A LOGICAL ANALYSIS OF RELAY PARAMETERS

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PREFACE

In recent years the demand for reliable relays has been accelerated by a sizeable amount. Much of this is due to the increased complexity of the control systems now being used. The size of the relay has had to be decreased to meet the low weight specifications of air and space travel. At the same time the speed of operation has been increased many times, compared to relays of twenty years ago. All of these exacting specifications dealing with the speed and reliability of the relay have created many problems. Many of these problems confront the manufacturer while many others are faced by the application engineer.

At the present time there is no exact method of analyzing the relay to give the answers to many of these problems. The methods used in analyzing the relay are analytical and graphical. The methods used in testing the relay are mostly experimental and sometimes destructive. The problem of checking the sealed relay for internal adjustments, air gap, residual gap, and spring tensions without a destructive test seems to have created a need for a new type of analysis. This thesis is associated with this specific problem and is directed toward using a different method of analysis. This method is not new to many systems but is new to this type of relay analysis.

The author wishes to express his sincere appreciation to Professor Charles F. Cameron, who is the Technical Advisor to the National Association of Relay Manufacturers, for the guidance and support so generously given in the preparation of this thesis. He is also indebted to Assistant Professor D. D. Lingelbach for his valuable assistance. Also, the author is indebted to the personnel of the Office of Engineering Research for their generous help in constructing the manuscript.

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CHAPTER I

INTRODUCTION

Since the time when electricity became available for serving man, many uses and devices have been discovered. One of the first uses of this new source of energy was the Electro-Mechanical switch, commonly called a relay. Since the first crude devices were made, the demand for these switches has increased by a staggering amount. The size, shape, and purpose of these switches today hardly resemble those of fifteen or twenty years ago.

Since relays were among the first devices to appear with the electrical age it would seem logical that their performance would be one of the easiest to analyze with accurate results. Unfortunately this is not the case. To know how an electro-mechanical switch will perform by inspection of its electrical and mechanical parameters is still quite far from a reality. "Performance by Inspection of Parameters," is meant in the same way that a lumped or distributed circuit of linear parameters (i. e. resistance, inductance, capacitance) can be analyzed by circuit theory with a high degree of accuracy. This situation is by no means peculiar to electro-mechanical switches alone, but exists in many components and systems encountered and used by engineers. Most new devices discovered, however, make rapid progress between the time of discovery and the time of wide application. This has not been as true with the relay as with many other components or systems.

Almost all analyses of relays and other electro-mechanical devices are still graphical with little generality existing between different circuits. However, the analysis of the steady-state conditions of relays has been investigated quite extensively, as compared to transient or dynamic conditions, and graphical as well as workable formulas for desired quantities cover a great many cases.[1] The transient or dynamic conditions, however, have not been evaluated analytically and only a few graphical methods for simple cases have been outlined.[2] There are probably two main reasons for the lack of transient analysis in electro-mechanical devices. The primary reason, the non-linearity of the electro-mechanical devices, has hampered many components and systems from analysis by analytical methods. This non-linearity is present and acute during the transient period of a relay. Also, not much need arose for transient condition evaluation before modern circuits involving relays imposed high speed action upon the relay.

Although the relay has not been reduced to an equation with which

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[1] Roters, Electro-Magnetic Devices, John Wiley & Sons, Inc., New York, New York, 1941, 5th ed., p. 84.

[2] Ibid., p. 363.

to work, it has probably become as widely used as any other single type of component excluding the vacuum tube. The reason for its wide use with few precise methods of analysis is probably due to the services it can perform for a circuit, that can be analyzed, without actually being connected in that circuit. This condition was easy to fulfill as long as space, power, and speed of action were not important requirements of the circuit. However, in the last ten years, which is now commonly called the missile or electronic age, these factors have become increasingly important and in some cases are the criteria governing design. This means that in many cases the relay needs to be inserted in the circuit, (driven by the circuit), in order to save space, weight, or power. There are many other problems similar to those mentioned which have imposed a demand for exacting performance upon the relay and the relay industry. These increasing demands have pushed the cost of manufacturing relays and similar electro-mechanical devices to a high level because the experimentation and testing of relays, (which is essentially the only reliable method of insuring satisfactory performance), have become increasingly costly. The problems involved in the manufacturing and use of relays have become so great in the last ten years that the relay industry and other interested groups have formed an association called National Association of Relay Manufacturers to advance the knowledge of these devices.

There are many systems today that cannot be synthesized by any one method. The airplane, missile, and complex control systems are good examples. These types of systems are usually broken down into smaller units which can be developed using the conventional equations and methods developed from the physical relationships involved. The task then requires a logical method of connecting these individual units so that the desired result is accomplished.

The problem of analysis involves the same technique as synthesis, since it is the testing of a system after the system has been assembled. This work is directed toward a method of analyzing a relay by breaking it up into smaller systems that can be analyzed by methods already developed. After this is done the results of the individual analyses can be reconstructed to give information about the relay as a whole.

The relay usually is not thought of as a complex system, but as a device that is simple in principle and construction. Actually the relay is quite complicated. This is especially true during the transient period of a relay. The number of parameters that affect the operation of a relay make the task of analysis by the conventional methods seem insurmountable.[3] This becomes even more of a task when the relay is sealed and measurements of the system inside cannot be made.

With the sealed relay in mind, the parameters influencing the performance of the relay have been associated with certain parts of the

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[3] This would involve the simultaneous solution of all six equations needed to describe the relay.

system. The effects of changing different parts of the system are then analyzed separately by use of the transient coil current. The boundary conditions that separate the different parameters can be established from the equations of the relay and verified by the transient coil current trace.

The parameters are then related together through a logic network based on the conclusions of the individual parameter analyses, and their influence upon the transient coil current.

CHAPTER II

TRANSIENT THEORY OF A RELAY

General Equations of a Relay

Many devices used by engineers can be described by analytical expressions. Most devices, however, do not require more than one system of physical units to describe the parameters involved in the device. There are some devices which do require more than one system of units to describe them and one of these is the electro-mechanical relay. Using Fig. (1) to represent the relay, the general equations of the circuit are:

$$E = iR + n\frac{d\phi}{dt} \qquad \text{(A)}$$

1

$$T = I\frac{d^2\theta}{dt^2} + k\frac{d\theta}{dt} + h\theta \qquad \text{(B)}$$

E = Electro-motive Force
i = Current in the Coil
R = Electrical Resistance of Circuit
N = Number of Effective Turns Linked by Flux
ϕ = Flux
T = Torque
I = Moment of Inertia of Moving Function Acting on Armature Parts
k = Resistant Coefficient of Angular Velocity
h = Effective Spring Constant
θ = Angular displacement

where (A) represents the electrical circuit and (B) is the equation of

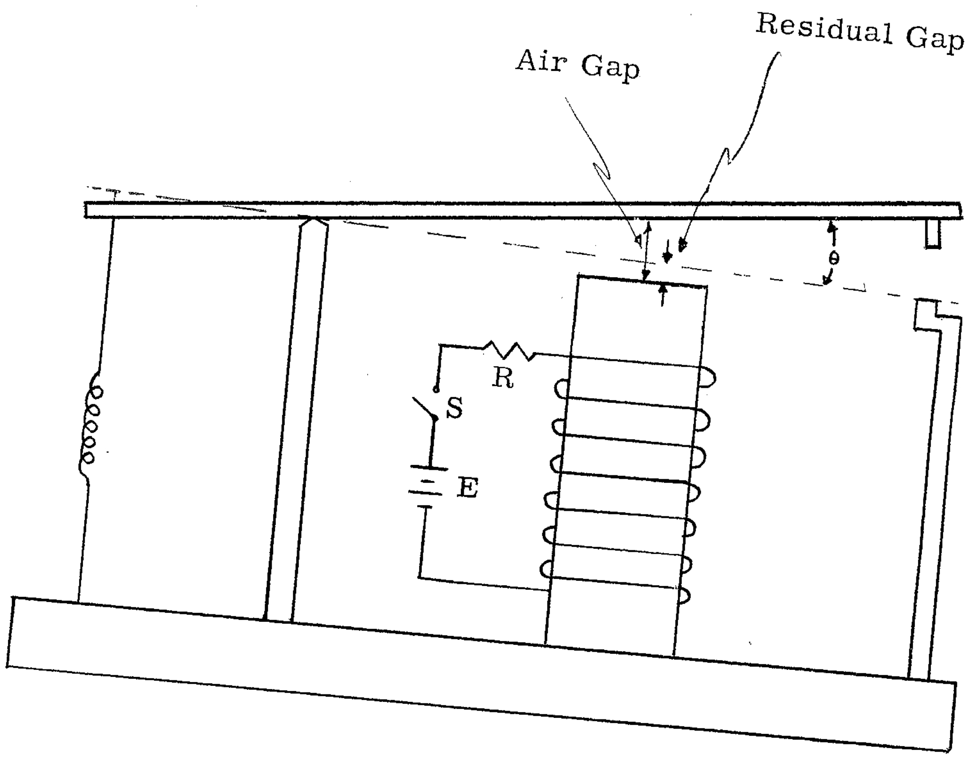

Fig. 1. Basic Diagram of a Relay

motion for the mechanical circuit.

The exact equations of the mechanical system involve the rotational quantities of torque, moment of inertia and angular displacement. For most relays however, the angle of movement is so small that the assumption $\theta = \tan\theta$ is well within engineering measurement standards. Since the solution of these equations is not attempted in this paper the system will be converted from polar form to rectangular form. This could be done exactly or approximately by the assumption above. The only difference in the form will be in the quantities mentioned above. They will be converted to force, mass, and linear displacement.

This converts the equations in (1) to:

$$E = iR + n\frac{d\phi}{dt} \tag{1a}$$

$$F = M\frac{d^2x}{dt^2} + k_1\frac{dx}{dt} + k_2x \tag{1b}$$

M = Mass of Moving Parts
F = Force Function Acting on Armature
k_1 = Resistant Coefficient of Velocity
k_2 = Effective Spring Constant
x = Displacement

If the coil on the relay were air core instead of iron core, the electrical equation could be written in the form of

$$E = iR + L\frac{di}{dt} \tag{1c}$$

which simply means that the flux (ϕ) and current (i) have a linear relationship when the iron is not present.

Unfortunately, most relays are iron cored so that equation (1a) is the exact equation and the flux (ϕ) is related to (i) by a variable coefficient u, called permeability. The force (F) in equation (1b) also is a function of ϕ which makes it a nonlinear equation. Also equations (1a) and (1b) have different forms depending upon whether the switch (s) is just being closed or opened.

Specific Equations of a Relay

Until the armature starts to move or operate, equation (1b) is identical to zero since (x) is zero (x being the dynamic displacement). To see when equation (1b) becomes not equal to zero the flux force (F) must be examined to see when the flux (ϕ) becomes great enough to overcome the bias force of the spring.

$$F = k\phi^2 \geqq \text{bias force} . \qquad (2a)$$

When this condition exists, the armature starts to move and the mechanical circuit reflects back into the electrical circuit until the armature strikes the pole piece. Until the armature starts to move and after it has stopped, the equation involved in the transient is the electrical equation (1a) and if the magnetic circuit is not saturated then good approximations can be made by assuming that the flux ϕ is a linear function of (i) which gives equation (1c). This is often done in analyzing electro-magnetic devices operating in the region shown in Fig. 2.

When the armature starts to move, equations (1a) and (1b) are both unequal to zero and the solution of the relay analytically during

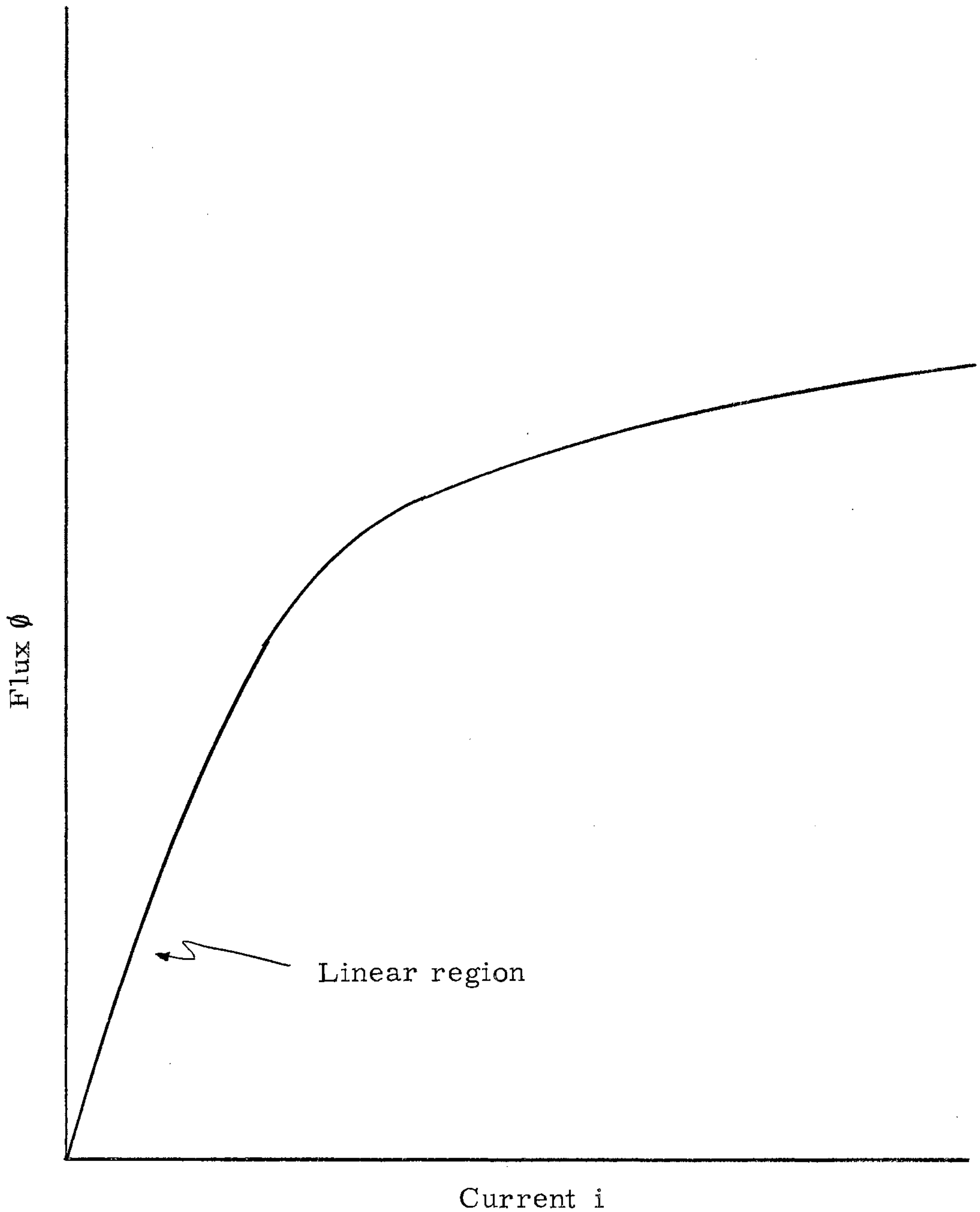

Fig. 2. A Typical Flux vs. Current Curve

this period requires the simultaneous solution of the two equations:

$$E = iR + n\left(\frac{\partial \phi}{\partial i}\frac{\partial i}{\partial t} + \frac{\partial \phi}{\partial x}\frac{\partial x}{\partial t}\right) \tag{1d}$$

$$k\phi^2 - \text{bias force} = M\frac{d^2x}{dt^2} + k_1\frac{dx}{df} + k_2 x \,. \tag{1e}$$

When the relay is in steady state operation and switch (s) is opened, a situation similar to the operate conditions takes place. Until the armature starts to move the force equation (1b) is identical to zero and no movement can take place until the dynamic force caused by the magnetic flux diminishes to a value equal to or less than the restoring spring force. This can be stated mathematically by:

$$F = k\phi^2 \leqq \text{restoring force} \,. \tag{2b}$$

During the period that the armature is stationary the electrical equation can be used to evaluate the relay. Since (E) is zero, equation (1a) becomes:

$$0 = iR + n\frac{d\phi}{dt} \,. \tag{1f}$$

If the relationship between ϕ and (i) is known to be linear, (1f) is an ordinary differential equation of the first order. It should be mentioned that if the relationship between ϕ and (i) is known to be linear on the operate condition, until the armature starts to move, this may not be the case for release since Fig. 3 shows that the ϕ-i curve is different since the magnetic path is different. Even if the relationship between (ϕ) and (i) is linear the constant that relates the two will necessarily have a different value on open air gap and closed air gap.

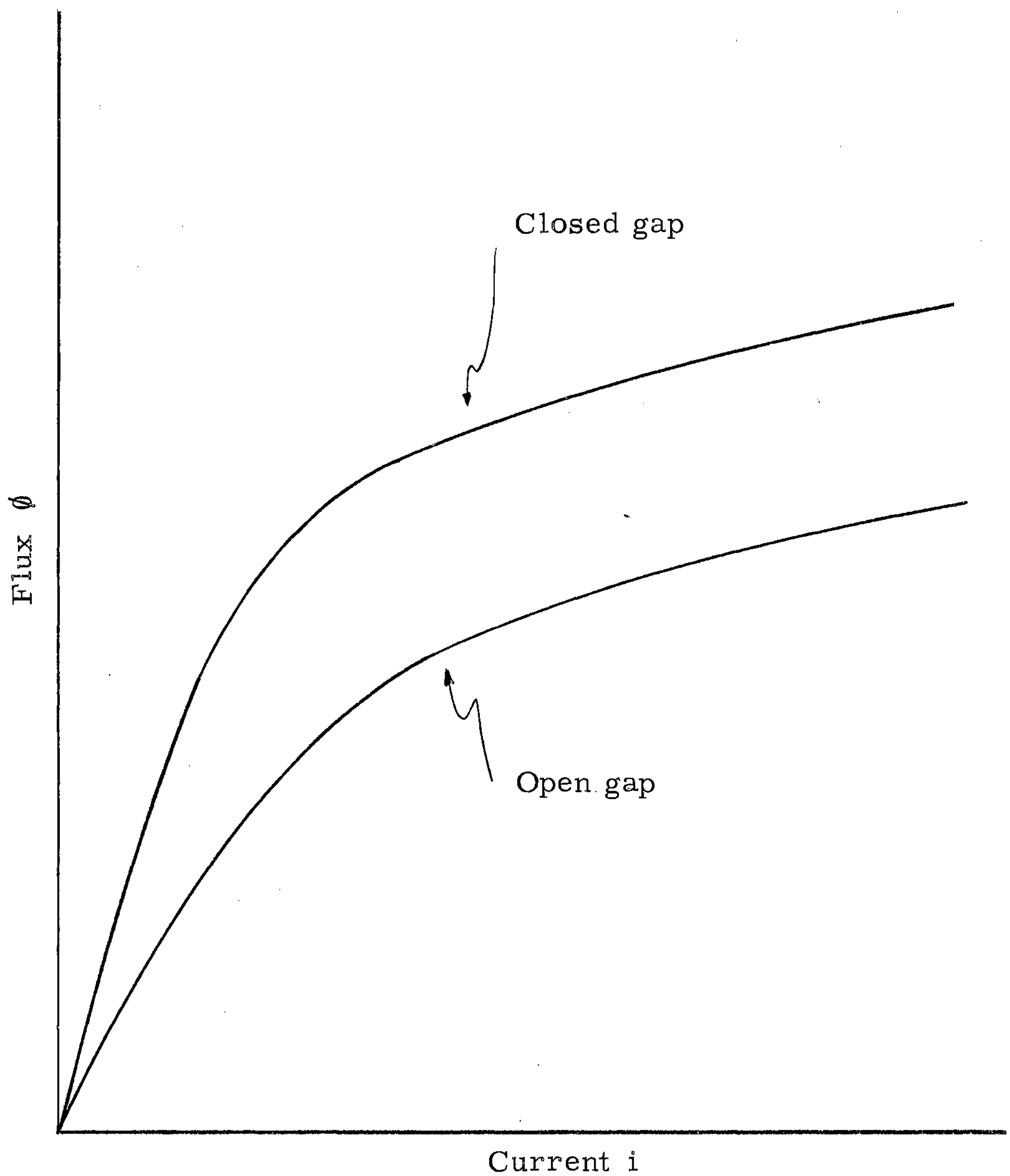

Fig. 3. A Typical Flux vs. Current Curve
for Open and Closed Air Gap

This means that two (ϕ) vs. (i) curves would be needed to analyze the transient periods of a relay for operate and release.

