PRINCIPLES OF INDUSTRIAL ELECTRONICS

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By

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Preface

The increasing application of electronic devices to industrial control and manufacturing processes indicate a definite need for a basic course of this nature in the cirriculum of the Electrical Engineering student. The actual applications are so varied, in fact, we dare only wonder how far reaching or how varied these applications can be in the future - it is believed that a course of this nature should primarily emphasize fundamental aspects of control and industrial electronics.

It is intended that this course be preceded by a thorough understanding of electron tube characteristics, d-c and a-c circuit networks in addition to the usual required mathematic courses through differential equations. This background is necessary for the student if he is to have sufficient time to adequately cover the principles of industrial electronics.

The first chapter briefly outlines the general terminology applying to the very broad field of automatic control. The student must not only extend his vocabulary in this field; but he must realize that there may be many methods of accomplishing the same final result, including electronic methods. Several examples and illustrations are offered as an indication of methods of analysis which are employed in control problems. Incidentally, it is hoped that the mathematical treatments and analogies may encourage analytical thinking and indicate the necessity for a strong mathematical background. The student must not lose sight of the fact, although very elaborate and expensive electronic control devices can be constructed and arranged to govern a process, there may be much simpler and less expensive methods also available. There is a tendency to lose sight of this fact when the "mystical" electronic unit is made available. If electronic applications are to receive their deserved attention, they must be cautiously and judiciously applied in the field only after considered evaluation.

The second section of the course deals with principles of conversion and circuit elements in combination with electron tubes under both steady and changing conditions. It has been found that the student will obtain a much firmer concept of specific applications if he is able to analyze circuit combinations dynamically rather than from a point by point approach. This procedure lends itself readily to circuit study and analysis based upon oscilloscopic studies.

The last portion of the course deals with electronic systems. In some instances, specific applications are introduced to illustrate a method of combining circuit elements to satisfy a predetermined control process, but, in general, it is desirable to develop a <u>system</u> to satisfy the predetermined process and arrange the circuit elements as a part of the system.

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THE PRINCIPLES OF CONTROL

The general concepts of control are more or less familiar to us all. We must have control and control methods in government, in the church, in human action, in manufacturing; in fact, any process must be controlled if a definite goal is to be attained. From an engineering standpoint, control may be accomplished either manually or automatically. The automatic controller is any kind of device which will measure the variation of a process, either continuously or at stated intervals, and then make corrections according to some predetermined rule, thus holding the process within prescribed limits. Continuous processes involving high speed, and high accuracy mass production lines have given added emphasis to automatic control within the past few years. High accuracy has demanded control methods more reliable than possible through direct manual manipulation. The simple process of applying the acetylene cutting torch to a sheet of steel may be done by hand, or some mechanical gadget may accomplish the same result. Simply cutting a gash across the steel plate is of no value to us however. The cut must be of such a nature that it fits into a general plan previously conceived; that is, regulation must be applied to the control process.

The actual control devices which may be applied to regulate a process are essentially unlimited. Some very simple arrangement of levers and gears may accomplish exactly the same control as some other very elaborate complex device. Yet there must always be some few fundamental laws of science which apply to the control problem of industrial manufacturing. As long as these laws are satisfied the process may be regulated manually or it may be done automatically. The final method of regulation becomes a study of relative product cost. Yet, in any case, control is an exact science, the basic laws apply here as they do in all other branches of science, and the problem should be analyzed by the same methods as used in any of the exact sciences. Once the laws governing the required process have been established, it becomes a problem of engineering ingenuity to devise mechanical or electrical means to satisfy these laws and control the process.

Until recent years the laws of regulation were satisfied by some manual operation which involved the human elements. The result was a product which was not entirely uniform. Automatic methods of accomplishing the regulation of a process may be devised, often with increased efficiency and economy resulting. Automatic control of an entire industrial process may be required or perhaps only some one operation in a process may be made automatic. The final product will ultimately determine whether it is economical for the manufacturer to participate in the research and development required for the automatic control of the process or whether semi-automatic, or manual control can economically satisfy the tolerance requirements of the final product.

Terminology: Before proceeding further with the discussion, it is necessary to establish certain definitions. The general terminology in the field of automatic control seems still to be in some confusion. Recently terms and concepts of automatic control have been prepared by the ASME Industrial Instruments and Regulators Division Committee on Terminology.

Automatic Control System

Automatic control of any process must be arranged so that a balanced state exists. The term process, as used, is general and may be considered as being composed of the demand or output, and the supply or energy source. In general, a balanced condition can be satisfied by a control system consisting of (1) some means of measuring the process medium and (2) some method of controlling this medium. This latter system acts to regulate the control agent. The measuring part of the control system will consist of the (1) primary sensitive element and (2) the measuring or converter element. The controlling part of the system consists of (1) the controller proper and (2) the final control element, fig. 1.

The primary sensitive element is subjected directly to the instantaneous variations of the controlled medium. It may be some device like a thermometer bulb, or a pressure chamber. The measuring element is arranged to convert the variation of the primary sensitive element into some kind of indication of the state of the controlled variable. Often times these two elements of the control system are combined in a manner so that one device performs both functions. For instance a mercury thermometer can

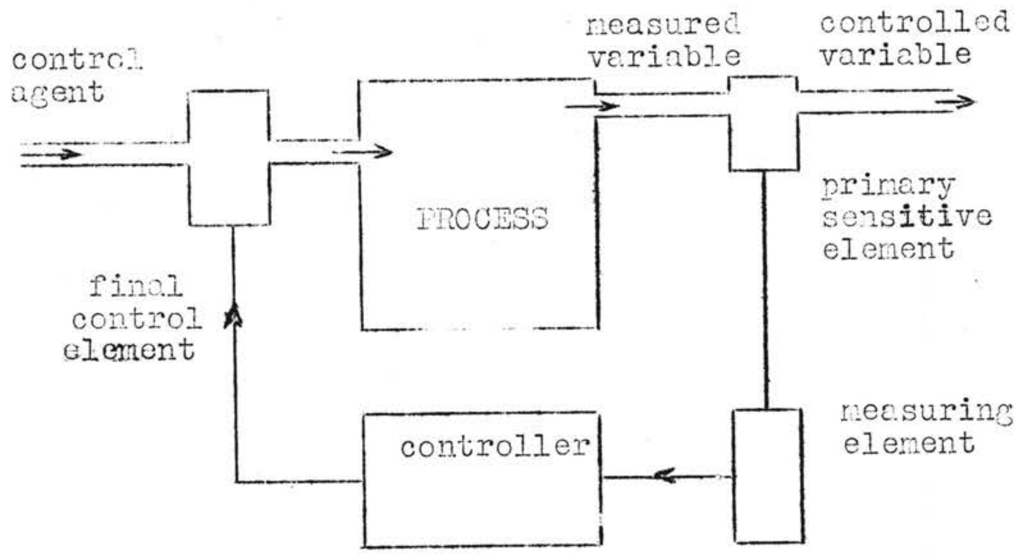


Fig. 1. General arrangement of an automatic control system applied to a process.

easily be arranged to act as an electric switch. Fig. 2 shows a common mercury thermometer. Two fine platinum wires are sealed in the glass envelope so that they protrude through into the inner opening in the glass column. As the temperature of the mercury is increased due to heating the mercury will rise in the column and complete the electrical circuit between the two contacts. The limits of operation can be set between any desired points by proper placement of the contacts. It may happen that more control points may be desired. This can be obtained by including other contact wires

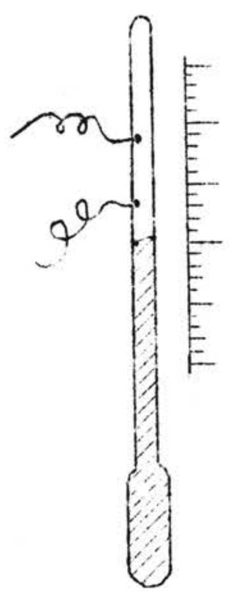


Fig. 2. Mercury thermometer switch.

perhaps arranged to give two speed or multi speed control of the final control element. An auxiliary temperature scale might be included if actual temperature readings are also desired. It often happens that temperature may have to be controlled within very close limits. The above type of thermometer switch can be arranged to operate on a temperature differential of only a few hundredths of a degree by carefully constructing the glass tubing in the region of desired control, thus giving a magnified mercury movement.

The controller is a device arranged to detect the variations in the measuring element and initiate corrective action through the final control element. The final control element must then operate upon the control agent in some manner to off-set the change which occured in the controlled medium. Quite often one or more of these elements are combined into a single device, yet the various steps in the automatically controlled process must be satisfied in the order indicated.

The balanced condition of the process is governed according to some prearranged schedule and is referred to as regulation. In practice many variable factors in the system present serious problems if stable operation is to be maintained. The process requirements will determine the degree of stability demanded of any control system. Stability of regulation may be compared to a resonant inductive-capacitive circuit. The amount of damping resistance introduced in the L-C circuit ultimately determines the current-time reaction. In the control system the flow-time reactions likewise determine the stability of the system (fig. 3).

