnitudes of the currents in the restraint coil and the operate coil are much the same in these oscillograms as in the previous oscillograms. Current flows principally in the restraint coil during the first cycle of impressed current, effectively restraining operation of the relay on both fault current and inrush current. This effect is shown very clearly when the restraint current for an asymmetrical fault is compared with that for magnetization inrush current. The maximum values of the restraint currents are seen to be very nearly equal, although, in the case of the fault current, the magnitude quickly falls off, allowing the operate coil to overcome the effect of the restraint coil.

Second harmonic test. It can be shown by Fourier analysis that the second harmonic of the 60 cycle fundamental is a large component of magnetization inrush current. This would indicate that a second harmonic pass filter might allow current to flow in it during magnetization inrush, and would block current flow for fault currents.

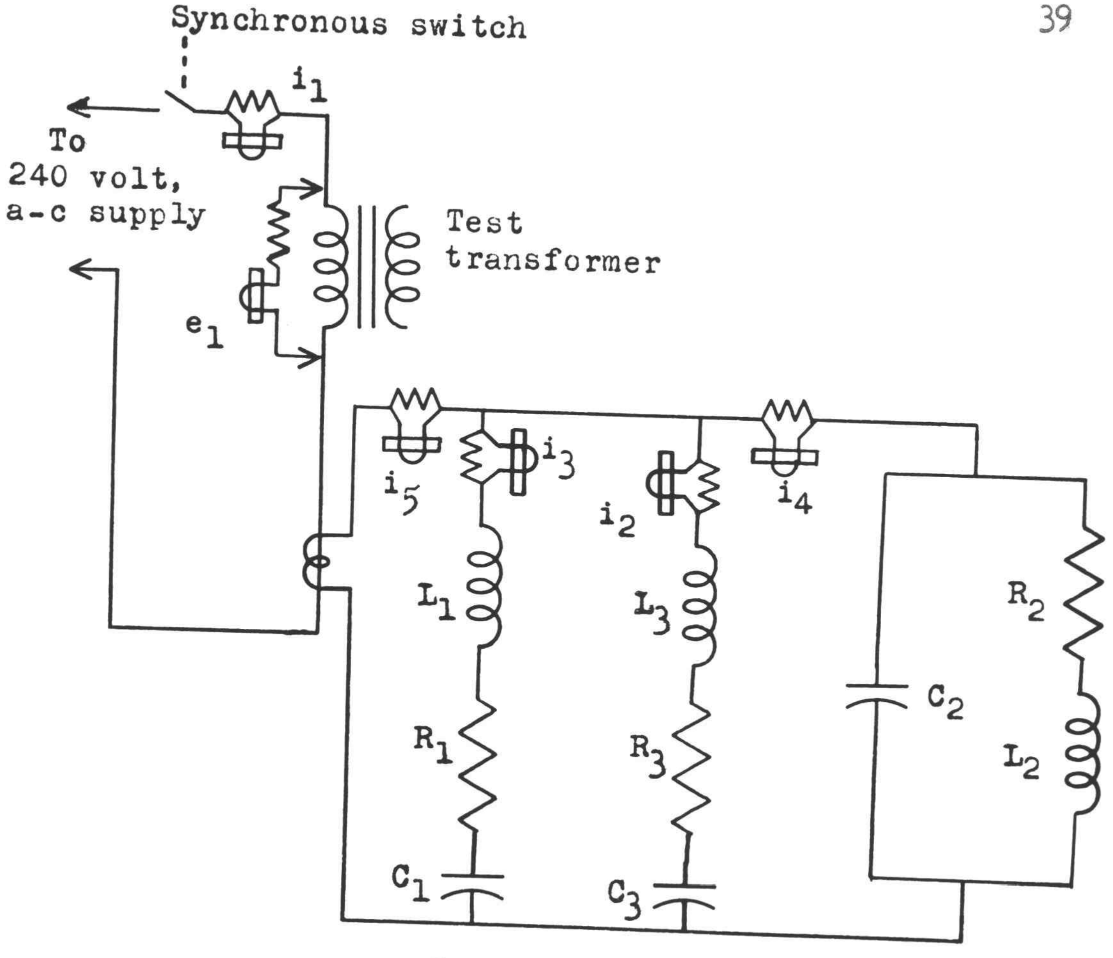


FIGURE 11A

Circuit for test of tuned circuits, including second harmonic pass circuit, under magnetization inrush current.