When the armature starts to move on the release condition it necessitates the simultaneous solution of equations (1a) and (1b) for evaluation of the relay during this period. The forms of equations (1a) and (1b) during this period are:

$$0 = iR + n\left(\frac{\partial \phi}{\partial i}\frac{\partial i}{\partial t} + \frac{\partial \phi}{\partial x}\frac{\partial x}{\partial t}\right) \tag{1g}$$

$$\text{bias force} - k\phi^2 = M\frac{d^2x}{dt^2} + k_1\frac{dx}{dt} + k_2(x - x_0)\,. \tag{1h}$$

However, some authors neglect the dynamic force on release since the dynamic flux is usually such a small value when the armature starts to move.

Problems Involved in Solution of the Specific Equations of a Relay

Many of the problems that would be encountered in the solution of the specific equations of a relay on operate and release are self-evident. Some of the more obvious problems are: the non-linear relationship between ϕ and (i), the third degree equation of force, finding the relationship of $\phi = f_1\ (i, x)$ and force $= f_2\ (i, x) = \psi(\phi)$. Besides the mathematical difficulties involved there are many physical problems such as: coefficient of friction, coefficient of velocity, and the amount of leakage flux present for any type construction. Some of these problems can be overcome by intelligent assumptions that eliminate some of the difficulties. Even with these simplifying assumptions, however, total solution of the relay must be evaluated by difference equations or graphically. Unless the device is of a shape and construction such that the leakage flux is small, the total solutions are complex.[1] Also these analyses would only be accurate for the known set of conditions such as temperature, applied voltage, discharge resistance, etc.

These are some of the reasons an experimental approach to evaluation of relay transients was started.[2] This approach afforded a simple method of studying the effects, on the coil current trace, caused by the different relay parameters.[3] From this type of analysis very interesting and important phenomena can be observed and analyzed in a short length of time. It is from this type of analysis that the results and conclusions used in this thesis were made.

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[1] Roters, Electro-Magnetic Devices, John Wiley & Sons, Inc., New York, New York, 1941, 5th ed., p. 2.

[2] Cameron, C. F. and Lingelbach, D. D., Relay Characteristics, Relay Conference, 1956.

[3] See Appendix A for the method used to record relay transients.

CHAPTER III

RELAY PARAMETERS

When steady state operation of a relay is considered, there are not many parameters that can influence the operation. For steady state the relay is either closed or open and the amount of force holding the relay closed or open is the only parameter that need be considered as far as satisfactory operation is concerned. The parameters influencing this situation are: (1) supply voltage, (2) magnetic force for rated current, and (3) restoring forces. These parameters can be varied quite easily, analytically or graphically, to give the desired results and most relays can be made to meet the steady state specifications without much difficulty.

Steady state performance tells very little about the relay, however, since relays of the same type can have identical steady state performance, but be very different in many other respects. These differences in the supposedly same type relays show up in the transient period of the relay. When speed of operation is involved, these differences can be very important. Also many of the relays used today are sealed after construction. This means that if the relay is not adjusted to meet the specifications before sealing, the relay is useless from the consumer's standpoint. Almost all of the parameters that affect the speed of operation of a relay affect the transient coil current of a relay.

Parameters Affecting the Transient Operation of a Relay

Depending upon the type of relay and who is interested in the relay, there are parameters that can be classified as controllable or non-controllable. For instance, if the relay is sealed, the manufacturer can adjust the springs and air gap, but the consumer cannot. However, if the relay is not sealed, both the consumer and manufacturer can make internal adjustments on the relay.

Since this is true, the parameters will not be classified as to the controllability. Also, many of the parameters have a greater influence on the speed of operation and the transient coil current than others, but the importance depends upon how the relay is to be used and what parameters are most likely to be critical. Therefore, the parameters cannot be classified as to importance.

The parameters influencing the transient operation of a relay are:

A. Driving force
B. Spring bias
C. Magnetic circuit
D. Electric circuit
E. Mechanical structure
F. Temperature
G. Shock
H. Induced flux

Driving Force: Only D. C. power supplies are being considered in this discussion since for alternating voltage the transient operation is determined to some extent by the portion of the voltage cycle during which the relay is energized. There are many types of D. C. power supplies varying from extremely low impedance regulated supplies to high impedance non-regulated supplies. Some of these different type driving forces have been investigated.[1]

The results show that the speed of operation changes greatly depending on the impedance of the driving force. The release condition as well as the operate condition is only affected by the value of steady state current when the battery and its internal impedance are disconnected. Also the driving force partly determines if the relay is saturated.

Spring Bias: The spring bias can best be separated into two types, restoring springs and contact springs. Some relays have both, while some have only one type or the other. The effect of varying the spring biases shows a noticeable influence on the transient coil current. Some of these conditions have been investigated.[2] Both the operate and release conditions are influenced by the spring biases. The two conditions, operate and release, can be influenced separately or

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[1] Cameron, C. F. and Lingelbach, D. D., Evaluation of Relay Transients, Relay Conference, 1958.

[2] Ibid.

simultaneously by the spring force. This depends on the type of springs present and the adjustments of the mechanical structure. This work assumes that any change in spring bias influences both the operate and release conditions.

Magnetic Circuit: The magnetic circuit is very important and after the relay is constructed only a small portion of the circuit can be changed. This portion is the air gaps for open and closed positions of the armature. The material and construction used in building the magnetic circuit determine whether the core will become saturated under rated voltage. If the core becomes saturated, then the relationship between ϕ and i becomes non-linear.

The most variable parameters of the magnetic circuit are the open and closed air gaps, usually called air gap and residual gap respectively. Both of these air gaps have an influence upon the transient operation, and affect the transient coil current. Other factors such as shorted coil turns influence the magnetic circuit also.

Electrical Circuit: The electrical circuit of a relay is partly determined by the manufacturer and partly by the consumer. The manufacturer predetermines the coil circuit in design. Therefore, the resistance and inductance of the coil are determined. However, the circuit in which the relay is operated also plays an important role in the transient operation. The driving force has already been discussed. Other components in the circuit such as resistance, capacitance and inductances can have a marked effect upon the speed of operation of a relay.

The electrical circuit always has two different conditions, the operate circuit and the release circuit. External resistance in series with the coil on operate has been investigated.[3] The release condition also is affected by the external circuit components and can change the release time by as much as one hundred percent. The transient coil current indicates this change.

Mechanical Structure: The mechanical structure on a sealed relay cannot be changed after the seal is made. It is important to know then how much the armature and spring structures affect the operation of the relay during the transient period. The spring spacing usually is used to make the contacts close in the specified time. Also, on multiple contact relays, the spring spacings are usually the parameters used to set the sequence of closing. Since this has to be done by hand there is usually a big variation in the spring bias caused by the contact springs. In many cases the spring settings cause the restoring force to vary considerably, which changes the release time of the relay.

Overtravel and bounce are determined by the mechanical settings of the springs. Unsealed relays can be examined for these conditions and adjusted.[4] Sealed relays, however, can only be inspected

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[3]Ibid.

[4]Foster, J. Vance, "How to Adjust Relays for Smooth Operation," Industrial Laboratories, Vol. 10, Number 5, 1959, p. 93.

externally to the mechanical structure. The consumer then needs a method for detecting these conditions to see if the relay should function properly without having to destroy the sealed relay. The transient conditions that can be recorded appear to afford a method of determining some of these mechanical adjustments.

Temperature: Temperature is a parameter of a relay as it is for practically all physical devices. There is hardly a parameter of the relay that is not changed by temperature. Since this is true, it makes the effects of temperature on the transient operation of the relay hard to predict. Every relay, depending upon the type, is affected to a different degree by each of its parameters. Temperature influences each one of the parameters to a different degree. Therefore, the prediction of a relay performance at a different temperature would depend upon the combination of the two sets of variables.

Certain parameters such as resistance and spring constants can be determined with changing temperatures. If they were the only parameters assumed to change with temperature, a prediction could be made based on what happened when these two parameters were changed independently of temperature.

Shock: Shock is mentioned here only because it can be classified as a parameter. The effects of shock on a relay during the transient period would require an infinite number of conditions. Shock tests are now run on the steady state conditions of a relay because as mentioned above, the results would be too inconclusive if tested during the transient period.

Induced Flux: Externally induced flux usually is present on relays that have heavy current carrying contacts. This condition has been explored to some extent.[5]

The parameters affecting the transient conditions of the relay have been discussed separately. Contrary to the discussion, however, the parameters do not act separately. Methods have been developed to adjust mechanical structure and compensate for the interaction.[6]

This thesis, however, is directed toward the sealed relay and the problem of examining these sealed relays. If a general procedure of this type were available, it would afford a fast inexpensive method for the consumer who buys relays in large quantities to check relays and see if the manufacturer was putting undesired features in the relay. Also the manufacturer could check his relays before they were sealed and make the necessary adjustments.

Parameters to be Analyzed by Transient Coil Current

To be able to evaluate any change in relay parameters by analyzing the transient coil current is a very high ultimate goal. This

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[5] Grobowski, Z. V., and Martin Abramovage, "Evaluating RF Interference of Relays," Jansky & Baily, Inc., Washington, D.C., Relay Conference, 1959.

[6] Foster, J. Vance.

thesis takes just a portion of the total problem with the hope that it can be included in the total solution by this type of analysis.

The parameters to be evaluated in this thesis are important ones but not necessarily the most important. There are four parameters involved in this work. For a sealed relay, three of the parameters, spring bias, residual and air gap, can be called non-controllable. These three are to be used in the final analysis. The other parameter, discharge resistance, can be called controllable to the extent that any external discharge resistance can be placed in the electric circuit.

The reasons for choosing these parameters from the total number of variables are: (1) the users of sealed relays have absolutely no control over spring bias and magnetic circuit; (2) the other parameters such as temperature and shock would require test equipment that is not available at this time, and (3) the relationship between discharge resistance and time can be combined in an empirical formula which can be used to set the release time.[7]

Method of Analysis

The procedure to be followed in this analysis is analogous to a switching circuit with four variables, Fig. 4, represented by relays A, B, C, D. Assume that the input represents the coil current trace

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[7]Sandia Corporation, Interim Report, covering period from 1 April, 1959 to 31 May, 1959, Purchase Order 15-6957, Oklahoma State University, Section V, p. 1.

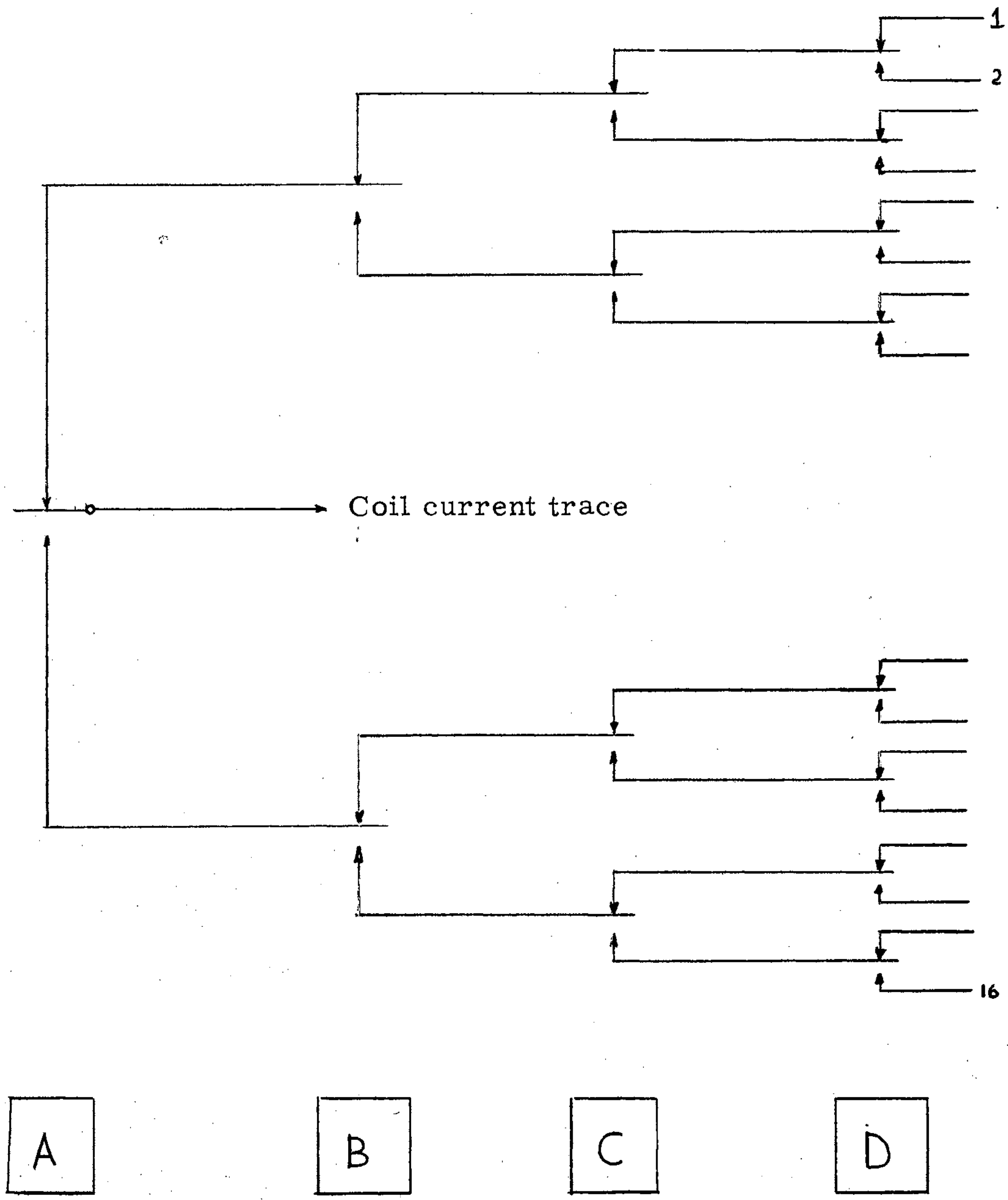

Fig. 4. Switching Circuit Tree

and relays A, B, C, D, represent the variable parameters that affect the coil current trace. Any one of the four relays is operated any time its peculiarity is recognized in the coil current trace. The output will always be different depending upon what variables are present. For example, line (1) represents the standard relay. Line (2) is on whenever the variable D has affected the trace. This illustration also helps indicate the complexity of problems that involve more than one or two variables. If eight variables could be detected simultaneously, the analogous switching arrangement would contain 2^8 outputs instead of 2^4 as shown.

Following this type of logic in the analysis, the procedure would be to find the identifying features of each variable. Then combine these variables and see if the individuality of each variable is still recognizable. If this could be done, a simple logical procedure would be available for evaluating a relay by just recording the transient coil current on operate and release. The problem becomes more involved when determination of how the variable changed, is attempted. This is true since the variable can change in any of two directions relative to the standard (increase or decrease), or remain unchanged.

CHAPTER IV

INFLUENCE OF PARAMETERS ON THE TRANSIENT COIL CURRENT

Air Gap During Operate

Fig. (5) shows a typical transient coil current trace (i) for the operate condition of a relay. The armature motion (x) is shown also to indicate the cause of the discontinuity in the current trace. The particular shape of the transient coil current trace of any relay is dependent upon the parameters discussed in the preceding chapter.

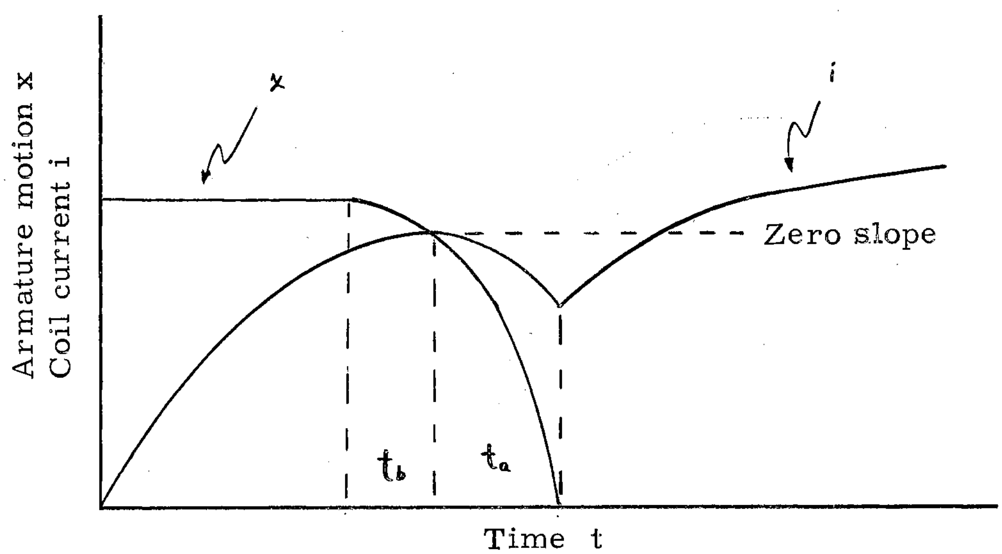

Fig. 5. Typical Transient Coil Current Trace and Armature Motion on Operate

Assume that all of the parameters are fixed with the exception of the four variables mentioned, spring bias, air gap, residual gap, and discharge resistance. The equations of the relay can be examined to see why the current trace has the general shape indicated in Fig. (5).

Until the armature starts to move, indicated by time (t_a), the only equation of interest is the electric equation (1c). There are three unknown conditions in this equation. Solving for current gives:[1]

$$i = \frac{E}{R}\left[1 - e^{\frac{-rt}{\alpha_o}}\right] \qquad (4a)$$

R = Coil Resistance and Shunt Resistance
E = Power Supply
α_o = Effective Inductance of Circuit

If the value of pull in current and the time the armature starts to move were known, the effective inductance of the open air gap magnetic circuit would be known. This effective inductance for any relay should not change unless the air gap, coil windings (heel gap), or the magnetic circuit material are different. Since the coil and the magnetic material are assumed to be constant "α_o" should be a parameter to indicate changing air gap.