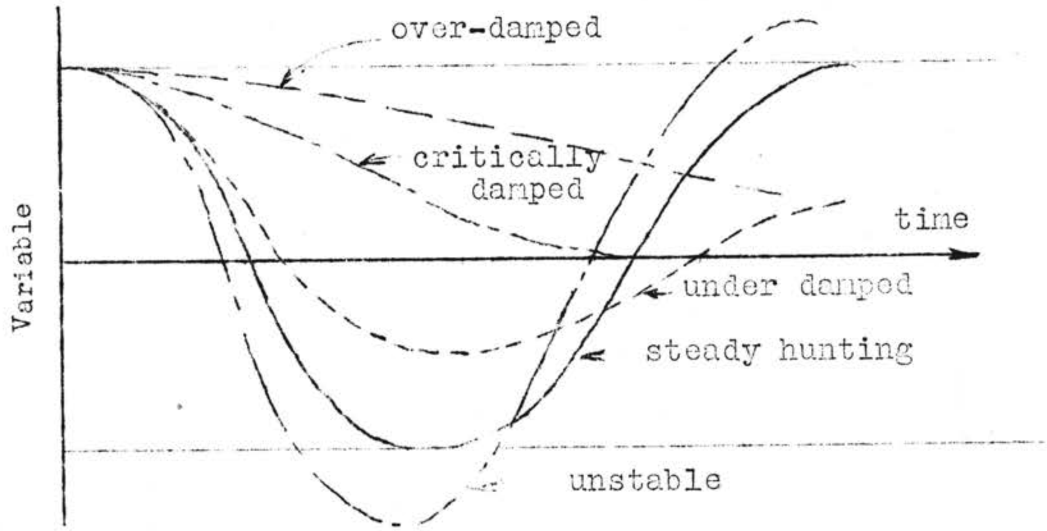


Fig. 3. Degrees of process regulation.

The control system should be so adjusted that it will respond at the earliest moment if there is to be a minimum of disturbance in the process. In general, however, the closeness and quality of control required will govern the final degree of stability. One of the greatest hinderances to stability results from system and process lags, which may cause hunting or even unstable or oscillating conditions.

If hunting or unstable regulation is to be overcome some sort of stabilization or feed-back must be introduced in the control system. This in effect regulates the sensitivity of the system, and, if properly applied, the system may be made as stable as the process requires. Stable action accurs when the active forces of the system oppose each other in time and magnitude and must be achieved regardless of cost.

Seldom does a control system maintain the controlled medium at a single constant value; this would impose most stringent conditions on the control system; but usually the controlled medium may be allowed to vary between certain limits (Fig. 4).

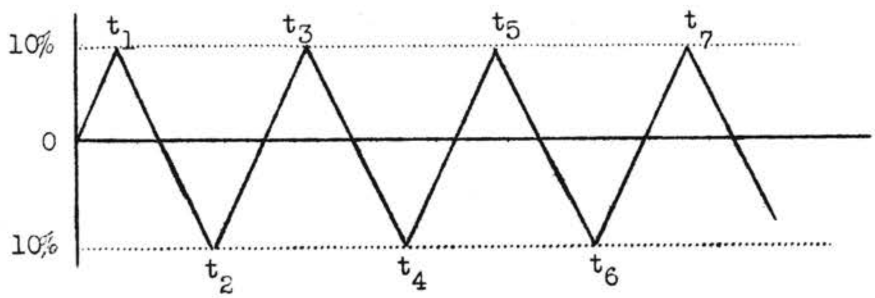


Fig. 4. Ideal differential of the controlled medium.

Process Lags

If the controlled system and the process had no time lags, the problem of automatic regulation would be somewhat simplified and the process differential could be reduced to zero. However these lags are present and must be counteracted in some manner. Further, these lags, combined with the method by which the controller produces the counteraction (mode of control), ultimately determine the rules governing the action of the controlled system. A number of lag factors may exist in a system which prevent the control agent from responding instantly to a differential variation of the controlled medium. The lags present in the process itself will first be considered. They include capacity lag, transfer lag, transportation lag, and reaction lag.

Process Lags

The ability of the process to absorb or store up energy is referred to as its capacity. The amount of energy stored represents the difference between the energy entering and leaving the process during a given interval of time. The opposition to instantaneous energy flow is generally referred to as resistance. If resistance is present, the process has not instantly conducted the energy flow, otherwise there could have been no energy storage; i.e., the system would have no capacity. There are many times when the capacity of the process proves advantageous, for the capacity has an inertial effect, and displays stabilitzing tendencies. If the process requires instantaneous response, however, process capacity is objectionable. The fact that the process does store energy, means that the controlled medium does not respond instantly to some change established in the control agent; in effect, a time interval exists which is referred to as process or capacity lag.

The greater the process capacity-often referred to as demand side capacity-the greater the time constant; or in effect, the greater the stability. Fig. 5 will indicate

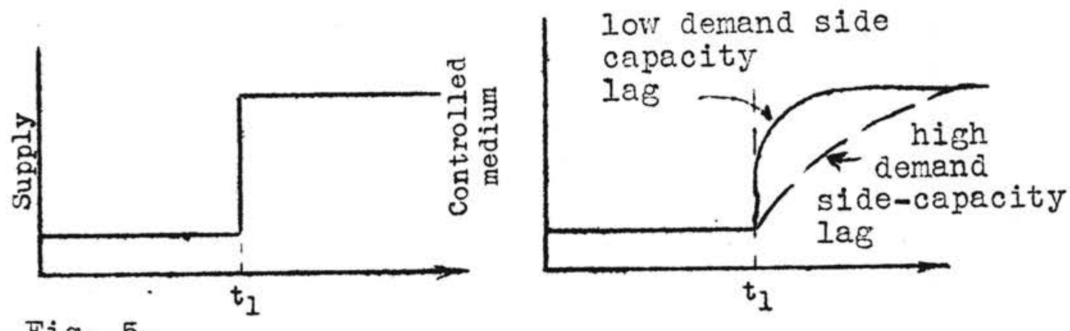


Fig. 5.

the uncontrolled process reaction of processes with high and low capacity and the resulting change on each system as a given supply change is made.

The second lag present in the process is <u>transfer lag</u>. Any sort of barrier between the supply and demand sides adds resistance and capacity to the system. If this capacity is high it also has high inertial effects, retarding any change in the demand side which might be attempted by the supply side. This supply side capacity, or transfer barrier results in transfer lag. As opposed to process capacity lag, transfer lag is usually undesirable in process control since the rate of supply change is not immediately effective on the demand side. This results in overshooting the process differential. Fig. 6 indicates the retarding effect of transfer lag which

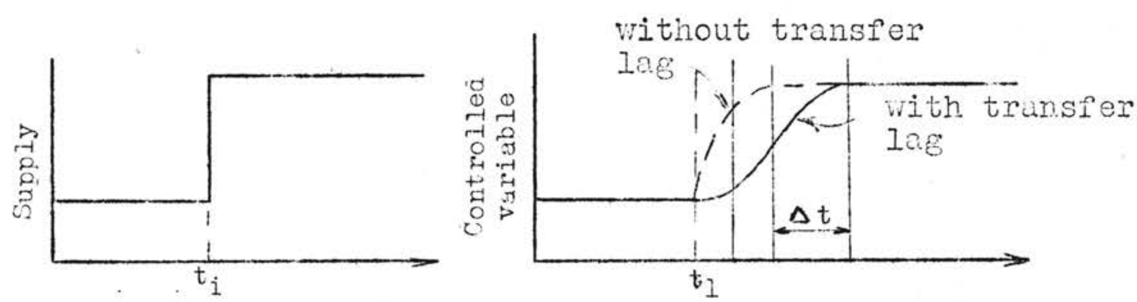


Fig. 6. Effect of introducing transfer lag in the process.

might be present in the system of fig. 7. The heating element is imbedded in a ceramic housing which has both capacity and resistance (transfer lag) in addition to the liquid capacity.

<u>Distance-velocity lag</u> results from the placement of the primary sensitive element with respect to the energy

supply. If the primary element is remotely located (fig. 7) there will be an interval of time (delay) required

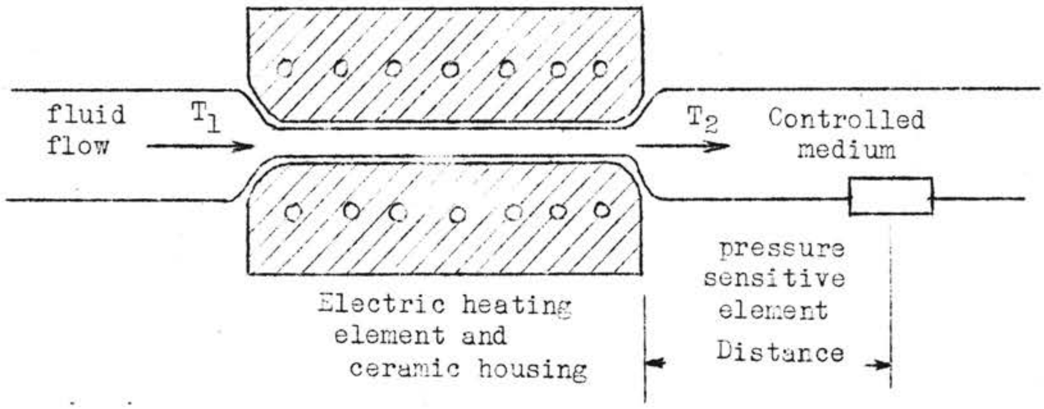


Fig. 7. System having transfer lag (supply side) and capacity lag (demand side).

for the controlled medium to reach the sensitive element after its temperature has been altered by the heating process. The delay may be expressed as

$$\text{lag} = \frac{\text{distance}}{\text{velocity}} = \text{dead time}$$

This interval between the time when the demand changed, and the time that the corrected medium required to meet the increased demand is the distance-velocity lag, sometimes called transportation lag. This effect on the process of fig. 7 is shown in fig. 8.