L_1 = 2.05 henries	L_2 = 0.83 henries
C_1 = 3.36 microfarads	C_2 = 8.45 microfarads
R_1 = 30 ohms	R_2 = 15.3 ohms

L_3 = 0.625 henries
C_3 = 2.81 microfarads
R_3 = 43 ohms

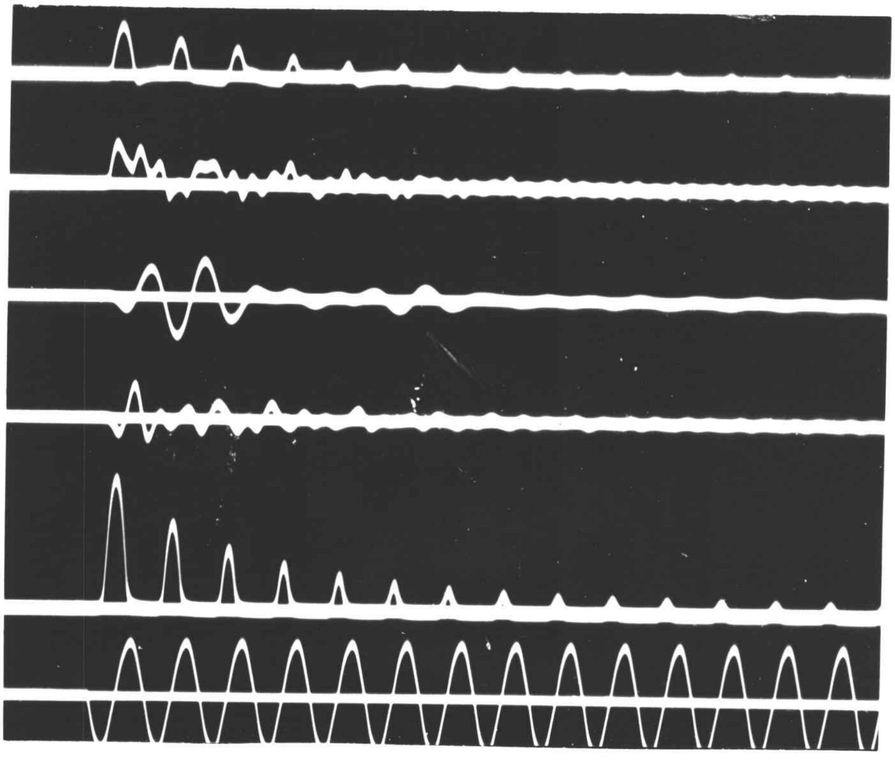


FIGURE 11B

Transient response of circuit of FIGURE 11A to magnetization inrush current.

e_1 = 247 volts (rms)
i_1 (peak) = 245 amperes
i_2 (peak) = 0.408 amperes
i_3 (peak) = 0.466 amperes
i_4 (peak) = 0.475 amperes
i_5 (peak) = 0.705 amperes