To see if equation (4a) can duplicate the build up coil trace for a given relay, Fig. (6) gives the actual coil current trace for a relay. To evaluate "α_o" a value of current can be selected any time before the

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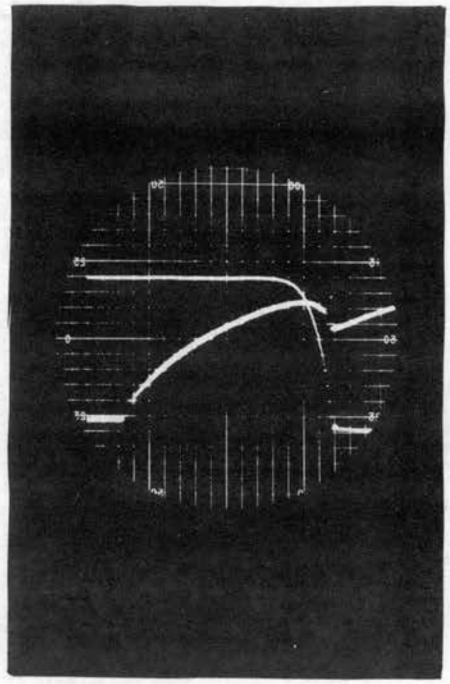
[1] Since most relays operate in the non-saturated region during the operate time, it will be assumed that the relationship between ϕ and i is linear.

V_{ss} = 25 VDC
I_{ss} = 23.4 MA
Air Gap = .050 inches
Residual Gap = .0057 inches
R_c = 1070 ohms
Spring Bias = 70 grams
V_{ss} = Steady State Voltage
I_{ss} = Steady State Current
R_c = Resistance of Coil and Shunt



Oscillogram Data:

Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .022 in/in.
Time Scale: t = 15 MS/in.

Fig. 6. Oscillogram of Transient Coil Current and Armature Motion on Operate

armature starts to move. This is done below.

$$\alpha_o = \frac{R\,t}{\ln\left[\dfrac{1}{1 - \dfrac{ip}{I_{ss}}}\right]}$$

$$\alpha_o = 24 \ h$$

$i_{pull\ in} = 17.3$ MA

$\frac{E}{R} = I_{ss} = 23.4$ MA

$t_{pull\ in} = 30.3$ MS

$E = 25$ VDC

$R = 1070$ ohms

Using this value of "α_o", (i) can be plotted against time with equation (4a). The results are plotted in Fig. (7) along with the actual curve. This duplication indicates that the assumption of flux and current being linearly related is quite accurate for this relay. Even for saturated relays, the form of the coil current trace until the armature starts to move is determined by the air gap. This can be seen in the equation for current (4a) where "α_o" is the only constant which is a function of the magnetic circuit.

This means that if two supposedly similar relays have a different coil current form, their air gaps are different.

To simplify the terminology, the constant "α_o" will be associated with the magnetic circuit before the armature starts to move on the operate condition. To find "α_o" using the value of current when the armature starts to move, there would be some question as to when the armature started to move. (This refers to the sealed relay where the armature motion cannot be recorded). Although there is some evidence, Fig. (5), that the time (t_b) before the zero slope on the current trace is approximately equal to the time (t_a) after the zero slope, there

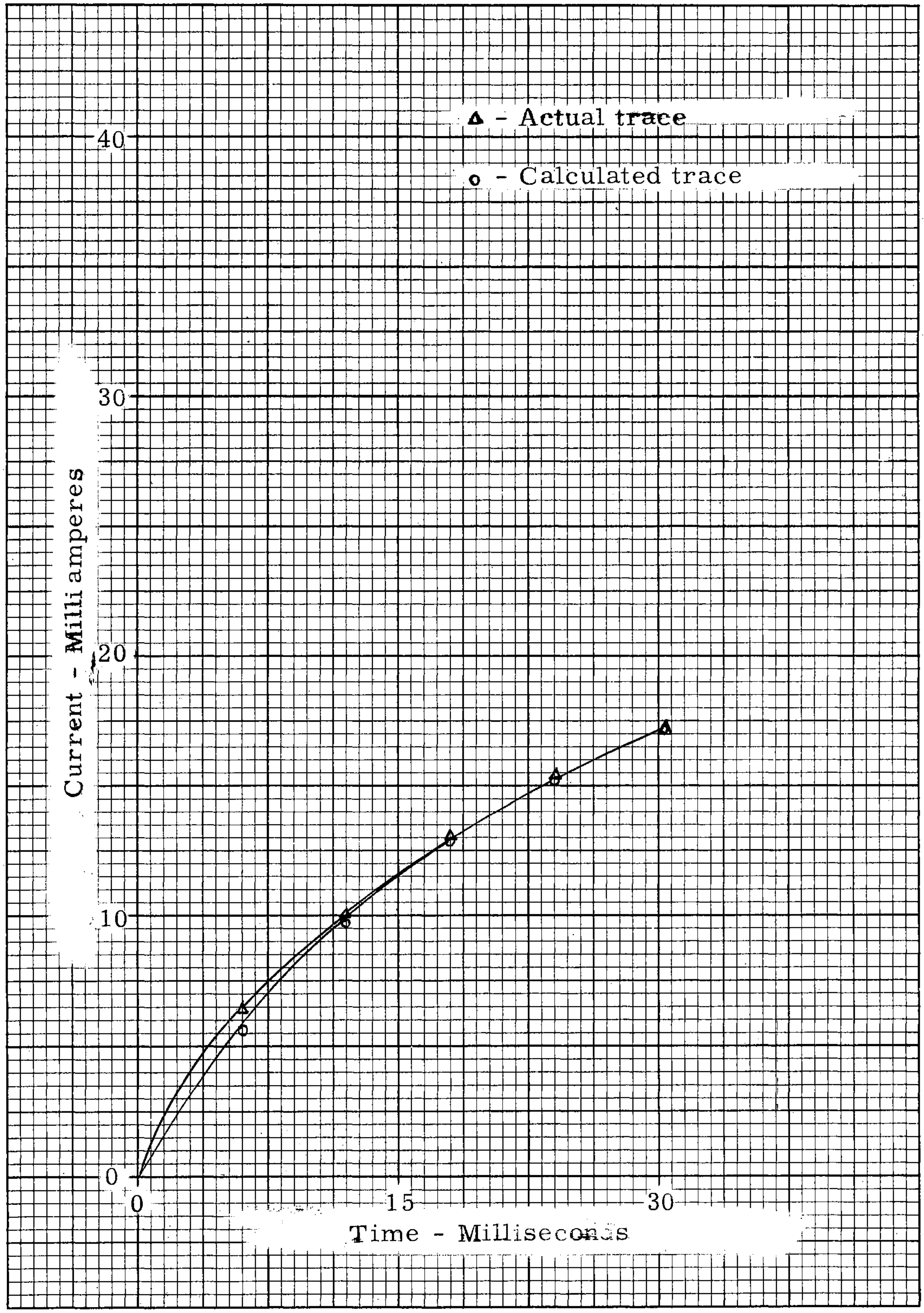
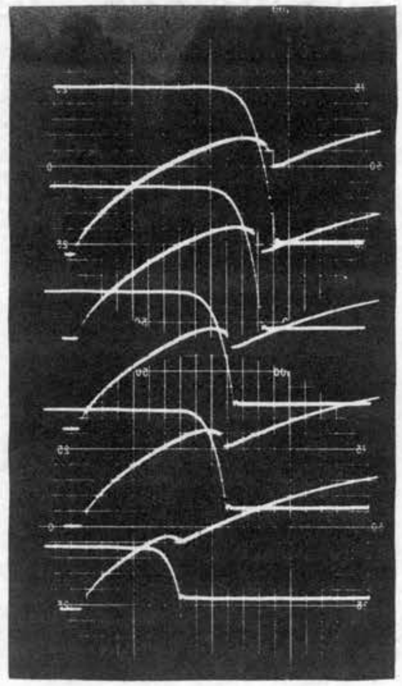


Fig. 7. Comparison of Actual Coil Current with the Calculated Value Until Armature Starts to Move on Operate

seems to be some deviation from this on multiple contact relays with unusual spacings and on some relays with very small air gaps. The time when the armature starts to move is illustrated in the oscillogram of Fig. (8). Here the coil current trace and the armature motion are shown for five different air gaps. Each trace shows that the times (t_b) and (t_a) are approximately equal.

To find "α_o" however, the exact time that the armature starts to move is not necessary. Any time before the armature starts to move is all that is needed since "α_o" can duplicate the coil current trace at this point. A good rule of thumb would be to make (t_b) twice (t_a). When the magnetic circuit is saturated, the same time should be used in all comparisons since "α_o" is not a constant in this case.

The transit time for the armature changes with air gap, which should be expected since the travel distance changes. However, the percentage of transit time vs. the time change in the current build up is very low. This can be seen from Fig. (8). For a total change in air gap of .0306 inches the change in build up time (until the armature starts to move) was 16.5 ms while the change in transit time was 3.6 ms. The total time change with air gap was 20.1 ms. The build up change comprises 80% of this change while the transit time accounts for only 20%. For this reason the build up curve is the most important part of the transient coil current trace in this type of analysis. For the analysis of the mechanical structure the transit portion of the coil current trace would be an important portion of the trace along with the



Air Gap Settings from Top Trace to Lower Trace:

A. G. (inches)

.050
.045
.036
.033
.019

V_{ss} = 25 VDC
I_{ss} = 23.4 MA
Residual Gap = .005 inches
R_C = 1070 ohms
Spring Bias = 55 grams

Oscillogram Data:

Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .0225 in/in.
Time Scale: t = 15 MS/in.

Fig. 8. Oscillogram Recording Different Air Gaps on Operate

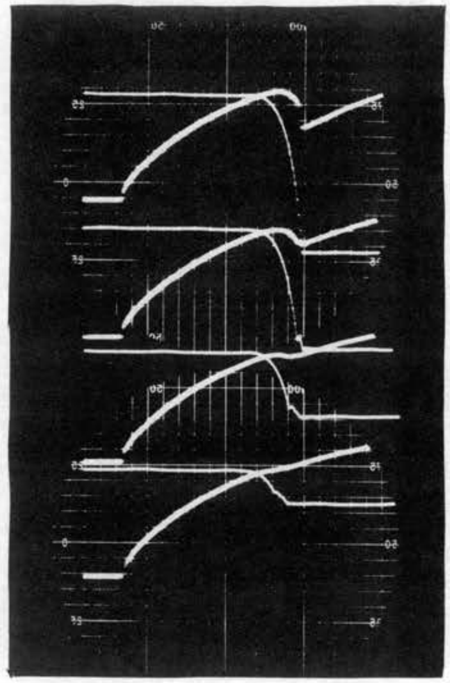
contact voltage.

Residual Gap on Operate

The residual gap on operate has no effect on the build-up form. The only effect the residual has is to change the transit time and the "α" that is associated with the release condition. This is illustrated in the oscillogram of Fig. (9). The residual pin has been changed keeping the air gap and spring bias constant.

For each different residual setting the armature always starts to move at the same time. The travel time and distance change considerably but the coil current shape, until the armature starts to move, is the same in all four cases. The "α" associated with the release condition of the relay appears in the operate condition after the armature has seated. After the armature has seated, the effective inductance of the circuit is the same as before the armature starts to move on release. The reason for this can be illustrated by a ϕ vs. i curve for the armature blocked open and blocked closed.

Figure (10) is a typical curve of this nature. Until the armature starts to move on operate the relationship between ϕ and i is determined by curve (A). Until it starts to move on release, the relationship between ϕ and i is given by curve (B). During the transit period the relationship between current and flux is some value other than that set by curves (A) and (B). However, since the air gap affects curve (A) and the residual affects curve (B), the current trace is also



Residual Settings From Top Trace to Lower Trace:

R. G. (inches)

Heel Average ≈ .001
.008
.020
.030

V_{ss} = 25 VDC
I_{ss} = 23.4 MA
Air Gap = .037 inches
Spring Bias = 97 grams
R_c = 1070 ohms

Oscillogram Data:

Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .0185 in/in.
Time Scale: t = 15 MS/in.

Fig. 9. Oscillogram Recording Different Residual Gaps on Operate

influenced in some similar manner. This condition permits the isolation of the two "α's" and gives a method of separating the influence of the two parameters, air gap and residual gap.

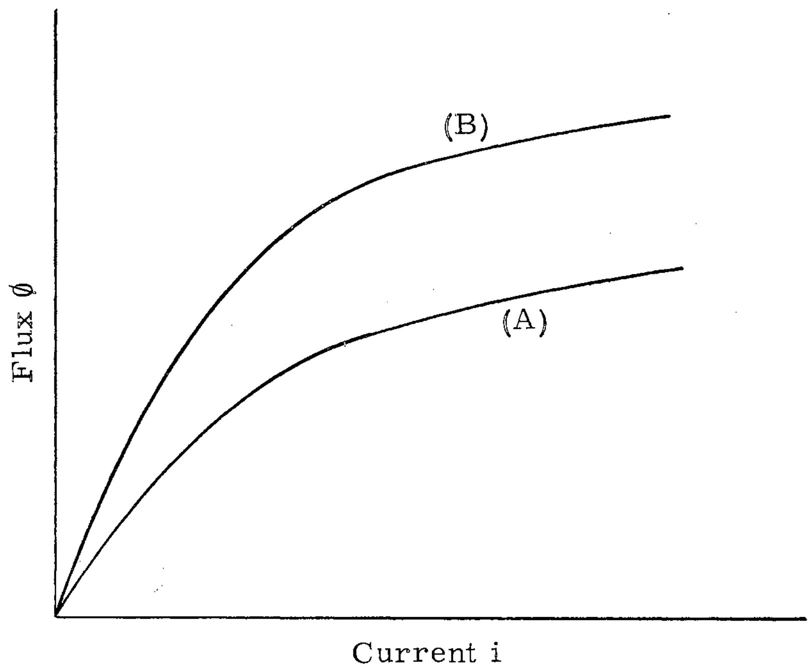


Fig. 10. Typical Flux vs. Current Curve for Open and Closed Air Gap

This can readily be seen in Fig. (9). The current trace before the armature starts to move is constant while the trace after the armature starts to move changes considerably, depending upon the residual gap. The effect is the same as shifting curve (B) in Fig. (10) closer to curve (A) until they are almost the same, as indicated in the lower trace of Fig. (9).

The residual gap will be discussed in more detail when the release condition of the relay is analyzed. There the "α" on release will be evaluated for determining residual gap change.

Spring Bias on Operate

The effects of changing spring bias on the coil current trace appear at first glance to have the same effects associated with changing air gap. Actually, there is only one thing they have in common -- the factor, time. They both cause an increasing or decreasing operate time for increased or decreased values of the two parameters. Fig. (11) shows an oscillogram with the spring bias changed through five different values. The armature motion is also present to give an idea of the transit time change.

Inspection of the equation (4a) will show why the spring bias has a different effect on the build-up current trace.

$$i = \frac{E}{R}\left[1 - e^{\frac{-rt}{\alpha_o}}\right] \tag{4a}$$

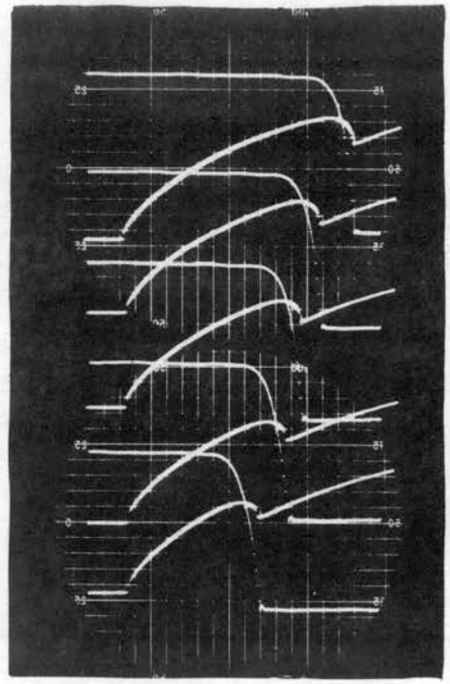
Since "α_o" is affected only by the magnetic circuit, the only other parameters that can influence the trace are R, E, and i. Since E and R have been called controllable, they can be eliminated. This leaves (i) as the factor which must be affected by spring bias. That this is true should be evident from equation (2a) which predicts when motion of the armature should commence. The dynamic flux has to build up to a certain value to overcome the restraining forces of the armature and spring. Since this restraining force is mostly determined by the spring bias, the value of current at which the armature

Spring Bias Settings from Top Trace to Lower Trace:

S. B. (grams)

120
95
80
60
45

V_{ss} = 25 VDC
I_{ss} = 23.4 MA
Air Gap = .031 inches
Residual Gap = .005 inches
R_c = 1070 ohms



Oscillogram Data:

Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .013 in/in.
Time Scale: t = 15 MS/in.

Fig. 11. Oscillogram Recording Different Spring Biases on Operate

starts to move will be a function of this force. Then equation (4a) can be written as

$$t = \ln \left[1 - \frac{I_{(fs)}}{I_{ss}} \right]^{-1} \Bigg/ \frac{\alpha o}{R} \qquad I_{(fs)} = \begin{bmatrix} \text{current as a} \\ \text{function of} \\ \text{spring bias} \end{bmatrix} . \quad (4b)$$

Since $I_{(fs)}$ increases as spring bias increases, equation (4b) easily explains why the time for operation increases as the spring bias increases.

The general shape of the build-up curve is unaltered with changing spring bias as was mentioned in the discussion on air gap. This gives a method of determining which of the two parameters has affected the coil current build up, assuming only one or the other has been altered.

The coil current trace after the armature has seated is changed slightly with changing spring bias. The cause of this is similar to the change caused by a changing residual gap or air gap. However there is a distinct difference. The difference can be explained using Figures (12a) and (12b).