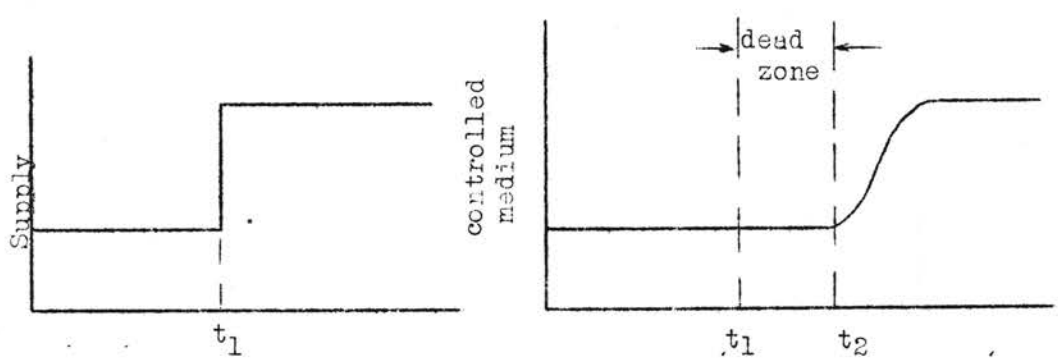


Fig. 8. Effect of transportation lag, transfer lag, and capacity lag.

The time from t_1 to t_2 is known as the process <u>dead-</u>

time, i.e., the controlled medium will not correct for demand changes for a definite time, and even though correction was started immediately in the heating process the primary element will not begin to indicate the [illegible] corrective measure for some time.

Reaction lag may be present in some processes, principally chemical processes. Many chemical processes require long periods of time before the process is [illegible] completed and a uniform average condition results. It is impossible for the primary sensitive element to "know" just when this time occurs and initiate corrections for any deviation from normal. When reaction lag is encountered in any process it usually proves more effective to control some "secondary" element in the process which in turn is related to the final process demand.

Controller lags

Not only may the process contain several lags but the controller itself may be guilty of introducing various lags. Obviously, it is desirable to have the controller respond instantaneously but this may not be achieved. Each element in the control system may introduce individual lags. The primary sensitive element may not instantly respond to changes in the controlled medium but may require definite time to reach equilibrium after the controlled medium has changed. Likewise the measuring element may not instantly synchronize with the primary measuring element. The controller itself may require some time to convert the information from the measuring element into an activating force for the final control element; and last, the control element is seldom instantaneous in its action.

A simple application of a controlled system like fig. 1 may best illustrate the action of a system containing several distinct lags. A liquid is forced to travel through the piping arrangement of fig. 9. The liquid emerges from process I with a temperature T_1. Before

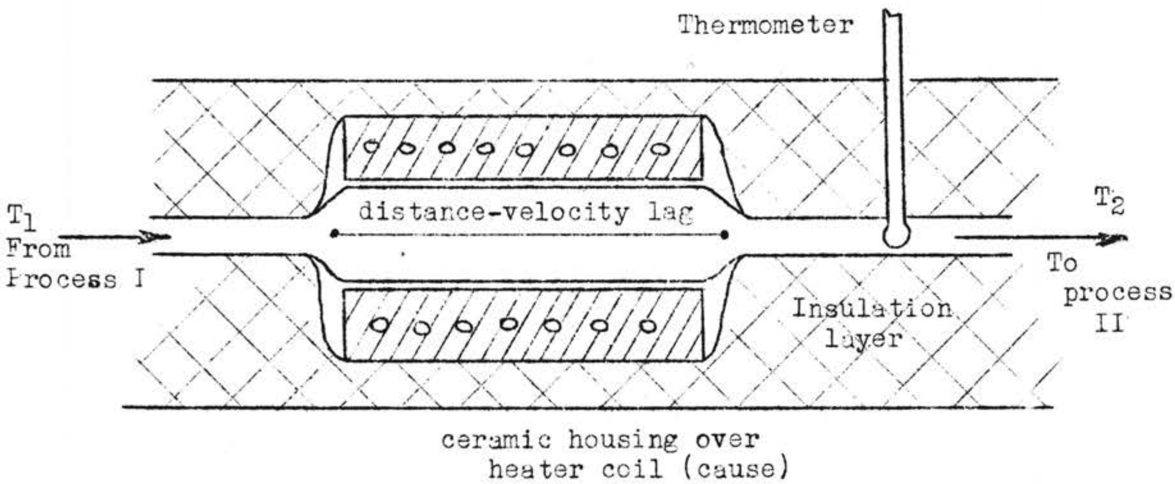


Fig. 9.

entering process II, the temperature must be increased to T_2. An enlarged area is introduced in the pipe to allow dead time for the applied heat to raise the liquid temperature so that it will emerge with a temperature T_2 as required in process II. There will be some predetermined transportation lag between processes I and II.

An electric heating element imbedded in a ceramic housing serves as the source of heat energy required to increase the liquid temperature to T_2. The ceramic housing will introduce a transfer lag, and the liquid can only respond slowly to any sudden application of energy to the heating coil. In a similar manner the outer insulation and the ceramic housing tend to retain their temperature even though the liquid temperature should drop suddenly, and this stored heat would transfer to the cooler liquid. This controller capacity lag displays an inertial effect. The ceramic housing may be considered as composed of two parts, the high heat capacity and negligible thermal resistance and a surface condition which has negligible heat capacity and high thermal capacity. As long as conditions are stable, the rate of transferring heat from the source to the demand side will depend only on the drop of temperature across the solid surface. But should the demand change, the thermal capacity of the inner ceramic requires time before its temperature changes.

This general process might be accomplished by a number of physical arrangements, but consider the electrical method proposed in Fig. 10. The electrical heating element

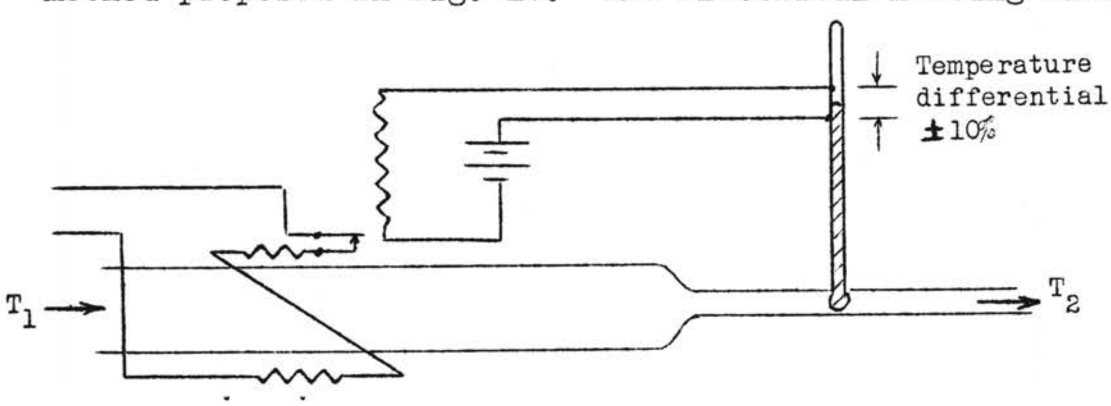


Fig. 10. Automatic heat control system

is controlled by a relay. A mercury thermometer acts as a monitor switch to energize the heater whenever T_2 drops below a predetermined level. Theoretically, the overall process might be pictured graphically as in Fig. 10. As represented here the temperature of the liquid to process II was allowed to have a variation of plus or minus 10% and we find these limits are reached in a time $\Delta t = t_2 - t_1$, which may be considered as the lag of the entire system. While it might be possible to reduce the temperature variation to perhaps plus or minus 2% it might prove uneconomical based upon a study of the entire process economy.

The lag ΔT might likewise be reduced but again the process might not require such close limits and economically could prove undesirable. It is interesting to note that the lag of this simple system is quite involved. We have already indicated several lags which occur in the system. We must also consider that there are slight lags introduced by the thermometer, and the heating element as it comes up to operating temperature, once the relay contacts have closed. The relay further introduces dead time in the system. Controller <u>dead time</u> is the interval between the change of the variable and the final movement of the relay to close the contacts.

Suppose that in our example the thermometer is located some distance from the heating element. The response of the thermometer would not instantly follow changes near the heating element but rather there would be a definite delay introduced which is proportional to the distance between the heating element and the thermometer location and to the velocity of the liquid. The remote location of the measuring element introduces process dead time (sometimes called distance velocity lag) which is equal to distance ÷ velocity and illustrated in fig. 11.