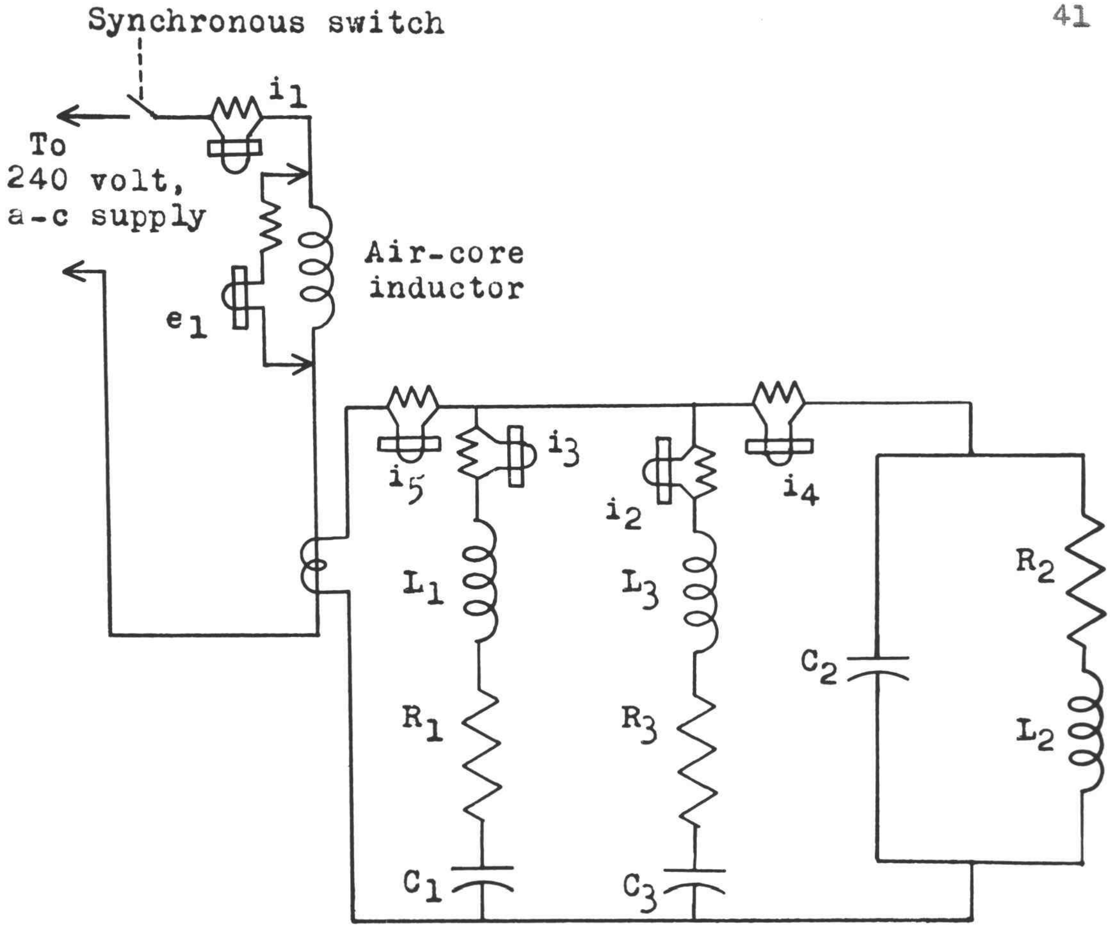


FIGURE 12A

Circuit for test of tuned circuits, including second harmonic pass circuit, under fault current.