Equation (2a) gives the general relationship between the bias force and the value of flux needed to overcome this force so that the armature will start moving.

$$\text{Bias Force} \leqq k\phi^2 \ .$$

The constant k is determined by the area of the effective air gap and the permeability of the space material. For small air gaps and small working angles the area could be assumed constant. This

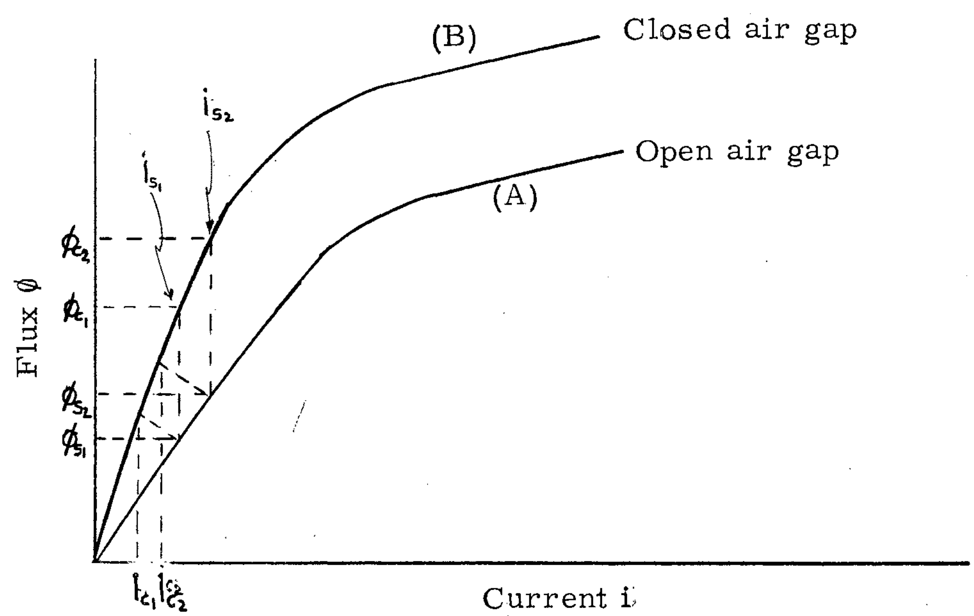


Fig. 12a. Flux vs. Current Curves for Changing Spring Bias

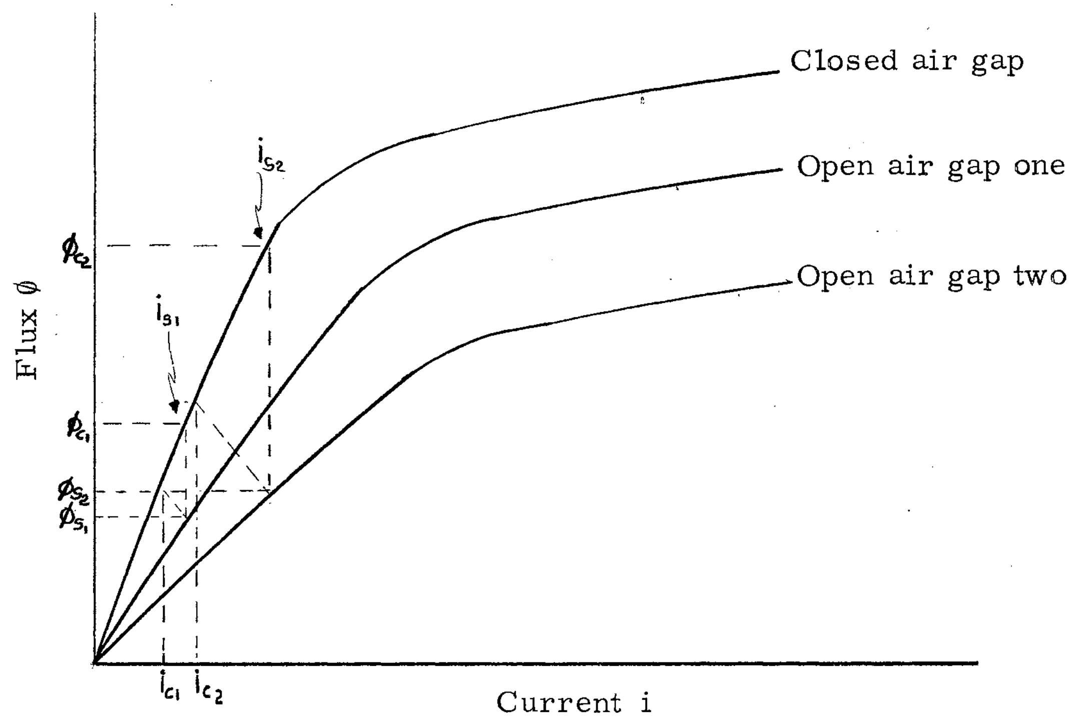


Fig. 12b. Flux vs. Current Curves for Changing Air Gap

makes the value of flux a constant for any air gap (small) as long as the spring bias is constant. However, if the spring bias is changed the value of flux to overcome this force is changed.

Figure (12a) gives a typical magnetization curve for a relay with the air gap open and closed. Assuming that ϕ_{s1} and ϕ_{s2} are the values of flux needed to overcome spring bias forces F_1 and F_2 respectively, the value of current to give ϕ_{s1} and ϕ_{s2} is shown as i_{s1} and i_{s2}. When the armature closes these currents i_{s1} and i_{s2} would give flux values of ϕ_{c1} and ϕ_{c2} if the armature closed in zero time and the flux could change in this same time. However, the flux cannot change this rapidly due to the property of inductance. Therefore the flux goes to some value less than ϕ_{c1} and ϕ_{c2}, which in turn gives values of i_{c1} and i_{c2} which are less than i_{s1} and i_{s2}. This is the reason for the decrease in current during the transit time of the armature. However, if the open and closed curves of Fig. (12a) were parallel, the difference between $(i_{s1} - i_{c1})$ and $(i_{s2} - i_{c2})$ would be zero, and the only noticeable difference on the transient current trace would be the times that the transit period occurred. Even if the curves are not parallel, the change in $(i_{s1} - i_{c1})$ and $(i_{s2} - i_{c2})$ with changing spring bias is not very noticeable unless the change in spring bias causes the values of flux to vary over a large portion of the ϕ vs. i curves.

The same type of analysis can be carried out for changing air gap with constant spring force. However in this situation the value of flux needed remains essentially a constant (assuming the effective area remains constant). This is illustrated in Fig. (12b) with two different air gaps. The difference between $(i_{s1} - i_{c1})$ and $(i_{s2} - i_{c2})$ is due not only to the magnetization curves being non-parallel, but also because the magnetization curves are shifted, with a changing air gap. This difference usually appears more noticeable in the transient current trace than is the case for changing spring bias. A comparison of the oscillograms in Figs. (8) and (11) will demonstrate this condition.

Results of the Build-Up Analysis

The analysis of the build-up coil current trace during the transient period has given a method of assigning a distinct peculiarity to the trace that can be associated with a certain parameter.

The air gap can be associated with a constant "α_o" which should remain unaltered for any particular relay as long as the air gap is unchanged. (This assumes the magnetic material, heel gap and coil inductance are unchanged.) The spring bias affects only the operate time and does not change the shape and form of the coil current trace until the armature starts to move.

These facts at the present are interesting, but do not allow the complete evaluation of the relay unless they can be identified together. The next section dealing with the release condition of the coil current trace will give other facts separate from the ones found on operate.

When combined, these facts will give enough information that combinations of the changing parameters can be detected.

Air Gap During Release

The air gap on the release condition can be eliminated as a parameter until the armature starts to move. This is apparent since the air gap is the residual gap until the armature starts to move. Figure (13) illustrates this fact. The oscillogram of Fig. (13) shows the release current and armature motion with variable air gap. The form of the release current remains unchanged until the armature starts to move. Also the time from de-energization until the armature starts to move remains the same independent of the air gap. Like the residual on operate, the air gap on release affects the transit time and the shape of the current trace after the armature has quit moving. The reasons for this are the same as explained by Fig. (12b).

Residual Gap on Release

The residual gap on release determines the relationship between the flux and the current in a manner similar to that of the air gap on operate. The equation to evaluate this relationship is the electric circuit equation (1c) with E equal to zero which gives equation (1f) .

$$iR = -N \frac{d\phi}{dt} \quad . \tag{1f}$$

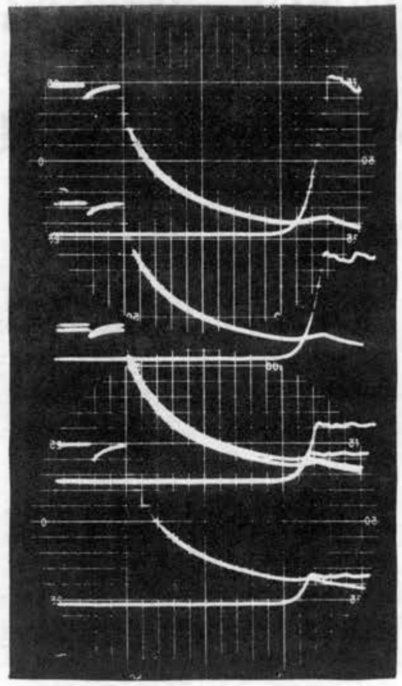
Assuming that the flux and current are related by a constant gives

Air Gap Settings from Top
Trace to Lower Trace:

A. G. (inches)

.045
.031
.018
.011

V_{ss} = 25 VDC
I_{ss} = 23.4 MA/in.
Residual Gap = .005 inches
Spring Bias = 100 grams
R_c = 1070 ohms



Oscillogram Data:

Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .020 in/in.
Time Scale: t = 15 MS/in.

Fig. 13. Oscillogram Recording Different Air Gaps on Release

$$iR = -\alpha_r \frac{di}{dt} \; .$$

Solving for current gives

$$i = \frac{E}{R_c} e^{-\frac{R_c + R_d}{\alpha_r} t} \; . \qquad (4c)$$

R_c = Resistance of coil and shunt

R_d = External discharge resistance

E = Voltage before switch is opened

α_r = Effective inductance on release

The "α_r" in this equation has the same function as "α_o" had on operate. The "α_r" of a relay is affected only by the residual gap.

To show that "α_o" and "α_r" are different for a relay, the same conditions are imposed on the relay that were imposed on the relay in Fig. (6). The release trace is recorded as shown by the oscillogram of Fig. (14).

Solving for "α_r" changes equation (4c) to the form

$$\alpha_r = \frac{(R_d + R_c)\, t_r}{\ln \left[\frac{I_{ss}}{i_r} \right]} \qquad (4d)$$

$I_{ss} = \frac{E}{R}$; i_r = value of current at t_r

R_d = 1040 ohms; R_c = 1070 ohms ; I_{ss} = 23.4 MA .

From oscillogram

time for release is 30.6 ms.

i_r = 2.92 MA

V_{ss} = 25 VDC
I_{ss} = 23.4 MA
Air Gap = .050 inches
Residual Gap = .0057 inches
Spring Bias = 70 grams
Restoring Forces = 85 grams
R_c = 1070 ohms
R_d = 1040 ohms
R_d = Discharge Resistor

Oscillogram Data:

Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .022 in/in.
Time Scale: t = 15 MS/in.

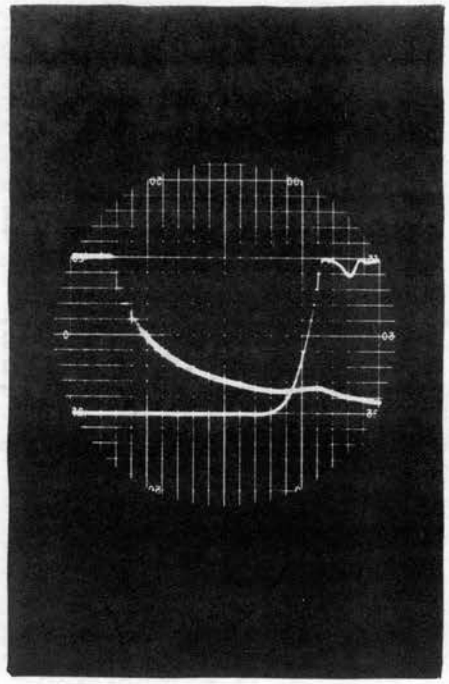


Fig. 14. Oscillogram of Transient Coil Current and Armature Motion on Release

$\therefore$

$\alpha_r = 31.0$ henries .

"α_o" from Fig. (6) was 24.0 henries.

Since "α_o" and "α_r" are different and independent of each other except for the magnetic circuit material, this gives an easy and fast method of checking the residual and air gap for any lot of relays to see if the two parameters have the same adjustment on all the relays.

The magnetic circuit for the release condition is more likely to be saturated than it is for the operate condition. For this reason, the current curve might not always be duplicated by the equation (4c). For the purpose of checking "α_r" however, this problem does not complicate the situation. The same time can always be used for checking each relay's coil current and "α_r" should still remain the same unless the residual has changed. This also eliminated the same problem on the operate condition for air gap.

To see if "α_r" remains essentially constant during the release condition the current trace is evaluated by equation (4c). The results are plotted in Fig. (15) along with the actual curve.

From Fig. (15) it is apparent the relationship is not linear as was assumed in the solution of equation (1f). However, as was mentioned above, as long as the same time (t_r) is used in checking all curves to be compared, the results should always be the same, unless the residual has changed.

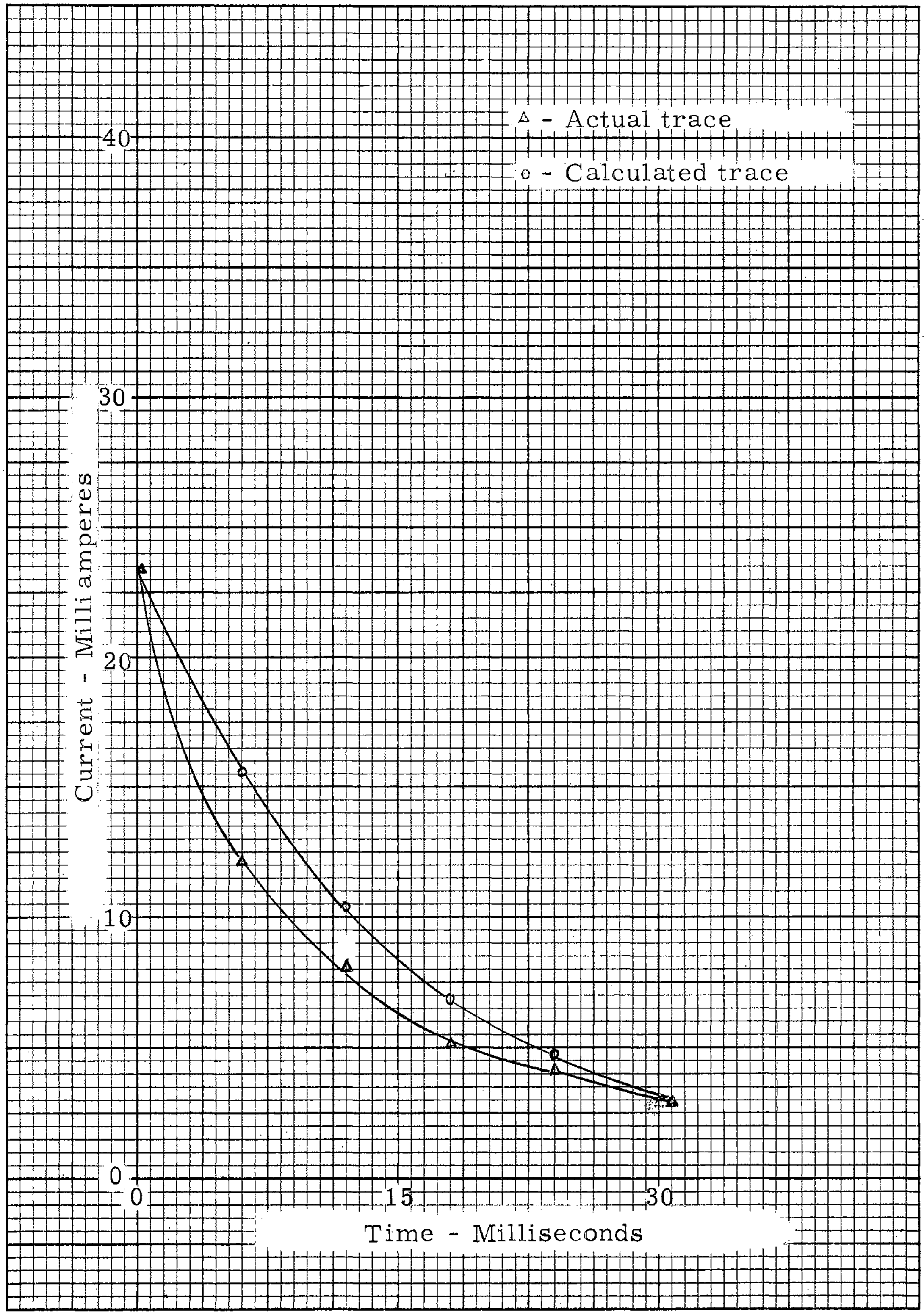


Fig. 15. Comparison of Actual Coil Current with the Calculated Value until the Armature Starts to Move on Release

The value of current used for checking "α_r" could be chosen at the minimum value of current just before the characteristic hump appears. This is illustrated in Fig. (16).

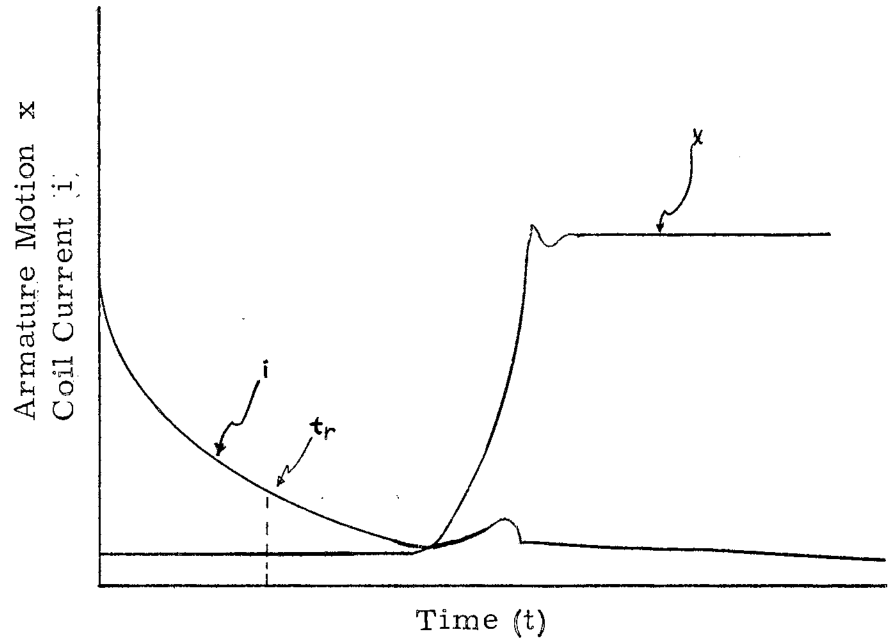


Fig. 16. Typical Release Curve for Transient Coil Current and Armature Motion on Release

This point is very nearly the position that the armature starts to move. The reason the current starts to change simultaneously with armature movement is that the residual is usually so small the change in magnetic circuit (residual gap) is very noticeable in this range. Equation (1g) which is the electric equation after the armature starts to move can be used to explain this situation.

$$iR = -N \left(\frac{\partial \phi}{\partial i} \frac{\partial i}{\partial t} + \frac{\partial \phi}{\partial x} \frac{\partial x}{\partial t} \right) \quad . \tag{1g}$$

For small air gaps (residual) the change of flux with respect to air gap (x) has its greatest value since the change in reluctance is greatest in this region. To illustrate the fact that the minimum current before the hump and the beginning of the armature motion occur simultaneously for different residual gaps, the oscillogram in Fig. (17) shows this condition.

Figure (17) also indicates that if a relay has a small residual gap (top trace) the setting on this relay would be very critical in determining the release time. The change in residual of the first two traces was .0046 inches and the time change was 68 ms. The total time change from first residual (.001) to last (.0226) was only 86 ms. This means that 80% of the time change was caused by only 20% of the residual change. This percentage will vary from relay to relay, depending upon the type of residual and magnetic material. The general trend should be present on all types of relays, however, since the force is a function of one over the residual gap squared. This can be seen by equation (2b) if flux is replaced in terms of current.