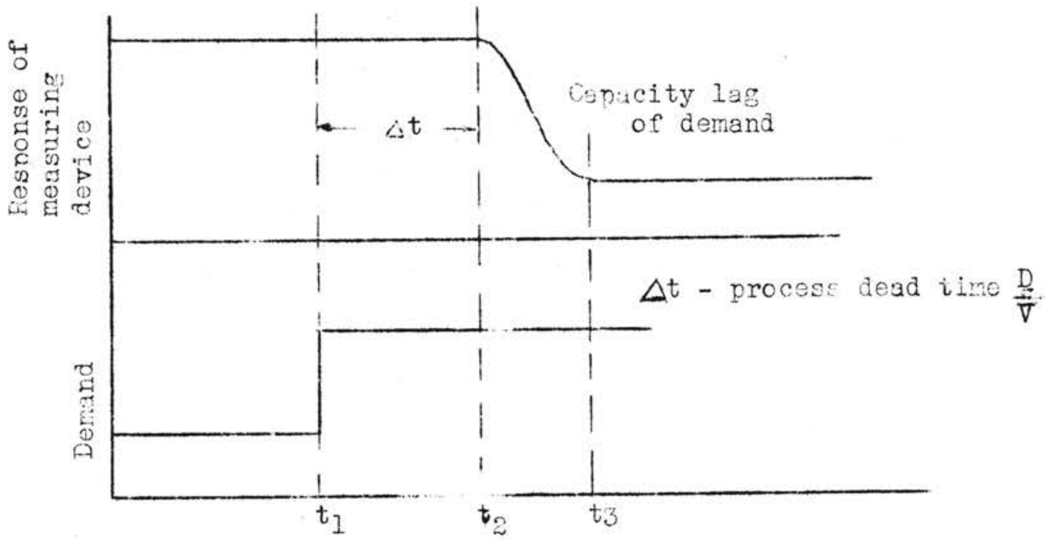


Fig. 11. Delayed temperature response due to process dead time in uncontrolled system.

Quality Control

Automatic control may be incorporated in almost any process. Whether this is desirable or not is another question which must finally be determined in relative economies. Automatic control may result in more uniform regulation of a process but this may not be called for; but in general, the outstanding advantages in favor of automatic control acrue from increased production, higher uniformity of product, decreased unit cost, increased efficiency, greater utilization of materials, etc.

The requirements imposed on automatic control equipment are generally more rigid than those demanded of individual manually controlled machines. Machines are usually satisfactory as long as they continue to operate without requiring too much maintenance and power, while control mechanisms must be depended upon to work accurately over much longer periods of time. A punch press may continue to operate even though certain of its mechanisms may be badly worn and even though the action time may vary within limits; but if it is automatically controlled, this control mechanism, must function at exactly the right instant with exactly the proper stability of regulation or the operator may lose a hand, or an expensive part may be destroyed in the tiny fraction of a second during which the controller is active.

The merits of automatic control are always evaluated by the end product in any process, for the final purpose of automatic control is to secure increased efficiency in the process, or to improve the quality.

It is seldom that any form of automatic controller operates directly from the final product of a process. More often the primary measuring element is arranged to respond to some intermediate step in the process. Actually the measuring element may introduce lags and static errors and specific values may have little meaning to the measuring element. Temperature distribution may illustrate our problem. Several thermocouples may be advantageously located throughout an oil cooled transformer and arranged to automatically shift loading should the temperature exceed some predetermined value. Actually the thermocouples may not have been placed at the "hot spots", but a relative position was chosen when locating thermocouples. The exact relation existing between the "hot spots" and the chosen location must be known however. Any absolute measurements made at the thermocouples would not give true "hot spot" temperatures and static errors might be high. Unless it is desired to know absolute values of temperature this system would prove entirely adequate for automatic control so long as operating cycles can be periodically repeated (reproducibility). It is possible that some sediment might accumulate about one or more of the thermocouples and cause the measuring element response to drift. This static error is of little consequence as long as some correction methods are available and adequate compensation can be introduced to maintain the desired degree of reproducibility.

If the above process required absolute metered values of temperature as well as automatic protection the control equipment becomes more difficult to maintain and service. Simple adjustments to off-set static errors may not also make necessary corrections for metering accuracy. However, it is seldom that both automatic control and absolute metering are required of the same equipment; although electrical and electronic control devices do lend themselves to this type of service most readily.

The dead time lag of electrical pickup devices or primary measuring elements is normally much less than the dead zone of mechanical measuring elements. Friction and lost motion in mechanical pressure gages, flowmeter, etc. may cause the dead time to be 4 to 10 times greater than a corresponding electrical converting element.

Process drifts due to ambient conditions have a marked effect upon dead time with a resultant effect upon the reproducibility. If ambient drift is rapid, variations are greater for each operation and inspection methods will catch the errors and necessary corrections can be immediately introduced in the controller. Slow drift may cause the variations to be so gradual that much material may actually be spoiled before inspection detects the drift. This is obviously related to the differential of the resultant product. Very limited tolerance (small differential) demands most exacting control and is reflected in the amount of drift tolerated by the automatic control system.

It is often possible to predict drift based upon experimental small scale models and this information is quite readily incorporated in electronic control devices, arranged with circuits which even give pre-emphasis to the known drift of a process.

The primary measuring element must be so chosen that it will respond to pressure, temperature, or some changing physical quantity in the process. Often the controlled medium is not measured but some indirect part of the process may be chosen, but the exact relation of this chosen condition to the controlled medium must be known. Should any unusual change occur in this relationship, automatic control instantly loses its value. Suppose that a process is arranged so that as a temperature change occurs a change in pressure results. This pressure change may in turn operate a piston and finally control the energy source supplying the increased temperature. Exact relations must exist for each step in the measuring procedure if the energy supply is to be made to exactly follow the demand caused by the temperature change of the controlled variable.

Any changes in load in an automatic system must be off-set by supply changes. Load changes result from:

(a) Changes in demand
(b) Changes in supply
(c) Changes in associated variables
(d) Changes in control point.

Any demand change is immediately reflected in the controlled medium while a change in supply reflects a delayed change in the measured variable. fig. 12.

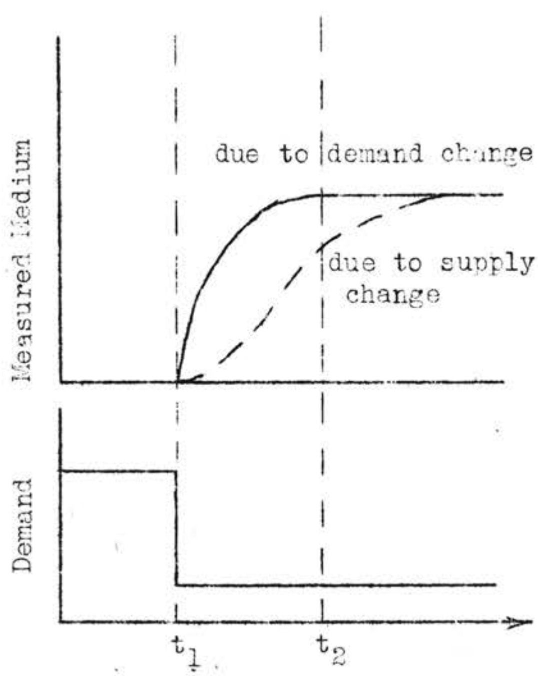


Fig. 12. Effect of load change on uncontrolled process.

It will be observed from fig. 12 that the measured variable responds rapidly to a sudden change in demand but the change due to supply change is quite sluggish due to transfer lag. Many processes must tolerate lags such as illustrated, and should automatic control be applied to such a system allowance must be made for these delays. Lags thus force the controller to indicate what the controlled variable <u>was</u>, not what it <u>is</u>, yet the automatic control system must function to return the variable to a prescheduled level, preferrably in as short a time as consistent with requirements of the process.

<u>Controlled Variables</u>

As previously indicated control devices are designed to respond to changes in temperature, pressure, liquid level, or some other physical quantity in the process. Practice indicates that a number of variables in the process may require control if the process is to retain balance. Only a limited number of these variables need to be measured however to control any particular process.

Undoubtedly <u>temperature</u> is the most important variable in industrial processes. Heat flow is difficult to control, often physical motion of matter is not involved, and processes are often influenced by several temperatures within the same process as well as ambient temperatures, and hence control devices must be arranged to respond to temperature differentials. The measuring element may assume a variety of forms arranged to convert temperature change into either physical movement or electrical impulse voltages depending upon the type of controller system.

<u>Pressure</u> or <u>vacuum</u> control is quite often associated with temperature control. Like temperature, pressure or vacuum changes usually operate within specified limits and some differential can be established for the process.

<u>Fluid flow</u> and <u>liquid level</u> control are especially

important in chemical processes. They are closely associated with temperature and pressure control. Fluids flowing in a process allow the introduction of materials in a process at the proper moment and also serve as a source or conveyor of energy.

Many other controlled variables may be associated with a process, humidity, concentrations, dimensions, density, evaporation, drying, purification, are only a few of the many variables which may be utilized for initiating control system operation.

Analytical Analysis.