$L_1 = 2.05$ henries
$C_1 = 3.36$ microfarads
$R_1 = 30$ ohms

$L_3 = 0.625$ henries
$C_3 = 2.81$ microfarads
$R_3 = 43$ ohms

$L_2 = 0.83$ henries
$C_2 = 8.45$ microfarads
$R_2 = 15.3$ ohms

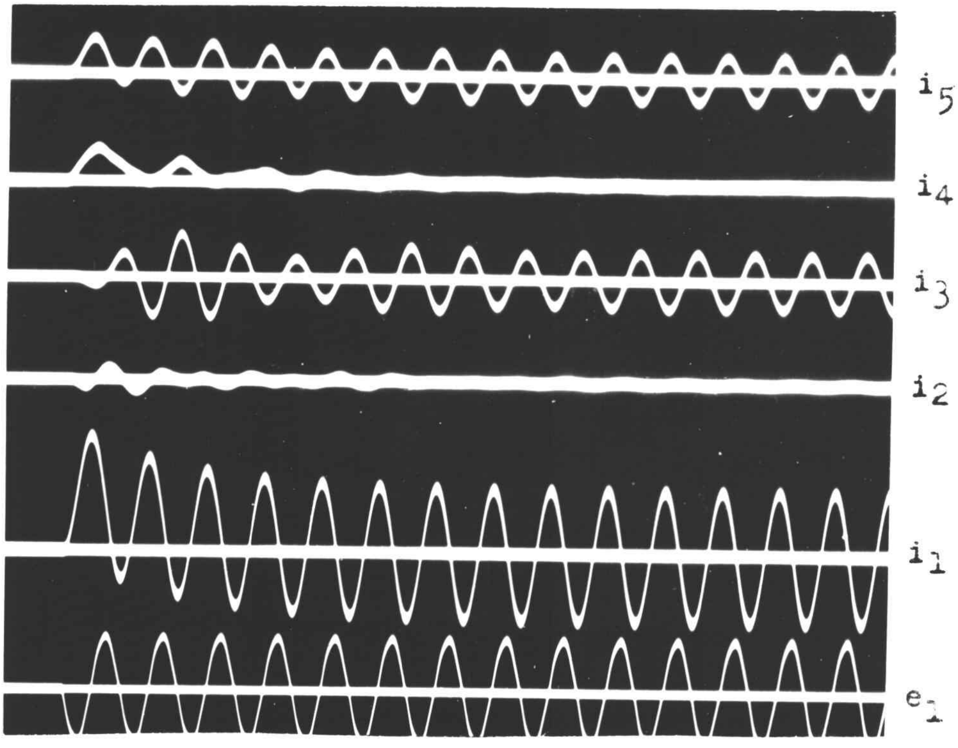


FIGURE 12B

Transient response of circuit of FIGURE 12A to asymmetrical fault current.

e_1 = 247 volts (rms)
i_1 (peak) = 214.5 amperes
i_2 (peak) = 0.179 amperes
i_3 (peak) = 0.49 amperes
i_4 (peak) = 0.40 amperes
i_5 (peak) = 0.529 amperes

A circuit was set up consisting of three tuned circuits in parallel. Two of these were series circuits, one tuned to 60 cycles, the other tuned to 120 cycles. The third was a parallel circuit tuned to 60 cycles. As shown on oscillograms 11A and 12A, the only time appreciable current was passed by the second harmonic series resonant circuit was during magnetization inrush current periods. This was the only circuit tested in this investigation which so clearly recognized the difference between magnetization inrush currents and fault currents. The peak current in the second harmonic branch of the test circuit during magnetization inrush was more than twice that obtained during the asymmetrical fault current period. Of equal importance is the fact that this difference appeared during the first cycle of applied current.

SUMMARY OF RESULTS OBTAINED. In this investigation some forty-six applicable oscillograms, including those illustrated here, were taken. The indication in all tests was that a circuit similar to the one used in the General Electric Harmonic Restraint Relay would be effective in preventing undesired circuit-breaker operation during magnetization inrush current periods. The tests also pointed to the inability of such a relay to operate in less than at least one and one-half cycles on a fault current.

The network containing three tuned circuits in parallel, one of the tuned circuits being resonant to the second harmonic frequency, was the only circuit tested which clearly differentiated between fault current and inrush current during the first cycle of impressed current.

CONCLUSIONS. The transient response of relay circuits is an important factor in the protection of power transformers, if high-speed operation on internal faults and restraint of operation on magnetization inrush current is required. The literature on harmonic restrained relays does not make this fact clear, although it is a fundamental limitation on the speed of operation of present harmonic restrained relays.

A circuit containing a second harmonic pass filter as well as a first harmonic offers possibilities for faster acting transformer protection. However, the results obtained in this investigation indicated no continuously available restraint current over the full period of magnetization inrush was present in this type of circuit. This very probably means that some kind of memory device, probably including electronic tubes, would be required to utilize the second harmonic scheme.

The problem of transformer differential relay protection as affected by magnetization inrush current has been defined. The use of certain resonant circuits in meeting the problem has been illustrated, and the way has been pointed for future work on this problem.

BIBLIOGRAPHY

1. American institute of electrical engineers, subcommittee on magnetization characteristics of transformers. Report on transformer magnetizing current and its effect on relaying and air switch operation. N.Y., 1950, 19p. (AIEE miscellaneous paper No. 51-113)

2. Corcoran, George F., Russell M. Kerchner. Alternating-current circuits. Second edition. N.Y., Wiley, 1943. 553p.

3. General Electric Company. Instructions, transformer differential relays with percentage and harmonic restraint, types HDD15A and HDD16A. Schenectady. Apparatus department. GEI-28764A. 15p.

APPENDIX A

CIRCUIT REQUIRED FOR SYNCHRONOUS SWITCH OPERATION

The schematic diagram of the synchronous switch connections used in this thesis investigation are shown in Figure 1. Switches S_3 and S_4 are motor-driven slip-ring segments, contact being made with the slip-rings through brushes. The slip-ring segment on S_3 covers an arc of approximately 15 degrees mechanical, and that on S_4 covers an arc of approximately 180 degrees mechanical. Switch S_3 was adjusted so that it opened just before S_4 closed. The slip-rings were driven at a speed of 180 revolutions per minute by a synchronous motor.