Spring Bias on Release

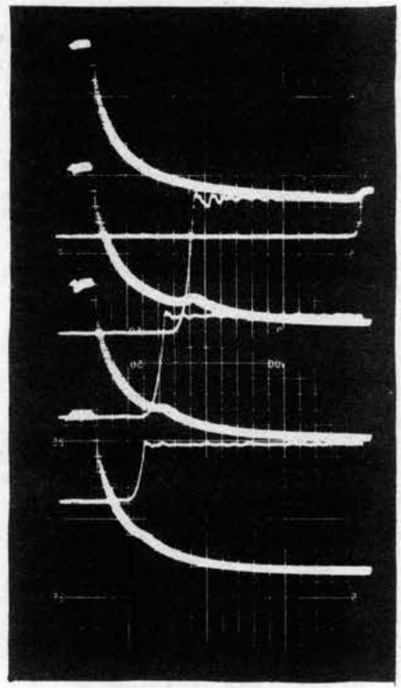
The restoring force of a relay affects the coil current trace in a manner similar to the spring bias effect on operate. The "α_r" is not changed by a different spring bias, only the value of drop-out current is altered. This in turn affects the release time of the relay. This is illustrated by the oscillogram of Fig. (18) in which only the

Residual Settings from Top
Trace to Lower Trace

R. G. (inches)
Heel Average $\approx$ .001

.0056
.013
.023

V_{ss} = 25 VDC
I_{ss} = 23.4 MA
Air Gap = .033 inches
Restoring Force = 105 grams
R_c = 1070 ohms
R_d = 1040 ohms



Oscillogram Data:

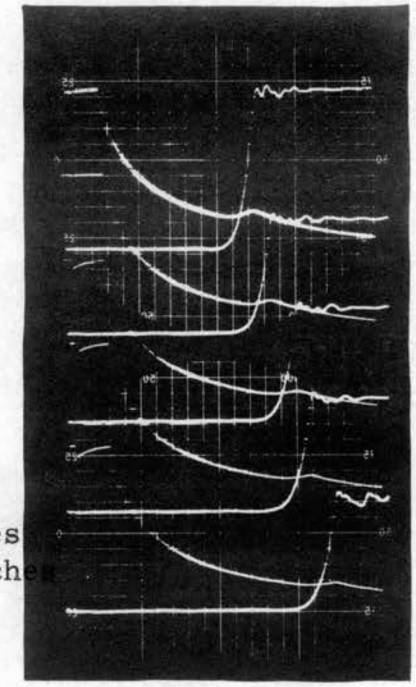
Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .0165 in/in.
Time Scale: t = 30 MS/in.

Fig. 17. Oscillogram Recording Different
Residual Gaps on Release

Restoring Force Settings from
Top Trace to Lower Trace:

R. F. (grams)

130
115
100
87
65



V_{ss} = 25 VDC

I_{ss} = 23.4 MA

Air Gap for First Time = .025 inches

Air Gap for Other Traces = .019 inches

Residual Gap = .005 inches

R_c = 1070 ohms

R_d = 1040 ohms

Oscillogram Data:

Current Scale: i = 11.7 MA/in.

Displacement Scale: x = .010 in/in.

Time Scale: t = 15 MS/in.

Fig. 18. Oscillogram Recording Different Restoring Forces or Release

restoring force of the relay was changed. The armature motion is also recorded to show that, as in the case of spring bias on operate, the transit time is unaffected by the changing restoring force.

Another interesting and useful characteristic of changing spring bias is apparent in Fig. (18). The size of the hump when the armature starts to move is increased with increasing restoring bias. This characteristic can be used to separate the parameters, residual gap and restoring force, since the residual gap, Fig. (17), has the opposite characteristic. As the residual gap is increased, the characteristic hump is decreased.

Discharge Resistance

The discharge resistance of a relay is the only controllable parameter discussed in this analysis.[2] However, since the discharge resistance can have such a noticeable effect upon the coil current trace and change the release time of a relay to a great degree, it is included with the other parameters discussed.

The discharge resistance is composed of two parts: (1) the coil resistance, and (2) the external resistance. The equation relating discharge resistance to the coil current is the same equation (4c) used to relate "α_r" to the current.

$$i = \frac{E}{R_c} e^{-\left(\frac{R_c + R_d}{\alpha r}\right) t} \quad . \tag{4c}$$

[2]Controllable to the extent that any value can be used in conjunction with the coil resistance.

The effect which the discharge resistance has on the current form also serves to emphasize how "α_r" would affect the current form if its relative change were large enough.

The reason for this is apparent from the fact that $R_c + R_d$ and "α_r" are all part of the time constant in equation (4c).

The effect of discharge resistance on the coil current trace is illustrated in the oscillogram of Fig. (19).

The reason the coil current shape has such a noticeable change in Fig. (19) is that the discharge resistance was changed through a value of 980 percent of the coil resistance. If the relative value of discharge resistance to coil resistance is small, the change in the coil current shape and release time will be small. The reason for the time change being small can be seen from rearranging equation (4c) in terms of time. This has the form

$$t = \frac{\alpha_r \ln\left[\frac{I_{ss}}{i_r}\right]}{R_c + R_d} \quad . \tag{4c}$$

Results of Release Analysis

The release condition of a relay has several given characteristics which can be associated with certain parameters. These parameters, residual gap, restoring bias and discharge resistance, could not be detected readily by observing the operate condition of the relay. A brief description of the characteristics associated with the three

Discharge Resistance from Top Trace to Lower Trace:

R_d (ohms)

185
1040
10000

V_{ss} = 25 VDC
I_{ss} = 23.4 MA
Air Gap = .038 inches
Residual Gap = .0057 inches
Restoring Force = 90 grams
R_c = 1070 ohms

Oscillogram Data:

Current Scale: i = 11.7 MA/in.
Displacement Scale: x = .016 in/in.
Time Scale: t = 15 MS/in.

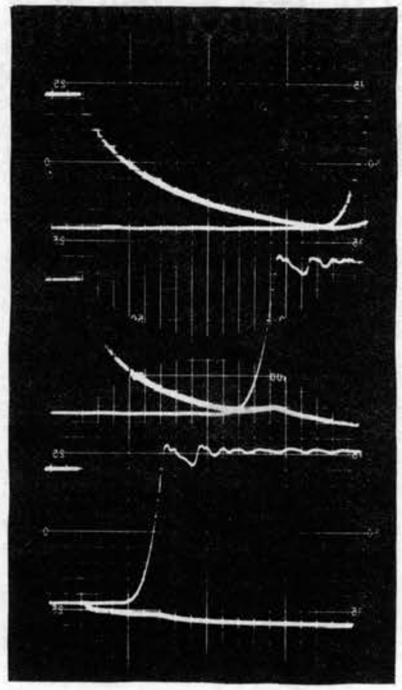


Fig. 19. Oscillogram Recording Different Discharge Resistances on Release

parameters will be given.

The residual gap changes the "α_r" of the relay and gives a noticeable change in hump during the transit period. This change in hump with "α_r" increases with decreasing residual gap. The change in shape of the coil current trace was not as noticeable on the release condition as was the case on operate for changing air gap. The transit time of the relay had a noticeable change with changing residual gap.

The restoring force of the relay affected only the value of dropout current which in turn affected the release time. The transit time did not have a noticeable change which was the case for the operate condition with changing spring bias. The characteristic hump during the transit condition had a noticeable change which increased with increasing restoring force.

The discharge resistance had a noticeable effect on both the coil current shape and the release time. The discharge resistance is a controllable parameter, however, and was varied over a much larger range than the other parameters.

Summary of Chapter

The different parameters outlined in Chapter III have been investigated in Chapter IV to see their individual effects upon the transient coil current of a relay. Each parameter has exhibited a characteristic that is distinguishable from the coil current trace. Some of the characteristics are more pronounced than others, but this seems to be caused by different relay designs more than by the parameters themselves.

The problem of labeling the different relays in the switching circuit tree of Chapter III could now be accomplished.

The problem, however, is to detect different combinations of the different parameters from the coil current trace and be able to tell in which direction they have changed (relative to some standard relay of the same type).

CHAPTER V

LOGICAL CONCLUSIONS FROM INDIVIDUAL ANALYSES

The investigation of individual parameters in Chapter IV revealed many interesting but seemingly unrelated facts. For example, the discussion of air gap on operate, and the oscillogram of Fig. (8) indicate that the operate time increases for increasing air gap while the "α_o" decreases.[1] Many more conclusions of this type can be extracted from the individual analyses performed on the various parameters. The purpose of this chapter is to relate these facts so that dependable conclusions about the change in the parameters can be obtained by inspection of the transient coil current trace.

The method with which this is done was associated with the switching circuit analogy of Chapter III. However, the circuit of Fig. (4) merely indicates if a parameter has changed or not, and does not tell how it was determined that the parameter changed. The method of determining that a parameter changed and how it changed (increased, decreased or remained the same) is like the process used in a mathematical proof, or contradiction, of a statement. First, the system to

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[1]"α_o" can be evaluated by using equation (4a) and the same time t_o on all five traces of Fig. (8).

which the statement pertains is defined; then the facts about that system are gathered to be used in analyzing the statement. From the boundaries of the system and the facts about the system, the statement can be evaluated using traditional logic.

The accepted logical argument or inference is a statement saying: If certain propositions are true, then some other proposition must be true.[2] The example usually cited in a basic logic course contains the three categorical propositions, "All animals are mortal," "All cats are animals," and "All cats are mortal." In this example the third proposition necessarily follows from the first two. The second proposition replaces "animals" in the first proposition with "cat" which yields the third proposition exactly.

One of the important things about this accepted logical process is the truth of the propositions used have no effect on the process itself. For example, using the two categorical propositions "All trees are red," "All dogs are trees," necessarily infers that "All dogs are red." The logical argument is valid, but the propositions used are obviously untrue.

This type of reasoning allows a synthesis or analysis process to be constructed without regard for the truth of any propositions used in the process. For engineering work, however, the emphasis is

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[2] Culbertson, James T., Mathematics and Logic for Digital Devices, D.Van Nostrand Company, Inc., Princeton, New Jersey, Toronto, New York, London, p. 87.

usually placed on making certain that the propositions are true. The method of obtaining conclusions from these propositions is usually available in the form of an equation.

The logic network to be constructed in this Chapter necessarily has to be based on some system and must use facts about that system. This was the reason for the time and space used in the previous chapters dealing with the relay system. The facts determined about the relay and the conditions under which these facts were established are needed to have a logical network which might be useful. It should be stressed, however, that the network itself is not dependent upon the absolute truth of these facts.

The statements to be made in this system come from the transient coil current. The statement contains two portions, the operate and the release conditions of the transient coil current. The system is defined by the conditions about the relay and the experimental facts concluded from the individual analysis of each parameter.

Before a logic circuit can be constructed, the conditions and conclusions from the individual analyses of Chapter IV should be stated in an orderly and concise form. The Tables I and II are symbols and abbreviations which will help to accomplish this task. Also, the standard relay should be defined. The standard relay is any relay that has the desired performance and is the same type as the relays to be evaluated.

TABLE I

LIST OF ABBREVIATIONS

α_o	effective inductance associated with air gap
α_r	effective inductance associated with residual gap
C. H.	changing hump (refers to discontinuity in current trace on release)
i_{o1}	current at t_o of standard
i_{o2}	current at t_o of test relay
i_{r1}	current at t_r of standard
i_{r2}	current at t_r of test relay
R. F.	restoring force
S. B.	spring bias
S. T.	spring tension
t_o	time to be used in comparing operate current trace of test relay against standard relay trace
t_r	same as t_o except for release condition
t_{r1}	time for armature releasing of standard relay (minimum current before hump)
t_{r2}	time for armature releasing of test relay
t_{s1}	time for armature seating of standard relay (minimum current after hump)
t_{s2}	time for armature seating of test relay

TABLE II

LIST OF SYMBOLS

$\longleftrightarrow$	if and only if	$\therefore$	therefore
$\longrightarrow$	implies that	$>$	greater than
$\uparrow$	increased	$<$	less than
$\downarrow$	decreased		
$-$	no change		

Conditions and Conclusions from Chapter IV

Conditions: I. All other variables of a relay are fixed except air gap, residual gap, and spring tension.[3]

II. The spring tension affects both the spring bias and restoring force in the manner prescribed below.

S. B. $\uparrow$ and R. F. $\uparrow$ $\longleftrightarrow$ S. T. $\uparrow$

S. B. $\downarrow$ and R. F. $\downarrow$ $\longleftrightarrow$ S. T. $\downarrow$

III. A standard relay has been selected.

With these conditions, the conclusions of Chapter IV are:

1. α_o changes $\longrightarrow$ air gap changes
2. α_r changes $\longrightarrow$ residual gap changes

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[3] The discharge resistance can be measured external to the inside of the relay so will not be included in this logic network.

3. Both operate and release times are influenced by a change in S. T.
4. α_o changes the operate time and current form.
5. α_r changes the release time and current form.
6. Time is influenced by the change of any one variable.
7. α_o does not influence release trace before armature starts to move.
8. α_r does not influence operate trace before armature starts to move.
9. The size of the hump on the release curve changes with α_r.
10. The size of the hump on the release curve changes with S. T.

There are other facts that could be mentioned from the results of Chapter IV. Assuming the ten above are true, however, enough information is available to evaluate a sealed relay as to what parameters have been changed. These same ten facts can be expanded to indicate in what relative direction the parameters have been changed. This direction is, of course, relative to the parameters of the standard relay. The information that cannot be obtained is the degree of change in absolute magnitudes. However, this type of analysis is intended for quality control and diagnostic analysis, not absolute control.

Expanding the conclusions with the relationships of Chapter IV gives

1. $\alpha_o = Rt_o / \ln\left[\frac{1}{1 - \frac{i_o}{I_{ss}}}\right]$ $\qquad \alpha_o \downarrow \longleftrightarrow i_o \uparrow \longrightarrow A.G. \uparrow$

$\qquad \alpha_o \uparrow \longleftrightarrow i_o \downarrow \longrightarrow A.G. \downarrow$

Therefore, for an increase or decrease in air gap there is adecrease or increase in α_o.

2. $\alpha_r = \frac{t_r(R_c + R_d)}{\ln\left[\frac{I_{ss}}{i_r}\right]}$ $\qquad \alpha_r \downarrow \longleftrightarrow i_r \downarrow \longrightarrow R.G. \uparrow$

$\qquad \alpha_r \uparrow \longleftrightarrow i_r \uparrow \longrightarrow R.G. \downarrow$

Therefore, for an increase or decrease in residual gap, there is a decrease or increase in α_r.

3. S.T. $\uparrow \longrightarrow$ operate time $\uparrow$ and $\downarrow$ in release time

S.T. $\downarrow \longrightarrow$ operate time $\downarrow$ and $\uparrow$ in release time

4. $\alpha_o \downarrow \longrightarrow$ operate time $\uparrow$

$\alpha_o \uparrow \longrightarrow$ operate time $\downarrow$

5. $\alpha_r \uparrow \longrightarrow$ release time $\uparrow$

$\alpha_r \downarrow \longrightarrow$ release time $\downarrow$

6. Each parameter influences the operate or release time or both.

7. α_o does not influence release trace before armature starts to move.

8. α_r does not influence operate trace before armature starts to move.

9. $\alpha_r \uparrow \longrightarrow$ hump $\uparrow \longrightarrow$ time for release $\uparrow$

$\alpha_r \downarrow \longrightarrow$ hump $\downarrow \longrightarrow$ time for release $\downarrow$

10. S. T. $\uparrow \longrightarrow$ hump $\uparrow \longrightarrow$ time for release $\downarrow$

S. T. $\downarrow \longrightarrow$ hump $\downarrow \longrightarrow$ time for release $\uparrow$

From the above conditions a logic network can now be constructed to give the relative change in parameters by inspection of the transient coil current trace on operate and release. The two examples below show the basic steps used in construction of such a network.

Example I :

Given: Standard relay trace for operate and release

Find: The relative change in parameters of a supposedly identical relay

Steps:

1. Find i_{o1} and i_{r1} of standard relay for time t_o and t_r.
2. Note time armature seats and opens, t_{s1}, t_{r1} (minimum current at discontinuity on operate and release).
3. Record transient coil current of relay to be evaluated on operate and release.
4. Find new i_{o2} and i_{r2}, using same time t_o and t_r above.
5. Check to see if seating time t_{s2} and release time t_{r2} have changed.

For illustrative purposes assume the following statement is issued by the transient coil current:

(a) The operate trace indicates $i_{o2}\downarrow$, $t_{s2} > t_{s1}$.

(b) The release trace indicates i_{r2} - , $t_{r2} < t_{r1}$.

These facts imply that $\alpha_o\uparrow$, $t_{s2} > t_{s1}$ and α_r - , $t_{r2} < t_{r1}$ using the operate statement gives the following conclusion

$\alpha_o \uparrow \longrightarrow$ air gap $\downarrow \longrightarrow$ time for operate $\downarrow$

but the operate time increased; therefore the spring bias must have decreased since "α_r" has no effect on the operate time. Using the release statement to check the above conclusion gives

α_r - $\longrightarrow$ residual gap - $\longrightarrow$ release time - but, the release time decreased; therefore the restoring force must have decreased since "α_o" has no effect on the release time. (In this case the release trace was used only as a check since the S. T. could have been determined by the operate statement.) From the above analysis the parameters that are different from the standards are air gap (smaller) and spring tension (smaller).

Example II :

Assume the transient coil current trace indicates the following:

(a) Operate trace: $i_{o2}\downarrow$, $t_{s2} = t_{s1}$

(b) Release trace: $i_{r2}\uparrow$, $t_{r2} = t_{r1}$.

These facts imply that $\alpha_o\uparrow$, $\alpha_r\uparrow$, $t_{s2} = t_{s1}$, $t_{r2} = t_{r1}$.

Inspection of the operate statement yields the conclusion:

$$\alpha_o \uparrow \longrightarrow \text{A.G.} \downarrow \longrightarrow \text{time for operate} \downarrow$$

but time for operate remained the same; therefore spring bias must have increased to counteract the time change the decreasing air gap should have caused. (This is true because α_r does not affect the operate time.) Inspection of the release statement yields the conclusion

$$\alpha_r \uparrow \longrightarrow \text{R.G.} \downarrow \longrightarrow \text{release time} \uparrow$$

but the time for operate remained the same; therefore restoring force must have decreased to counteract the effect of a change in residual gap. (This is true because α_o does not affect the release time.)

The total conclusion from this example is that the spring bias increased and the restoring force decreased. This could be possible except for the condition that stated

$$\text{S.B.} \uparrow \quad \text{and R.F.} \uparrow \longleftrightarrow \text{S.T.} \uparrow$$

$$\text{S.B.} \downarrow \quad \text{and R.F.} \downarrow \longleftrightarrow \text{S.T.} \downarrow \quad .$$

Therefore the only conclusion that can be drawn about the relay is that some parameter besides air gap, residual gap and spring tension is different from the standard relay.

Example II was given to illustrate that other conditions can exist when analyzing a relay by this process. The logic network could indicate these conditions giving an output which indicated some other parameter has changed besides the ones with which the network was constructed. The network constructed in this thesis has not included these other paths.