Before automatic control can be applied to any process, each step must be studied completely. Automatic control is a mathematically exact science. It obeys all the laws of the physical sciences. Even a simple process may involve many related variables. The exact relations of all of these to the complete process must be known and expressible mathematically. It is common practice to denote variables and their relation to the process as partial differentials. Velocity, acceleration, heat flow, vibration, oscillation may all be expressed as partial derivatives. Pure mathematical studies are cumbersome, though necessary. It is often convenient to supplement pure mathematical analysis with experiemntal test data. This data is often obtained from scale models arranged as a pilot process. This procedure is often necessary if the relation of the variables to one another and to the process are to be properly evaluated. Under some conditions it proves desirable to convert the process to some simple analogy, perhaps hydraulic, thermal, electrical or mechanical, and then determine the reaction of the system based on an analogy more familiar to the engineer. Of course the results can then be converted into terms of the actual process. The analogy is most easily explained by comparing the mathematical equations of the two systems. For example, the equation of a series electrical circuit containing resistance R, inductance L, and capacitance C, and acted on by a voltage e producing current i is:

$$e = L\frac{di}{dt} + Ri + \frac{1}{C}\int idt$$

$$= L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C}$$

where q is the charge. For a simple mechanical system containing mass M, and stiffness K, a resistance R, and acted on by an alternating force f, producing alternating velocity v, the differential equiation is:

$$f = M\frac{dv}{dt} + Rv + K\int vdt$$

by using compliance C as the reciprocal of stiffness K, this equation may be written in the same form as the electrical equation:

$$f = M\frac{dv}{dt} + Rv + \frac{1}{C}\int vdt$$

$$f = M\frac{d^2x}{dt2} + R\frac{dx}{dt} + \frac{x}{C}$$

where x is the displacement. From these equations we can set up the analogue where:

(a) Mass is analogous to inductance
(b) Compliance is analogous to capacitance
(c) Mechanical resistance is analogous to electrical resistance
(d) Velocity is analogous to current
(e) Displacement is analogous to charge
(f) Force is analogous to voltage.

This analogy between the mechanical and the electrical system may be summarized. Table I gives the relation between the electrical system and the corresponding mechanical quantities expressed in the metric system.

Table I

Mechanical			Electrical		
Quantity	Unit	Symbol	Quantity	Unit	Symbol
Velocity	cm/sec	v	current	amperes	i
force	dyne	f	voltage	volts	e
displacement	cm	x	charge	coulombs	q
mass	gram	M	inductance	Henry	L
compliance	cm/dyne	C_m	capacitance	Farad	C_e
resistance	dyne/cm/sec	R_m	resistance	ohms	R_e
reactance	dyne/cm/sec	X_m	reactance	ohms	X_e
impedance	dyne/cm/sec	Z_m	impedance	ohms	Z_e

In a similar manner electrical and mechanical equations may be analogous as indicated in Table II.

Table II

Mechanical	Electrical
$f = R_m v$	$e = Ri$
$x = C_m f$	$q = Ce$
$X_m = jwM$	$X_L = jwL$
$X_c = \frac{1}{jwC}$	$X_C = \frac{1}{jwC}$
$Z_m = R + j\,(wM - \frac{1}{wC})$	$Z_e = R + j\,(wL - \frac{1}{wC})$
$fo = \frac{1}{2\pi\sqrt{MC}}$	$f_o = \frac{1}{2\pi\sqrt{LC}}$
$f = kx = \frac{x}{C}$	$e = \frac{q}{c}$
Kinetic Energy $= \frac{Mv^2}{2}$	Kinetic Energy $= \frac{Li^2}{2}$
Potential Energy $= \frac{Cf^2}{2}$	Potential Energy $= \frac{Ce^2}{2}$
$f = Ma = M\frac{dv}{dt} = M\frac{d^2x}{dt^2}$	$e = L\frac{di}{dt} = L\frac{d^2a}{dt^2}$
$f = \frac{1}{C}\int vdt = \frac{x}{C}$	$e = \frac{1}{C}\int idt = \frac{q}{c}$
$v = C\frac{df}{dt}$	$i = C\frac{de}{dt}$

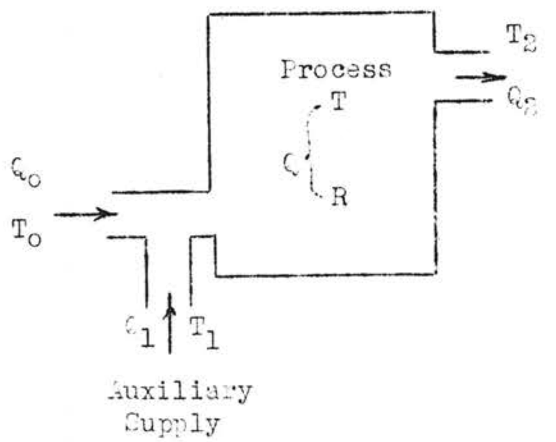
This sort of mathematical analogy may be extended to apply to any process analysis, Table III.

Table III

	Dimensional Symbol	Thermal	Pressure	Liquid Level	Electrical
Quantity	Q	BTU	Cu. Ft.	Cu. Ft.	Coulomb
Potential	V	Degree	Pounds/ Sq. In.	Foot	Volt
Time	T	minute	Minute	Minute	Second
Flow	Q/T	BTU/ Minute	Cu. Ft. / Minute	Cu. Ft. / Minute	Coulombs / Sec = Amp.
Capacity	$\frac{Q}{V}$	BTU / Degrees	Cu. Ft. / Pounds per Sq. Inch	Cu. Ft. / Foot	Coulombs / Volt = Fds.
Resistance	$\frac{VT}{Q}$	Degrees / BTU per Minute	Pounds Per Sq. Inch / Cu. Ft. Per Min.	Feet / Cu. Ft. Per Min.	Volts / Coulombs per Sec. = Ohms

There may be times when this sort of mathematical treatment may be simplified by graphical solution. Dynamic regulation involves several variables and lags acting simultaneously, but in a predetermined sequence. Plotted curves of cause and effect may lead directly to a solution of the complex problem. This sort of solution requires complete information about each part of the controlled system. The individual characteristics can then be properly coordinated to yield the final control action.

An example may perhaps best serve to illustrate the method of analogies. A simple thermal process is arranged as shown in Fig. 13. First consider the system as ideal, i.e., it will have no lags, hence all heat supplied the system will immediately flow out, or the rate of energy change across the process will be zero. The initial temperature of the entire process will be chosen at 0 degrees.



Q - instantaneous process heat (energy)
Q_0 - initial heat energy
Q_1 - auxiliary heat supply
Q_2 - heat flowing out
T - instantaneous process temperature
T_0 - initial temperature
T_1 - temperature of auxiliary supply
T_2 - final temperature flowing out
M - mass of variable
s - specific heat of variable (constant)
C - capacity of process ($M \times s$)
R - resistance of process ($R = \frac{T}{Q}$)

Fig. 13. Heat flow Process.

Before attempting a solution, it is desirable to recall a few facts regarding heat and heat flow.

1. If two bodies at different temperatures are placed in contact, the cooler body becomes warmer, and the warmer becomes cooler, until they are both at the same temperature.

2. The value of this common temperature depends not only upon the original temperatures, but upon the nature of the two bodies; $_1Q_2 = Ms(T_2-T_1)$

1. The amount of heat required to raise M lb. of a substance from T_1 to T_2 depends directly on the specific heat of the substance.

3. Equalization of temperatures, while it may be retarded, cannot be prevented by interposing anything between them.

Since the initial temperature of the system has been chosen as zero, $T_o = Q_o = 0$. For the moment we will consider the system as ideal, hence the inflow of heat will be equal to the outflow or $Q_o = Q_2$. Now if heat is suddenly supplied to the system through the auxiliary supply Q_1 then the temperature of the process will be in general $T = \frac{Q}{MS}$, and the rate of change of the temperature can be expressed as

$$\frac{d}{dt}(T) = T^1 = \frac{Q_1 - Q_2}{MS} \qquad (I)$$

and T^1 will be either plus or minus, depending on the value of Q_1 as compared to Q_o.

In an actual case, the process will have some definite capacity, i.e., any supply change will not be instantly equalized in the system, so the temperature of the process will possess a time rate change. Since the heat flow across the capacity is not instantaneous we may say that the capacity displays opposition to the flow of heat. This characteristic can be defined as a resistance so that $R = \frac{T_o}{Q}$. When a sudden change is effected in Q_1 the temperatures do not instantly equalize so $T_1 + T_o = T = T_2$, but T will assume a rate of change and the heat flowing out will be varying, for $R = \frac{T}{Q_2}$ or $Q_2 = \frac{T}{R}$. Upon making this substitution in equation (I), the rate of temperature change is $T^1 = \frac{Q_1 - \frac{T}{R}}{C}$ and clearing of fractions, the rate of temperature change at the outlet of the system is

$$T^1 = \frac{RQ_1 - T}{RC} \qquad \text{(II)}$$

Once equilibrium has been reached the outlet temperature will have reached a limiting value so that $T = T_2$. Likewise, the heat energy flowing out will then be $(Q_o + Q_1) = Q_2$. Therefore, applying the definition of resistence,

$$R = \frac{T_2}{Q_o + Q_1} \qquad \text{or}$$

$$T_2 = R(Q_o + Q_1) \qquad \text{(III)}$$

and in a similar way the initial temperature of the process could be expressed as

$$T_o = RQ_o$$

The initial heat entering the process was chosen as zero ($Q_o = 0$) so $T_2 = RQ_1$ and using this value in equation (II), it can be rewritten as

$$T^1 = \frac{T_2 - T_o}{RC} \qquad \text{or}$$

$$RCT^1 = T_2 - T_o \qquad \text{(IV)}$$

Since T_2 is the final <u>constant</u> temperature, equation (IV) may be rewritten as

$$RC(T_o - T_2) + (T_o - T_2) = 0 \qquad \text{(V)}$$

A general solution of this differential equation is

$$T_o - T_2 = K\epsilon^{-\frac{t}{RC}} \qquad \text{(VI)}$$

and the constant of integration can be readily evaluated by considering the process at the instant when $T = 0$, or