It was required that the synchronous switch close the circuit to the test transformer within plus or minus 10 electrical degrees (0.46 miliseconds of time) of the desired point on the voltage wave. Once closed, the circuit to the test transformer was to be maintained until opened manually by means of switch S_1. It was also required that the synchronous switch action be coordinated with the oscillograph so that the transient currents in the test network could be recorded on the oscillograph film.

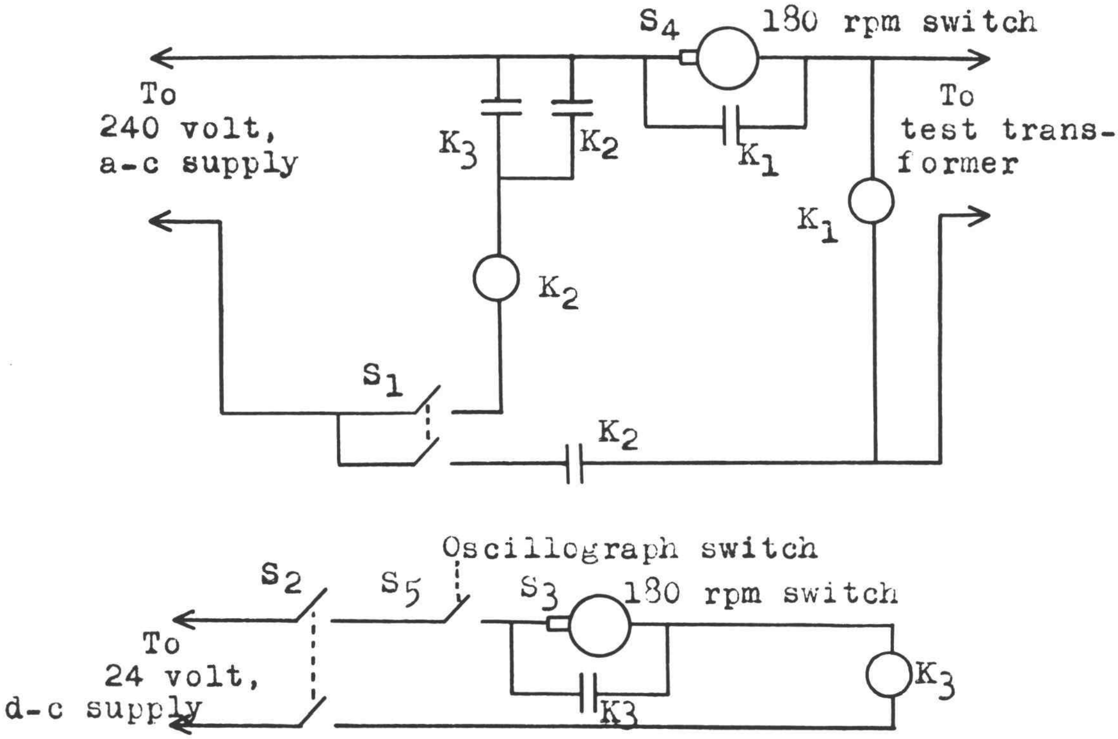
The sequence of operation was as follows:

1. S_1 and S_2 were closed manually.
2. S_5 was closed automatically by the

oscillograph shutter drive mechanism.

3. Relay K_3 was energized and remained energized because of its holding contact across S_3.
4. Relay K_2 was energized when K_3 was energized, and "armed" the synchronous switch so that the circuit to the test transformer was closed the next time S_4 closed.
5. When S_4 closed, relay K_1 was energized and remained energized to keep power on the test transformer until S_1 was opened manually.

The indication of the position of the brushes was obtained by replacing the test transformer with a cathode ray oscilloscope. The coil of relay K_1 was disconnected so that the 60 cycle voltage was applied to the oscilloscope signal input only during the time switch S_4 was closed. The point on the voltage wave at which S_4 closed was observed on the oscilloscope screen with switch S_4 turning at synchronous speed. Adjustment of the brushes on switch S_4 was made to cause the voltage wave to start on the oscilloscope screen at the desired point.



APPENDIX A
FIGURE 1

Schematic diagram of synchronous switch.