The network constructed in this thesis gives only the conditions that could exist with any combinational change of the three parameters A.G., R.G. and S.T. All other parameters have been fixed as stated in the conditions of the system. The general network is shown in Fig. (20).

From Fig. (20) it is evident the number of conditions that can exist on the transient coil current are many. Therefore even though the analysis process could be carried out independent of the network in Fig. (20), the process is greatly simplified by the construction of this logic network. The size of the network depends on the number of conditions that it takes to relate all of the parameters involved. Only three parameters were used in this analysis, but seventeen conditions were used to relate these parameters to the transient coil current. This gave for the one input (coil current trace) 57 paths or conditions.

To verify all of these paths experimentally is not feasible. Also, the procedure is the most important part of the analysis. The problem of determining whether or not the network allows a correct analysis of a certain physical system depends only upon the validity of the conditions and conclusions used in constructing the logic network.

It is obvious that the individual cases used in Chapter IV check with the results of the logic network. This follows from the fact that the network was built using the results of the individual parameter changes. To give experimental evidence that combinations of the different parameters, varied simultaneously, check with the results

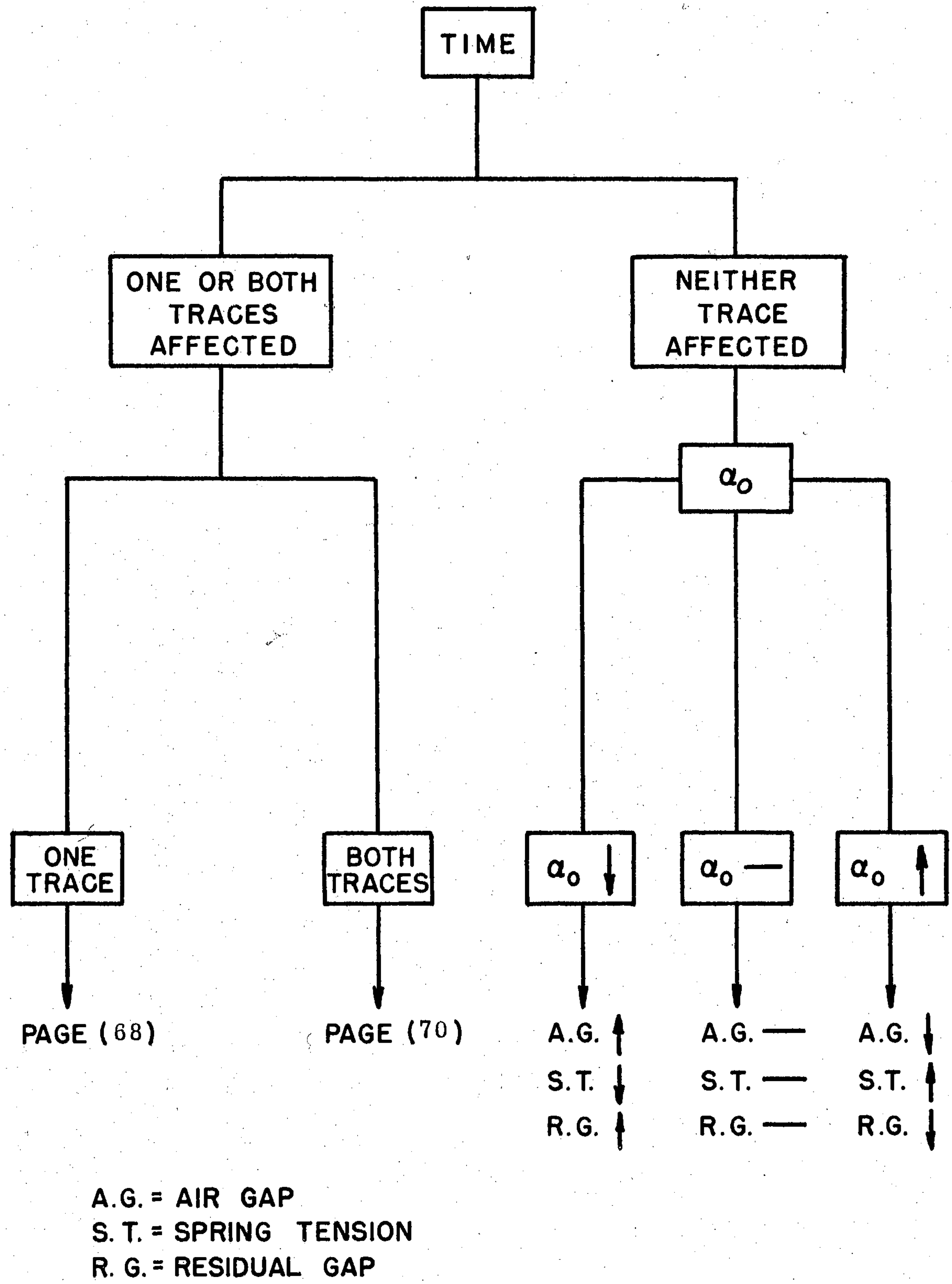
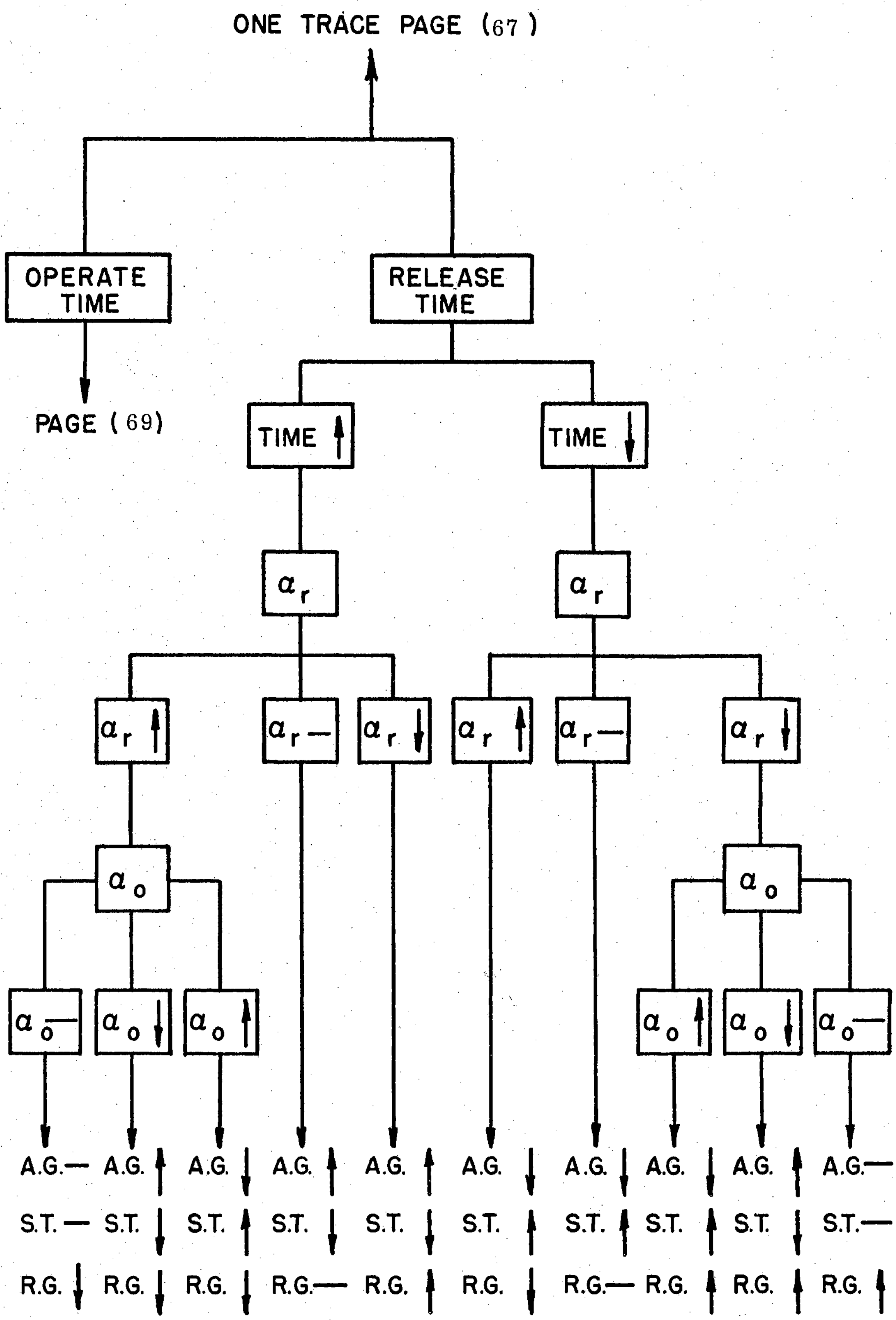
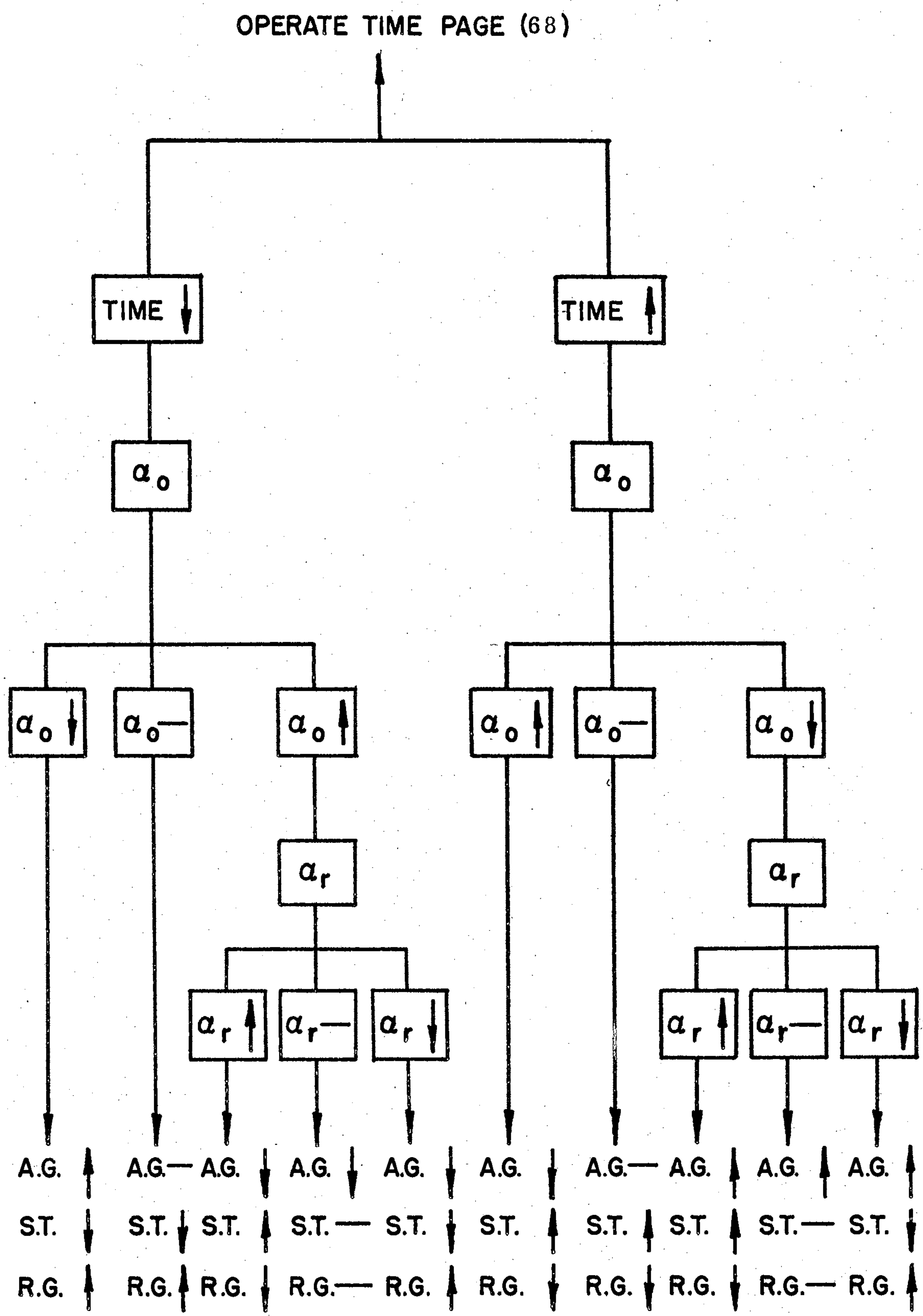
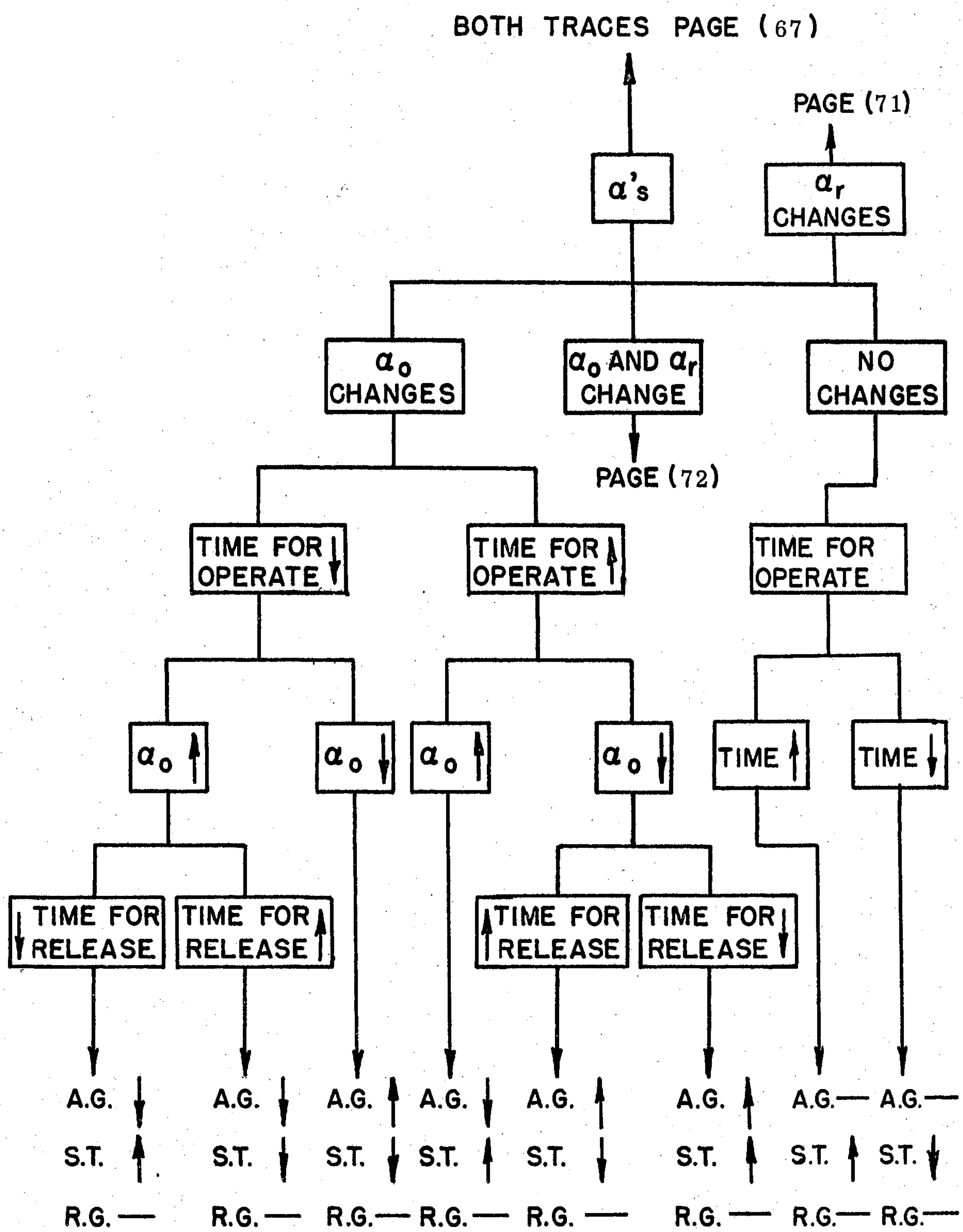
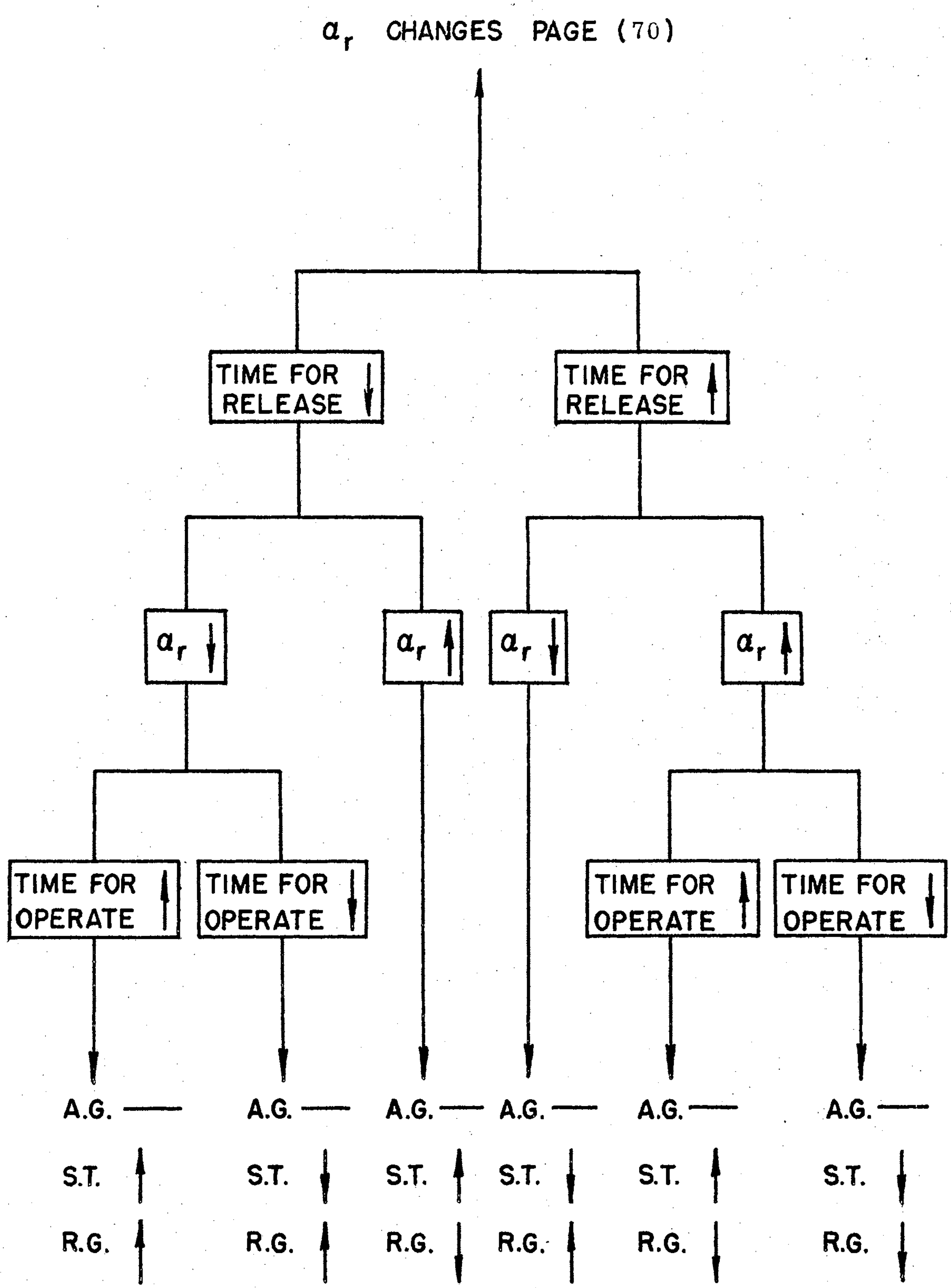