$K = (T_o - T_2)_{t=o}$. Putting this value of K in equation (VI)

$$T - T_2 = (T_o - T_2)_{t=o} \mathcal{E}^{-\frac{t}{RC}}$$

and solving for T gives an expression for the temperature at any instant during the process.

$$T = T_2 + (T_o - T_2)_{t=o} \mathcal{E}^{-\frac{t}{RC}} \qquad \text{(VII)}$$

The general form of equation (VII), should be immediately recognized by the electrical student as the type of expression used to investigate the potential distribution of a resistive-capacitive network. Fig. 14 and the foregoing process could have been analyzed just as

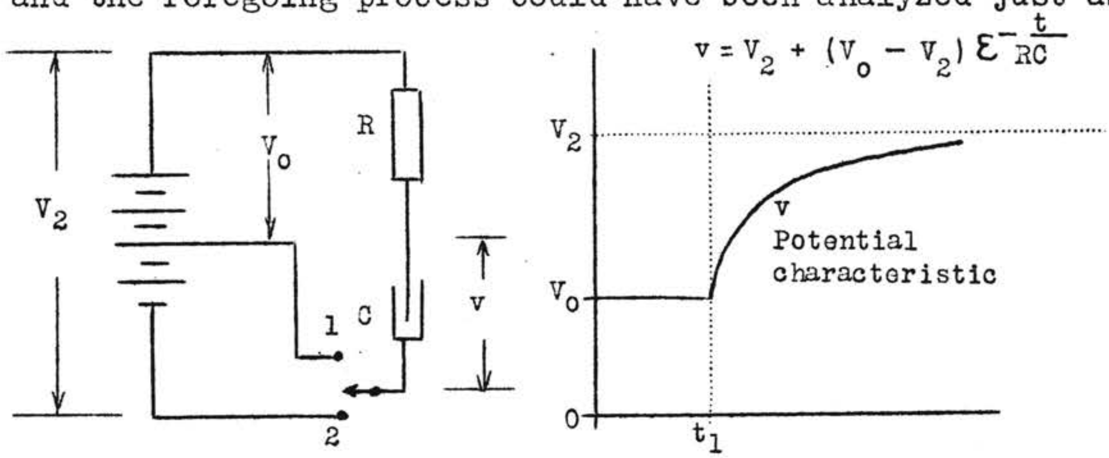


Fig. 14. Electrical network having the same characteristics as Fig. 13.

readily in terms of the electrical circuit and then interpreted in terms of the heat flow problem.

The circuit reaction depends upon both R and C and in the electrical system, the time constant represents the time required for the potential to assume 63% of its limiting value. This time delay represents the lag coefficient for any system. The process reaction rate is the reciprocal of the process capacity. In the electrical circuit a large capacity would take longer to charge or it would have a slow reaction rate as compared to a small capacity circuit.

It is seldom that a single capacity process would be encountered in practice. Usually, several capacities will be involved. In the above example, suppose the auxiliary heat supply was composed of an electrical heating coil embedded in a ceramic housing and carefully covered with an insulating layer. This would introduce a transfer lag. Again the system might be analyzed as an equivalent electrical system and later be interpreted in terms of actual conditions. Fig. 15 will illustrate the circuit conditions corresponding to the introduction of a transfer lag.

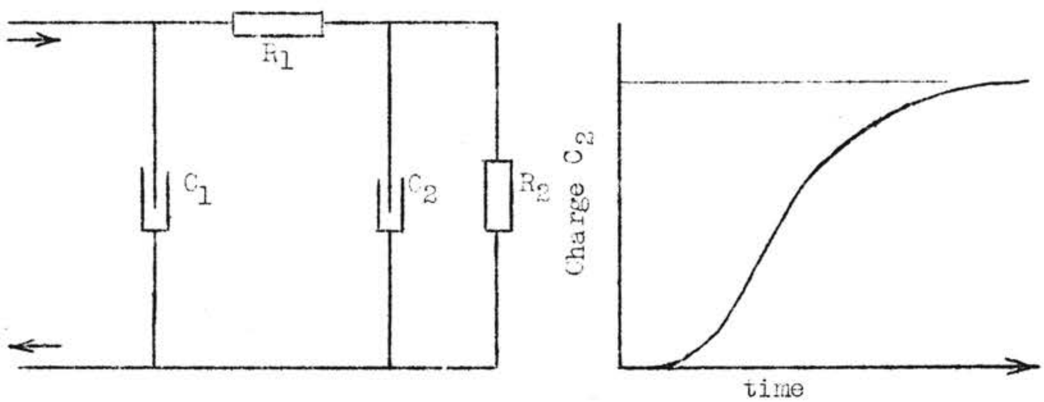


Fig. 15. Equivalent two-capacity process.

The ceramic housing has a certain capacity but is separated from the capacity of the liquid by an insulating layer, or resistance, and will behave in a manner as illustrated in Fig. 15. The total transfer lag of the system results from the combination of the two lag coefficients. As these lag coefficients (R_1 and R_2) approach equality the transfer lag approaches a maximum, but if either of the two lag coefficients are made small, the transfer lag is proportionally reduced.

Automatic control might be applied to such a process as described, and knowing the characteristics of the process the control device may be easily arranged to maintain the outlet temperature within very close limits should this be desirable.

Types of Controllers.

Several examples of process control have been used to illustrate system performance. While these processes would employ only simple devices to achieve the necessary control, it is desirable to consider in some detail the action of the more common types of controllers. The controller must be arranged to measure changes occuring in the controlled variable, or demand, and then using these measurements, operate on the control agent (supply) to correct the deviation of the controlled variable as soon as possible. Controllers may be classified in several ways but one of the more common methods is to group the controllers according to responses, as follows:

(a) Two-position or on-off controller.

(b) Two-position controller with pre-determined operation cycle.

(c) Proportional position controller.

(d) Floating controller (single speed, two speed, and proportional speed).

(e) Proportional plus floating controller.

(f) Proportional plus floating plus rate of change controller.

Two Position Controller.

The simplest type of controller used consists of an on-off device arranged so that the supply is turned on or off as required by the controlled medium or demand. The controller is arranged to turn on the supply at a predetermined demand low and to turn the supply off at a given demand high. The control will operate on a cycling principle and if arranged to operate between some fixed limits, the controller will have a cycling differential.

Consider an ideal situation similar to Fig. 16. Process II is to be used to heat treat small objects and we will assume for the moment that no lags are present.

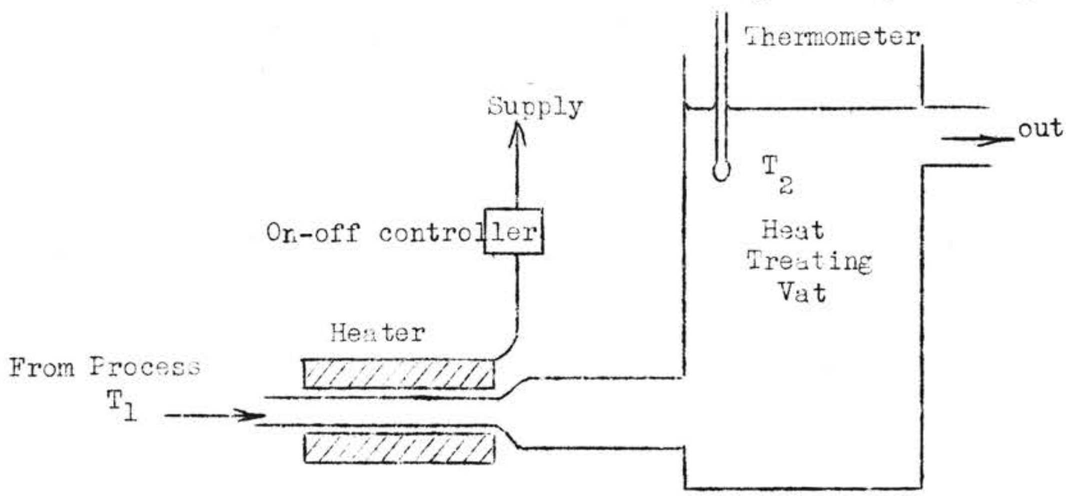


Fig. 16. On-off controlled process.

As a low temperature object is placed in the vat, the liquid temperature will drop below T_2, the heater must then be energized to supply enough energy to return the temperature of the liquid in the vat to T_2 at which time the heater is to be turned off. As different objects are placed in the vat, the controller will function to repeat the supply cycle. The demand will depend upon the size and initial temperature of the object placed in the vat and is represented in Fig. 17.

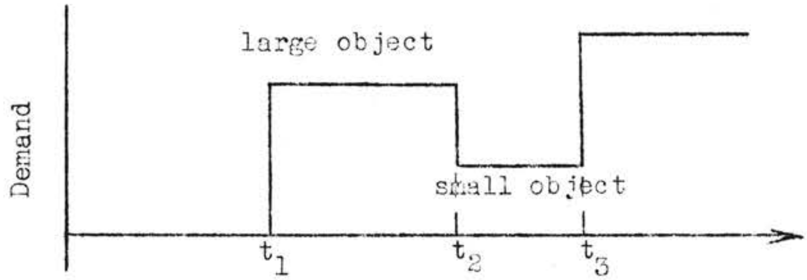


Fig. 17. Demand placed upon System

At time t_1, a low temperature object, is placed in the vat and left for a time $t = t_2 - t_1$ at which time it is withdrawn and a smaller object is simultaneously dropped in the vat. The on-off controller action should operate to make the supply cycle during this treating period and the operating differential is shown in Fig. 18.

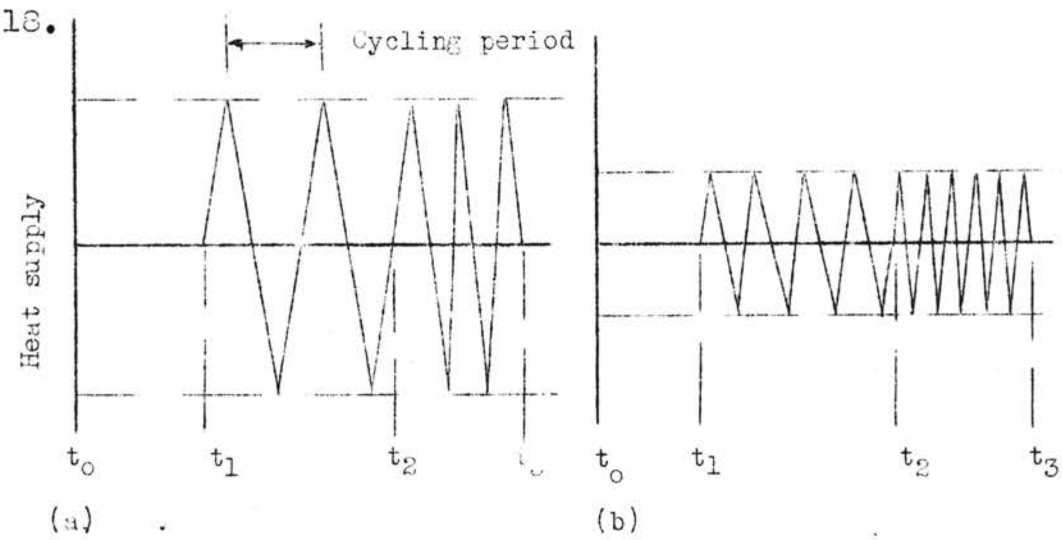


Fig. 18. Ideal cycling of on-off Controller.

During the time $t_2 - t_1$, when a large object is in the vat, the reaction rate is slow and the period of the supply cycle will be longer than for a smaller object placed in the vat from t_2 to t_3. The differential limit and process reaction rate determine the cycling period, being proportional to the width of the controller differential and inversely related to the reaction rate. If the differential width had been reduced to half that shown in Fig. 18., both the amplitude and the period of the supply differential would be halved, Fig. 18B.

If the cycling process becomes too short, undesirable conditions exist; and eventually the controller may not have time to operate satisfactorily between cycles. In this case, the heat supply would not shut off between cycles. Usually this could be overcome by introducing some dead time in the system. While this would allow the temperature to overshoot, plus or minus the differential of T_2, it will allow longer periods between on-off control. The amplitude of cycling is not only proportional to the process reaction rate but also proportional to dead time and the width of the controller differential, while the period is inversely proportional to the reaction rate and directly proportional to the width of the differential and the length of dead time. This effect is shown in Fig. 19.

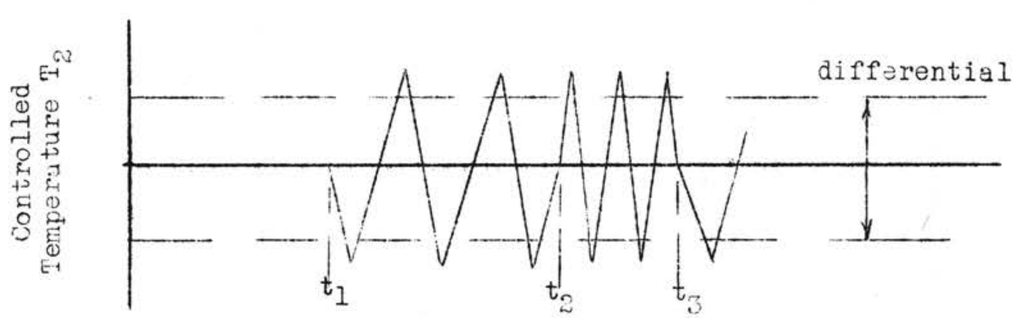


Fig. 19. Dead time in on-off controller.

The practical case differs somewhat because transfer lag is present in the system - both in the measuring controller device and in the process itself. This transfer lag will "round off" the peaks of the heat supply cycle and also as the smaller objects are placed in the vat, the demand is not as great as when larger objects are introduced, or the overshoot is reduced in proportion to the demand and the practical supply characteristic is shown in Fig. 20.

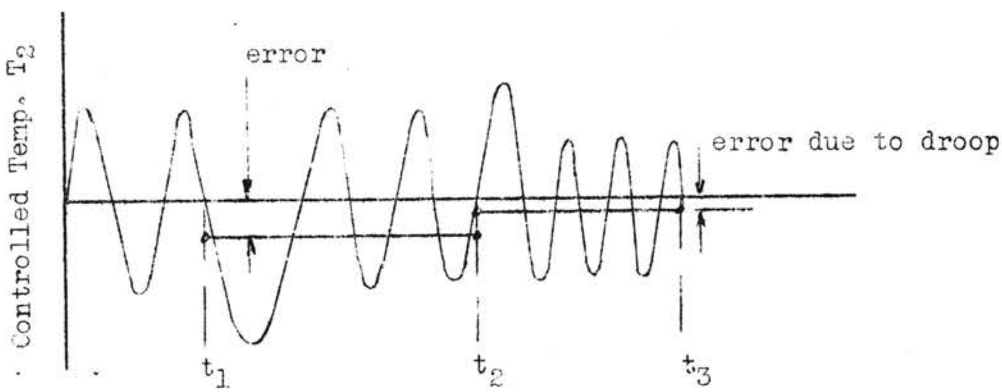


Fig. 20. Characteristics of a practical "on-off" controlled system.

The demand causes an error to exist in the average controlled temperature. As the object is introduced in the vat, a sudden large demand is placed on the system and the overshoot results in a large temperature increase while the smaller object demands less energy to raise its temperature to the desired value. This difference between the two averages is referred to as the <u>droop</u>. Immediate reaction of the controller and the process are necessary if this droop is to be minimized. This, of course, is vital in any process.

The supply action for this process is shown in Fig. 21. Up to time t_1 the supply is periodically timed on and off to maintain T_2, but when the object is

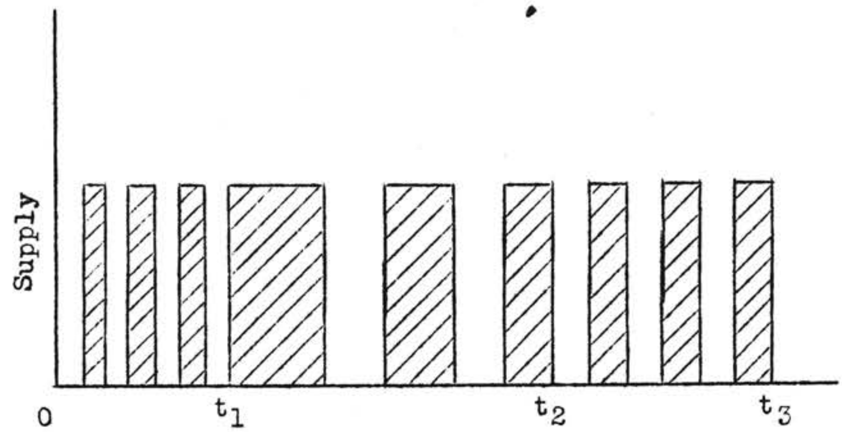


Fig. 21. Supply action of Process

introduced in the liquid at t_1, a sudden demand will cause the supply to operate for longer periods until the demand is satisfied while smaller objects will require shorter and less frequent on period than when the demand was higher. This process might be manually controlled by an attentive operator but a simple automatic device might be readily incorporated, (Fig. 10). The on-off control when automatically operated should be applied to processes which have the following characteristics:

1. Dead time and transfer lag of the process and measuring elements are small.

2. Reaction rate of the process is slow (high capacity).

3. Load changes relatively small and slow.

Two Position Controller with Pre-determined Cycle.

The two position controller just described has the disadvantage that the period of cycling and the amplitude of cycling varies widely and often tends to overshoot the desired differential. If this method of control is to be applied to a repeating process, it may be improved greatly by introducing an auxiliary cycling control which will result in lowered differential amplitude and cycling. By supplying the energy to the process in small quantities and at frequent intervals, the process variable oscillation can be almost eliminated.

By adding a cycle timer and relay in series with the arrangement of Fig. 16, our purpose could be accomplished. This new arrangement would be connected as shown in Fig. 22.