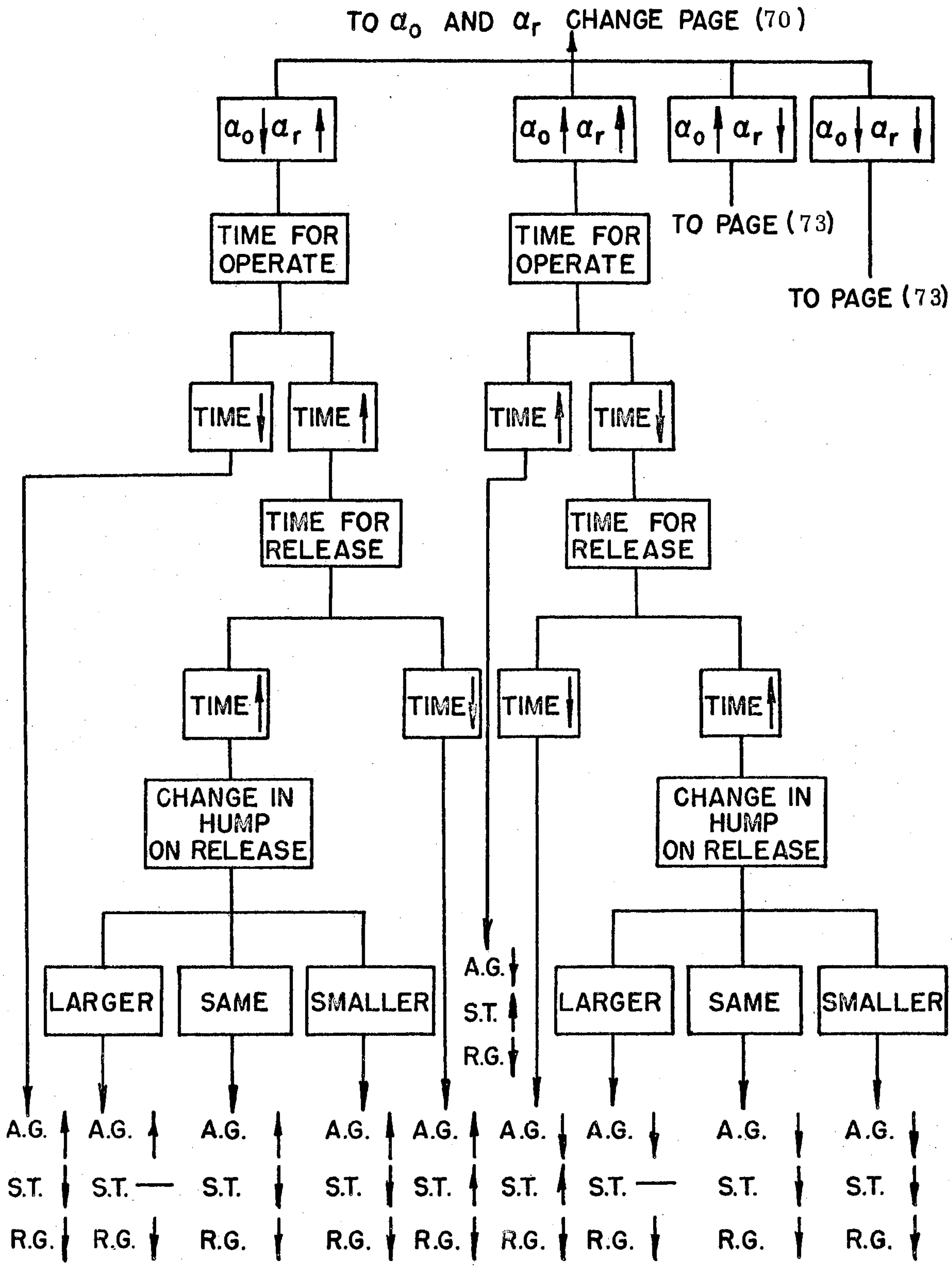
Fig. 20. Logic Network

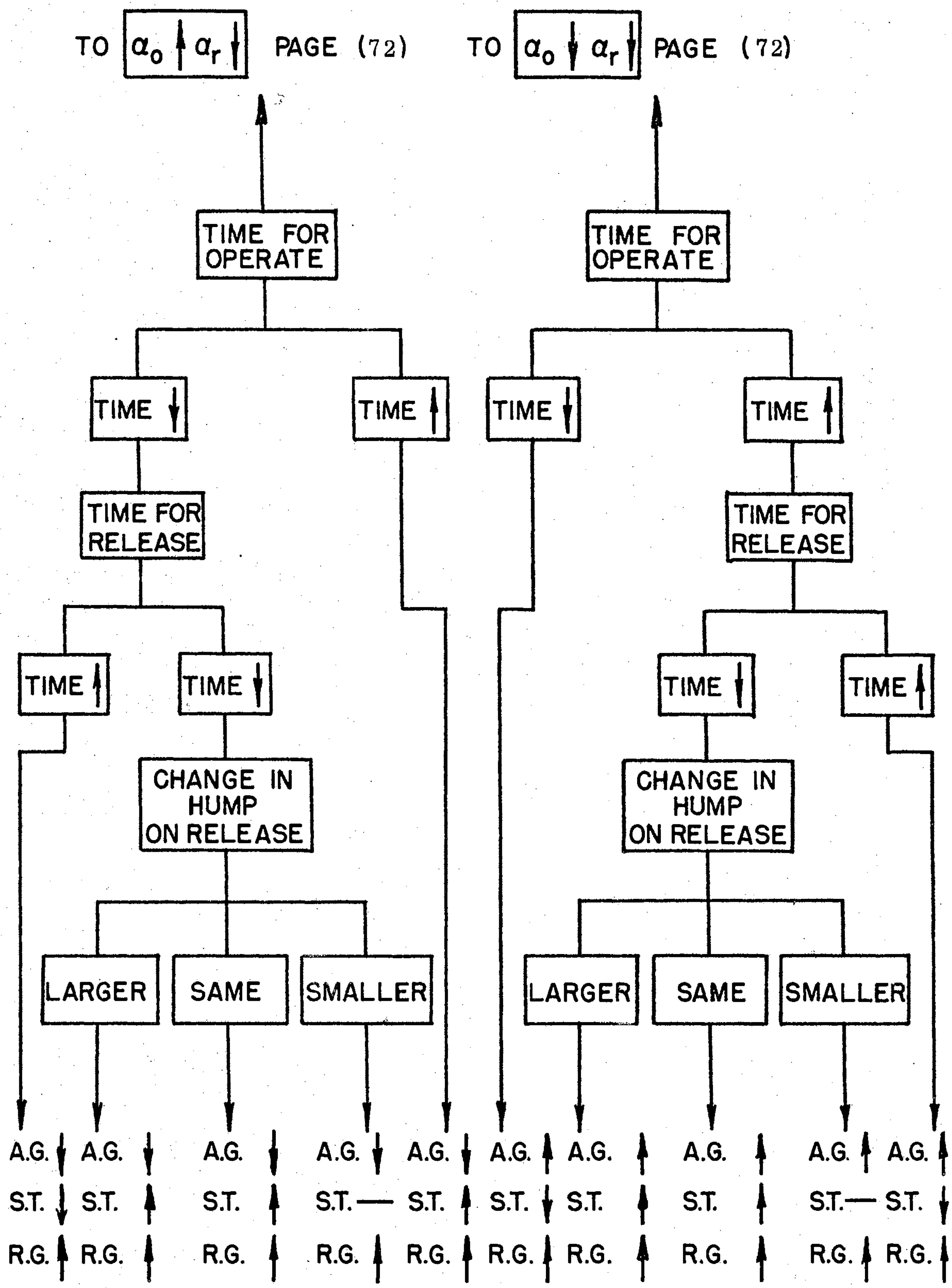

ONE TRACE PAGE (67)
OPERATE TIME
RELEASE TIME
PAGE (69)
TIME ↑
TIME ↓
a_r
a_r
a_r ↑
a_r —
a_r ↓
a_r ↑
a_r —
a_r ↓
a_o
a_o
a_o —
a_o ↓
a_o ↑
a_o ↑
a_o ↓
a_o —
A.G. — S.T. — R.G. ↓
A.G. ↑ S.T. ↓ R.G. ↓
A.G. ↓ S.T. ↑ R.G. ↓
A.G. ↑ S.T. ↓ R.G. —
A.G. ↑ S.T. ↓ R.G. ↑
A.G. ↓ S.T. ↑ R.G. ↓
A.G. ↓ S.T. ↑ R.G. —
A.G. ↓ S.T. ↑ R.G. ↑
A.G. ↑ S.T. ↓ R.G. ↑
A.G. — S.T. — R.G. ↑


OPERATE TIME PAGE (68)
TIME ↓
TIME ↑
a_o
a_o
a_o ↓
a_o—
a_o ↑
a_o ↑
a_o—
a_o ↓
a_r
a_r
a_r ↑
a_r—
a_r ↓
a_r ↑
a_r—
a_r ↓
A.G. ↑ S.T. ↓ R.G. ↑
A.G.— S.T. ↓ R.G. ↑
A.G. ↓ S.T. ↑ R.G. ↓
A.G. ↓ S.T.— R.G.—
A.G. ↓ S.T. ↓ R.G. ↑
A.G. ↓ S.T. ↑ R.G. ↓
A.G.— S.T. ↑ R.G. ↓
A.G. ↑ S.T. ↑ R.G. ↓
A.G. ↑ S.T.— R.G.—
A.G. ↑ S.T. ↓ R.G. ↑


BOTH TRACES PAGE (67)
PAGE (71)
α's
α_r CHANGES
α_o CHANGES
α_o AND α_r CHANGE
NO CHANGES
PAGE (72)
TIME FOR OPERATE ↓
TIME FOR OPERATE ↑
TIME FOR OPERATE
α_o ↑
α_o ↓
α_o ↑
α_o ↓
TIME ↑
TIME ↓
TIME FOR RELEASE ↓
TIME FOR RELEASE ↑
TIME FOR RELEASE ↑
TIME FOR RELEASE ↓
A.G. ↓ S.T. ↑ R.G. —
A.G. ↓ S.T. ↓ R.G. —
A.G. ↑ S.T. ↓ R.G. —
A.G. ↓ S.T. ↑ R.G. —
A.G. ↑ S.T. ↓ R.G. —
A.G. ↑ S.T. ↑ R.G. —
A.G. — S.T. ↑ R.G. —
A.G. — S.T. ↓ R.G. —


a_r CHANGES PAGE (70)
TIME FOR RELEASE ↓
TIME FOR RELEASE ↑
a_r ↓
a_r ↑
a_r ↓
a_r ↑
TIME FOR OPERATE ↑
TIME FOR OPERATE ↓
TIME FOR OPERATE ↑
TIME FOR OPERATE ↓
A.G. — S.T. ↑ R.G. ↑
A.G. — S.T. ↓ R.G. ↑
A.G. — S.T. ↑ R.G. ↓
A.G. — S.T. ↓ R.G. ↑
A.G. — S.T. ↑ R.G. ↓
A.G. — S.T. ↓ R.G. ↓


TO α_o AND α_r CHANGE PAGE (70)
$\alpha_o \downarrow \alpha_r \uparrow$
$\alpha_o \uparrow \alpha_r \uparrow$
$\alpha_o \uparrow \alpha_r \downarrow$
$\alpha_o \downarrow \alpha_r \downarrow$
TO PAGE (73)
TO PAGE (73)
TIME FOR OPERATE
TIME FOR OPERATE
TIME $\downarrow$
TIME $\uparrow$
TIME $\uparrow$
TIME $\downarrow$
TIME FOR RELEASE
TIME FOR RELEASE
TIME $\uparrow$
TIME $\downarrow$
TIME $\downarrow$
TIME $\uparrow$
CHANGE IN HUMP ON RELEASE
CHANGE IN HUMP ON RELEASE
LARGER
SAME
SMALLER
A.G. $\downarrow$ S.T. $\uparrow$ R.G. $\downarrow$
LARGER
SAME
SMALLER
A.G. $\uparrow$ S.T. $\downarrow$ R.G. $\downarrow$
A.G. $\uparrow$ S.T. — R.G. $\downarrow$
A.G. $\uparrow$ S.T. $\downarrow$ R.G. $\downarrow$
A.G. $\uparrow$ S.T. $\downarrow$ R.G. $\downarrow$
A.G. $\uparrow$ S.T. $\uparrow$ R.G. $\downarrow$
A.G. $\downarrow$ S.T. $\uparrow$ R.G. $\downarrow$
A.G. $\downarrow$ S.T. — R.G. $\downarrow$
A.G. $\downarrow$ S.T. $\downarrow$ R.G. $\downarrow$
A.G. $\downarrow$ S.T. $\downarrow$ R.G. $\downarrow$


TO $\alpha_o \uparrow \alpha_r \downarrow$ PAGE (72)
TO $\alpha_o \downarrow \alpha_r \downarrow$ PAGE (72)
TIME FOR OPERATE
TIME FOR OPERATE
TIME ↓
TIME ↑
TIME ↓
TIME ↑
TIME FOR RELEASE
TIME FOR RELEASE
TIME ↑
TIME ↓
TIME ↓
TIME ↑
CHANGE IN HUMP ON RELEASE
CHANGE IN HUMP ON RELEASE
LARGER
SAME
SMALLER
LARGER
SAME
SMALLER
A.G. ↓ S.T. ↓ R.G. ↑
A.G. ↓ S.T. ↑ R.G. ↑
A.G. ↓ S.T. ↑ R.G. ↑
A.G. ↓ S.T. — R.G. ↑
A.G. ↓ S.T. ↑ R.G. ↑
A.G. ↑ S.T. ↓ R.G. ↑
A.G. ↑ S.T. ↑ R.G. ↑
A.G. ↑ S.T. ↑ R.G. ↑
A.G. ↑ S.T. — R.G. ↑
A.G. ↑ S.T. ↓ R.G. ↑

given from the logic network, two such combinations are given. The first experiment gives the standard relay in Fig. (21). The test relay's transient coil current trace is shown in the oscillogram of Fig. (22). The second comparison uses the oscillogram of Fig. (22) as the standard and the test relay's trace is shown in the oscillogram of Fig. (23).

Experimental Results

1. Standard Relay:

$t_o = 21$ MS $\qquad t_{s1} = 34.5$ MS

$i_{o1} = 14.9$ MA $\qquad t_{r1} = 31.5$ MS

$i_{r1} = 6.3$ MA

$t_r = 15$ MS

Test Relay:

$t_o = 21$ MS $\qquad t_{s2} = 43.5$ MS

$i_{o2} = 14.9$ MA $\qquad t_{r2} = 17.5$ MS

$i_{r2} = 6.1$ MA

$t_r = 15$ MS

Therefore:

$i_{o1} = i_{o2} \longrightarrow \alpha_o$ -

$t_{s1} < t_{s2}$

$i_{r2} < i_{r1} \longrightarrow \alpha_r \downarrow$

$t_{r1} > t_{r2}$

Tracing through network gives: A.G. - , R.G.$\uparrow$, S.T.$\uparrow$.

V_{ss} = 25 VDC
I_{ss} = 23.2 MA
R_d = 1040 ohms
R_c = 1080 ohms
Air Gap = .051 inches
Residual Gap = .006 inches
Spring Bias = 57 grams
Restoring Force = 82 grams

Oscillogram Data:

Current Scale: i = 11.6 MA/in.
Time Scale: t = 15 MS/in.

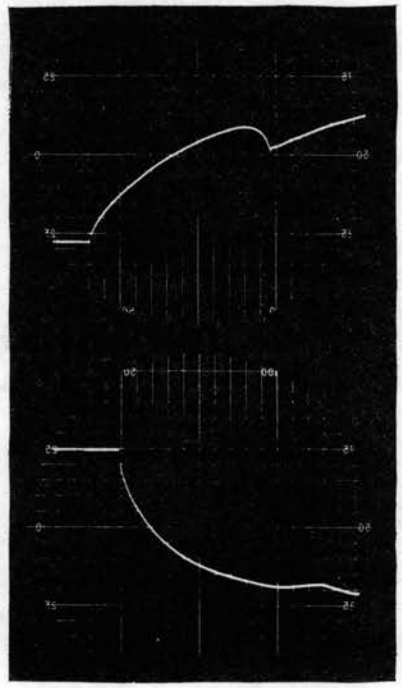


Fig. 21. Standard Relay for Comparison Number One

V_{ss} = 25 VDC
I_{ss} = 23.2 MA
R_d = 1040 ohms
R_c = 1080 ohms
Air Gap = .051 inches
Residual Gap = .014 inches
Spring Bias = 82 grams
Restoring Force = 107 grams

Oscillogram Data:

Current Scale: i = 11.6 MA/in.
Time Scale: t = 15 MS/in.

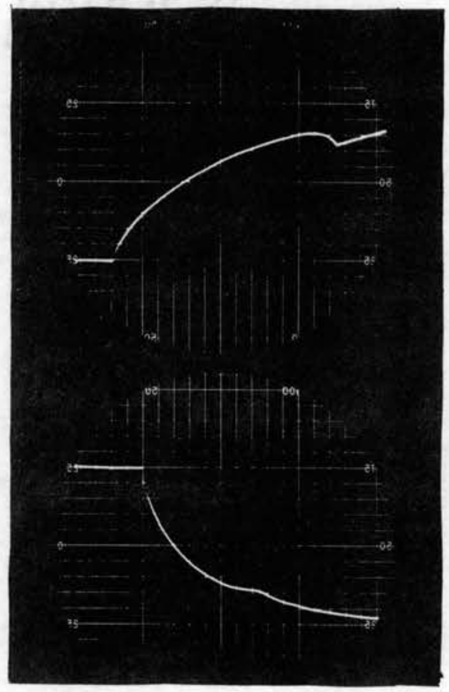


Fig. 22. Test Relay for Comparison Number One; Standard Relay for Comparison Number Two

V_{ss} = 25 VDC
I_{ss} = 23.2 MA
R_d = 1040 ohms
R_c = 1080 ohms
Air Gap = .039 inches
Residual Gap = .007 inches
Spring Bias = 55 grams
Restoring Force = 80 grams

Oscillogram Data:

Current Scale: i = 11.6 MA/in.
Time Scale: t = 15 MS/in.

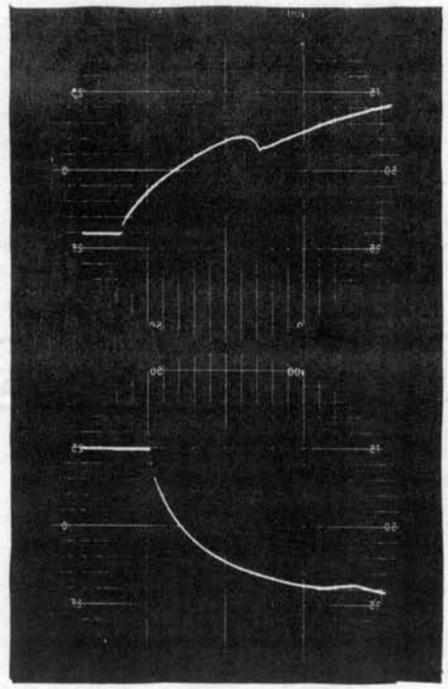


Fig. 23. Test Relay for Comparison Number Two

2. Standard Relay:

t_o = 21 MS $\qquad$ t_{s1} = 43.5 MS

i_{o1} = 14.9 MA $\qquad$ t_{r1} = 17.5 MS

i_{o2} = 6.1 MA

t_r = 15 MS

Test Relay:

t_o = 21 MS $\qquad$ t_{s2} = 27 MS

i_{o2} = 13.9 MA $\qquad$ t_{r2} = 33 MS

i_{r2} = 6.3 MA

t_r = 15 MS

Therefore:

$i_{o1} > i_{o2} \longrightarrow \alpha_o \uparrow$

$t_{s1} > t_{s2}$

$i_{r1} < i_{r2} \longrightarrow \alpha_r \uparrow$

$t_{r1} < t_{r2}$

Hump or release -

Tracing through network gives: A.G.$\downarrow$, R.G.$\downarrow$, S.T.$\downarrow$.

The actual changes can be observed from the information given with each oscillogram in Figs. (21), (22) and (23).

The results of the experimental evidence indicate that the logic network is a simple method of analyzing a system. There is only a limited amount of information given by the analysis in this thesis, but an extension of this logical process has no bounds as long as the individual analysis of parameters can be distinctly associated with the transient coil current. Also, the contact voltage of any relay, sealed or unsealed, can be recorded which could be included in the logical analysis. This should extend the useful information obtainable from a sealed relay.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The system to be analyzed was the relay. The relay was first investigated theoretically to see what would be involved in solving the relay equations directly. It was found that to describe the relay for all conditions of operation six basic equations were required. Also the relationship between the variables ϕ, i, x, and force needed to be established. It was concluded that this type of solution was too complex and time consuming. This would be especially true if many different relays were to be analyzed.

A logic network seemed to offer a method for analyzing a group of relays to detect changes in any of several parameters. Before this network could be constructed, the parameters and the conditions for test had to be selected. With the evaluation of the sealed relay in mind, the non-controllable parameters, air gap, residual gap, and spring bias were chosen. (The effect of the discharge resistance was included in the individual analysis for illustrative purposes and because it can be used to control the release time of a sealed relay.) The individual parameters were then investigated separately to see what the characteristic effects were in relation to the transient coil current trace. This was done for the operate and release conditions of the relay. No investigation was made to see what actual change in magnitude the different parameters had on the transient coil current. This is a suggested subject for further investigation.

After the individual analysis of the different parameters was complete, the conclusions and conditions were then put in a logical and concise form. From these conclusions, a logic network was then constructed to relate any or no change of the coil current trace to the different possible combinations of the variable parameters. This allowed the evaluation of any group of relays as to the relative change of the different parameters with reference to any one of the relays in the group. The logic network was tested for several different combinations of changing parameters and found to give the correct results.

The method of detecting changes in the transient coil current for the different parameters should be investigated further. The methods used in this thesis were valid for the relay used but the sensitivity was not great enough to allow small changes in parameters to be detected. Also the "α_r" on release gives the right indication only if the relay operates mainly in the non-saturated region of the magnetization curve. When a relay operates in the saturated region some other method of detecting the change in the effective inductance should be used. A suggested method is measuring the rate of changing of the release current and using the slope as the characteristic parameter.

A SELECTED BIBLIOGRAPHY

Cameron, C. F., and D. D. Lingelbach. *Relay Characteristics.* Relay Conference, 1956.

________________. *Evaluation of Relay Transients.* Relay Conference, 1958.

Culbertson, James T. *Mathematics and Logic for Digital Devices.* D. Van Nostrand Company, Inc. Princeton, New Jersey, Toronto, New York, London.

Roters, *Electro-Magnetic Devices.* New York: John Wiley and Sons, Inc., 1941, 5th ed.

APPENDIX

SWITCHING PANEL USED IN TESTING RELAYS

In order to simplify and speed the testing of relays a special switching panel is used. The basic requirements of a switching panel are: (1) a provision for handling D.C. or A.C. test voltages, (2) a means of supplying a signal to the oscilloscope which is proportional to the instantaneous current, (3) a means of supplying a signal to the oscilloscope which is proportional to the voltage across the contacts, (4) a means of providing different discharge resistances shunting the test relay coil (5) a means of providing a sweep triggering pulse before the relay coil is energized (6) a means of using different time calibrating methods such as a frequency generator or a time interval measuring device, and (7) a means of energizing the test relay from different locations.

The simplified diagram of the switching panel in Fig. (24) shows the basic elements and the arrangement to satisfy the requirements listed: The sync. relay is used to provide a D.C. signal to a pulse circuit which is used to trigger the oscilloscope sweep.

The operate relay provides the delay between the sweep trigger and the energization of the test relay. It also provides isolation

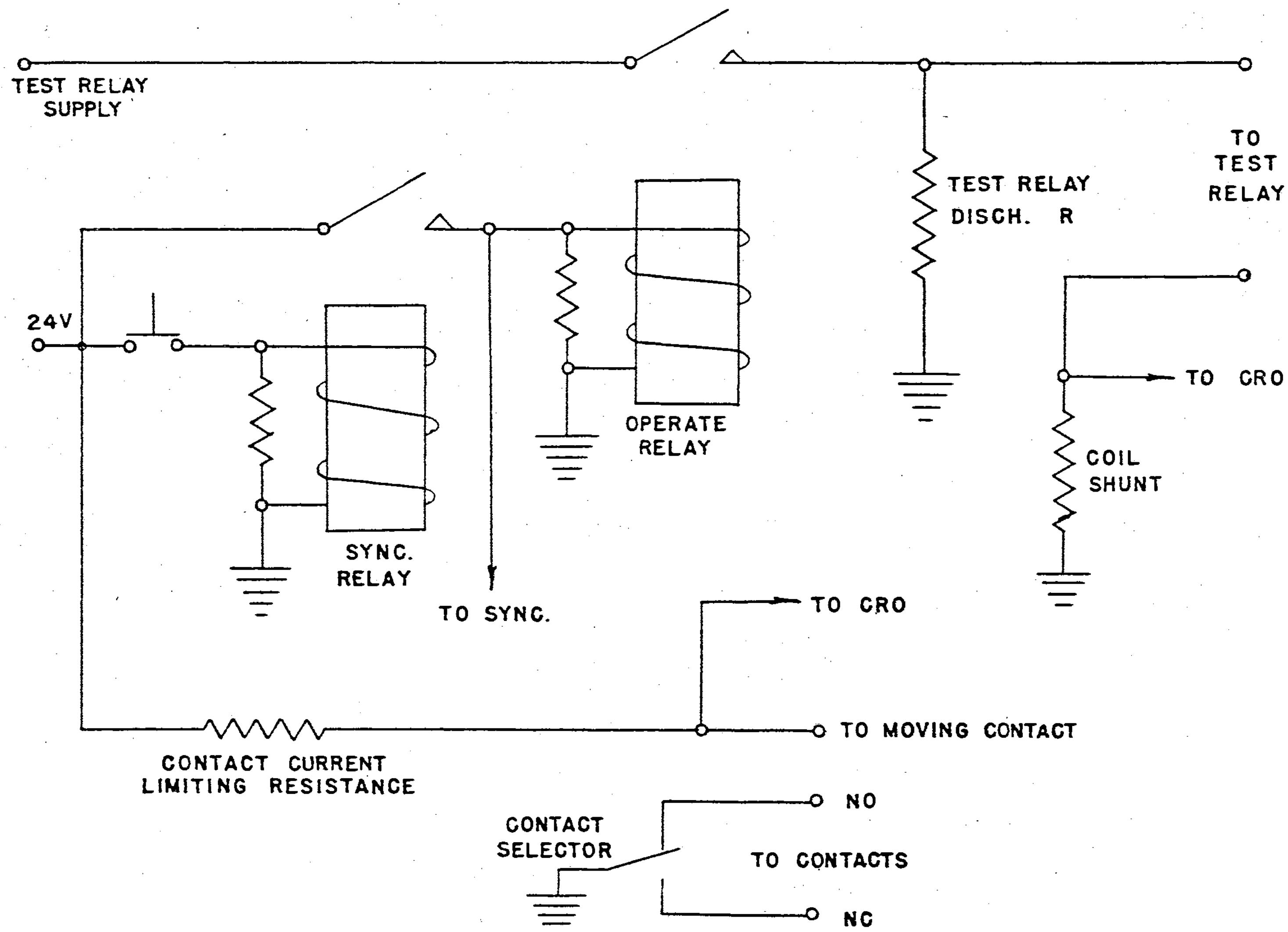


Fig. 24. Simplified Diagram of Switching Panel

between the 24 volts D.C. supply and the test relay supply. In this manner, the relay test voltage may be any value of D.C. or A.C. voltage.

The test relay discharge resistance is used to provide arc suppression for the contacts on the operate relay. The discharge resistance also provides a more definite current path to ground thereby allowing observation of the coil current during decay.

The contact current limiting resistance is used to fix the current in the contacts of the relay under test. The contact selector switch determines which stationary contact is grounded. The signal to the cathode ray oscilloscope (CRO) is taken from the moving contact. Since the Y input to the oscilloscope is used with one side grounded, the signal to the oscilloscope is the voltage across the contacts. Therefore, when the contacts are open, full voltage is applied to the oscilloscope and when the contacts are closed, the voltage should be practically zero.

The coil shunt is placed in the ground lead of the test relay and the voltage drop across it is fed to the Y input of the oscilloscope. The Y input has one side grounded to reduce extraneous pickup. Since the coil shunt resistance is low in value, outside pickup is eliminated.

A complete diagram is shown in Fig. (25). Selector switch S_1 in the upper left is used to select the timing method. The most convenient method of timing has been to measure, with a time interval meter, the time required by the sweep to cover a given distance on

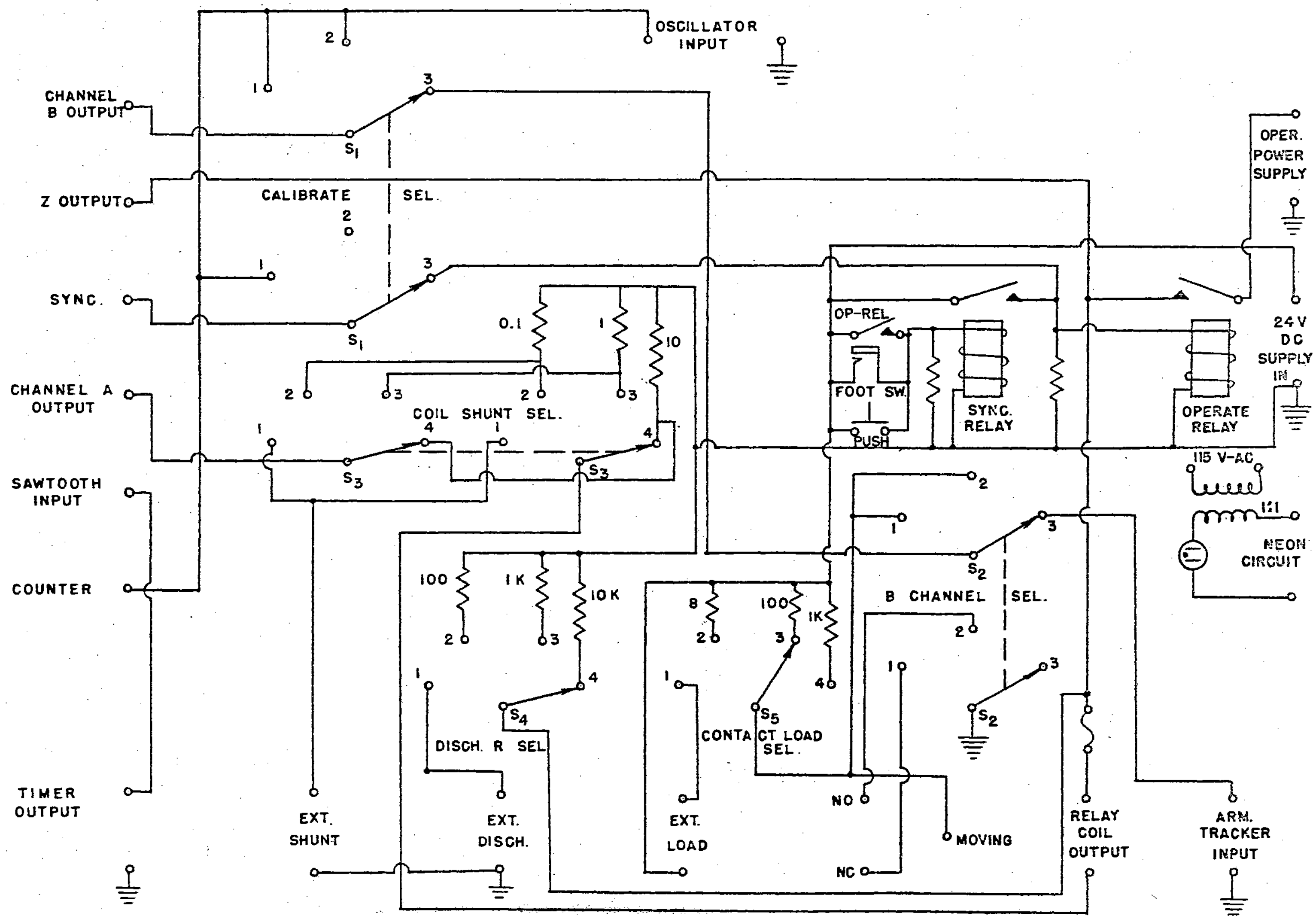


Fig. 25. Circuit Diagram of Switching Panel

the face of the oscilloscope. Some of the newer oscilloscopes have a time calibrated sweep so this timing would not be necessary.

Selector switch S_2, in the lower right, is used to ground the NO or the NC contact and to connect the armature motion input to the B channel output. It also connects the voltage of the moving contact to the B channel output when the armature motion input is not being used.

Selector switch S_3, in the center left, is used to provide the appropriate value of coil shunt resistance. Provision is made to use any value of external shunt resistance in case the values contained in the chassis are not appropriate.

Selector switch S_4, in the lower left, is used to give different values of discharge resistance to the relay coil. Selector switch S_5 is similar to S_4 in that it provides different values of resistance. By switch S_5 different resistance values are selected which determine the contact current.

The neon circuit is used as a convenient way of determining continuity. The push, operate-release, and foot switch control the sync relay allowing different locations from which operation may be initiated.

The "Front View of Switching Panel", Fig. (26), shows the physical location of the terminals and the selector switches. The cabinet is grounded and provides shielding for the components inside. Versatility has been kept in mind in the arrangement used so that as conditions change, the switching panel will still be a useful item in our relay testing.

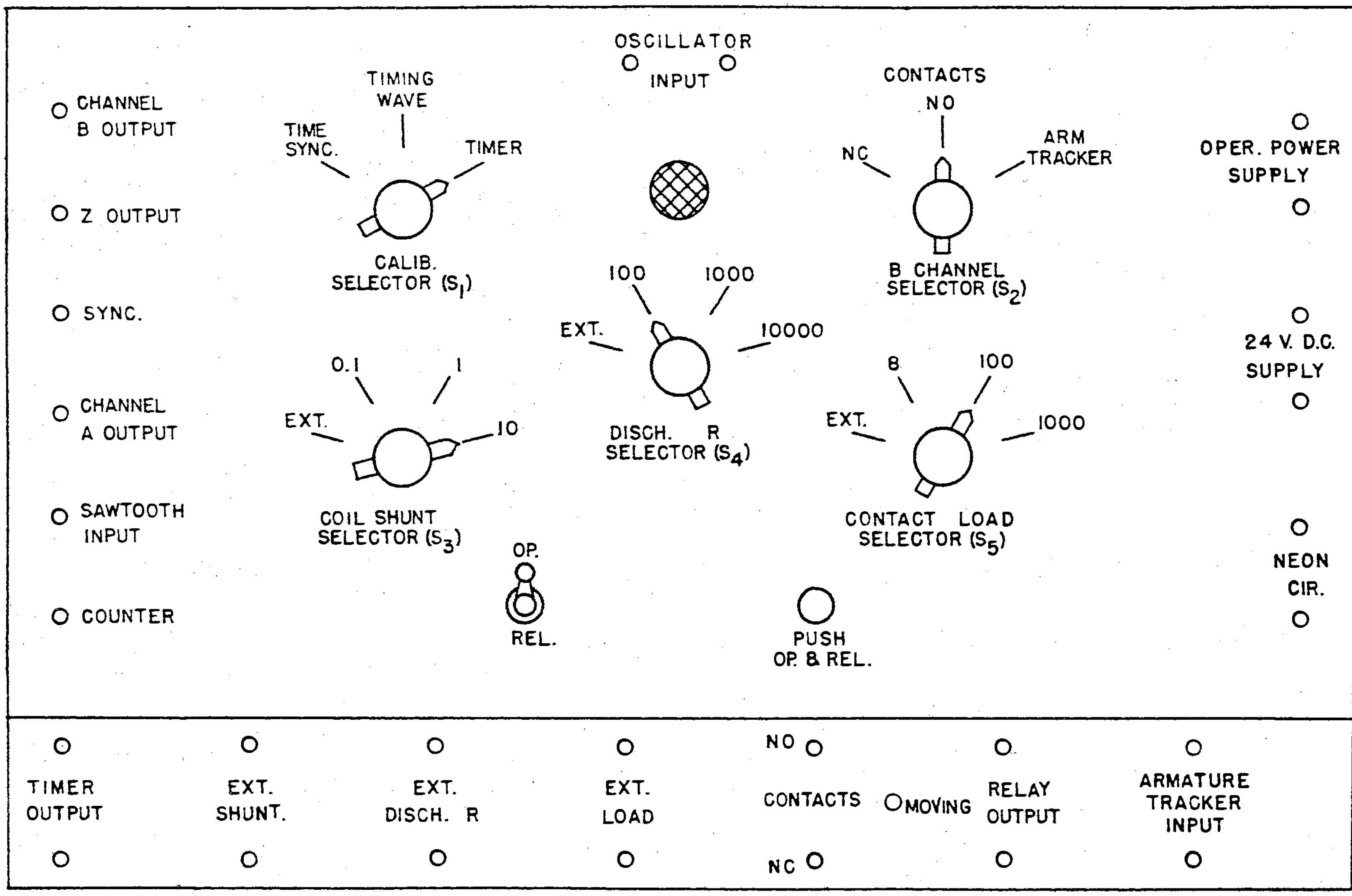


Fig. 26. Front View of Switching Panel

VITA

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