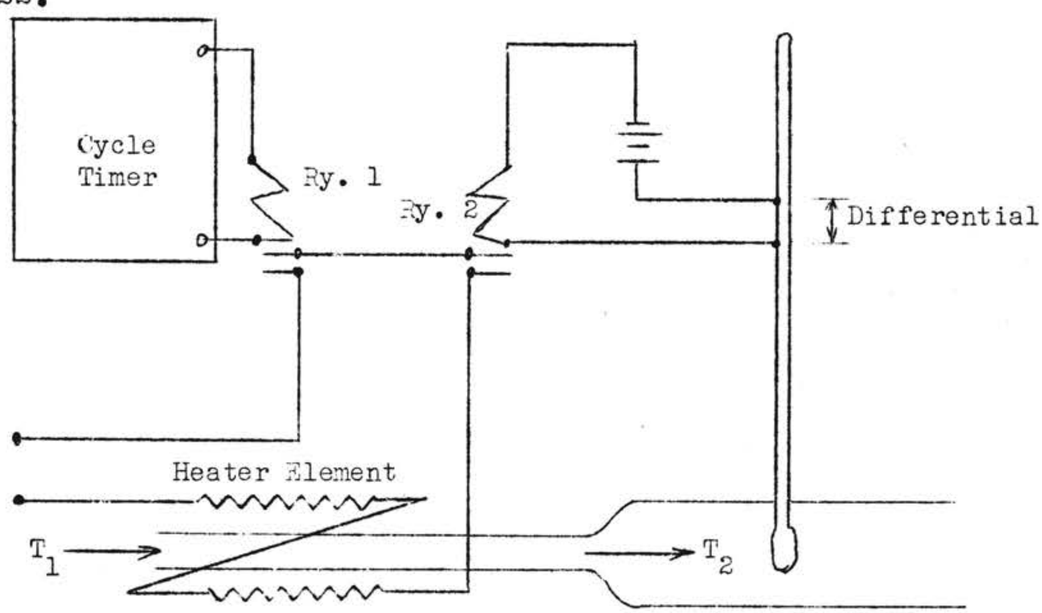


Fig. 22. Application to a system as shown in Fig. 16.

Two relays are connected so their contacts are in series with the heating element and its energy supply. Relay 1 is connected to a cycle timer so arranged that it periodically opens and closes the contacts at a predetermined uniform rate. The on-off time of the timer is adjusted so that it will be on for a period proportional to the period of the normal temperature differential. In this manner, energy is added to the system in short "bursts" and the total amount of added heat will be determined by the temperature deviation which activates Relay 2 only during deviation periods.

This type of control system is obviously best suited to repeating uniform processes. Sudden irregular demands cannot be readily compensated for as the amounts of heat added during the active intervals is limited by the action of the timer relay. So long as the demand remains reasonably uniform, however, the controller action maintains very constant temperature conditions and the energy is supplied at regular short intervals, thus reducing any oscillating tendencies.

Proportional-Position Controller.

Processes often require closer regulation than provided by the on-off controller, which produces cycling action. If the controller is so arranged that the final control element selected a definite but different position proportional to the rate of change in the demand side variable, it is known as a proportional position controller, thus the controller system allows energy to flow in proportion to the demand. This controller will operate over a band controlled by the predetermined response range of the measuring element as it moves the final control element between its two extremes of full on or closed. This control band may be referred to as throttling range or proportional band. Since each final control element position corresponds to a definite value of the controlled variable, the device will control at a definite point following every change in the controlled variable, which means the proportional controller will have a demand error or droop somewhat like the on-off controller.

The throttling range represents the ratio of the per cent of the full scale process variable required to produce a 100 per cent change of the final control element. The effectiveness of the controller is thus indicated by the throttling range. If the percentage is large, the change effected in the control agent will have only a small effect on the controlled medium. The effect of different throttling ranges is indicated in Fig. 23.

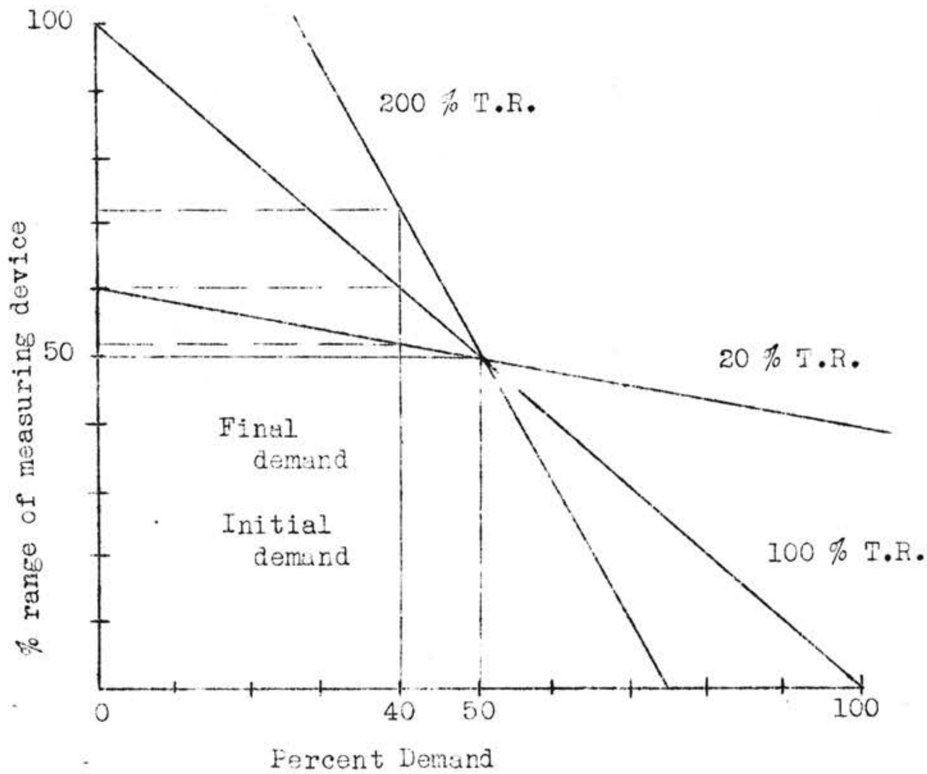


Fig. 23. Effect of throttling range on control.

As long as supply response remains proportional to the final control action, it will be observed that a 10% decrease in demand will result in a 10% change in supply for a 100% T.R. while only a 2% supply change would result if using a 20% T.R. While it would be ideal to reduce the control band to zero, this is impractical due to undesirable lags in the process. As the throttling range is reduced the process lags will finally result in system oscillation. The control band cannot be reduced beyond a critical value and, as with the on-off controller, there will be a definite characteristic droop, Fig. 24.

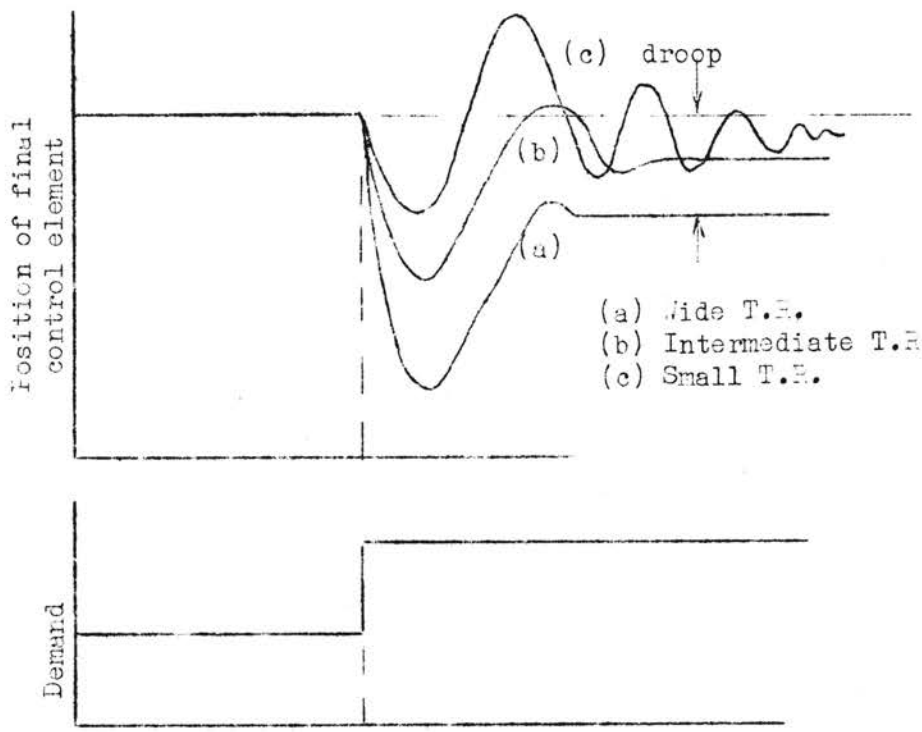


Fig. 24. Effect of throttling range upon process stability.

The throttling range must be carefully adjusted in terms of the process lags to prevent oscillating or hunting. Such controller action is obviously undesirable if controller wear and servicing is to be minimized. When using an electronic controller, hunting can be overcome by using negative feedback correction circuits. Obviously this will prove desirable as the control range can readily be reduced and system variations reduced to a minimum.

<u>Floating Controller.</u>

The floating controller is arranged so that the position of the final control element has no fixed relation to the variation of the controlled medium, but rather it operates continuously as deviation of the controlled medium occurs. The floating controller action may be single speed, two speed, or proportional-speed depending upon the desired tolerances allowed for the system variation. The final control element is normally operated very slowly and the controller is adjusted so that the variation in the controlled medium has run its course before the final control element reaches the limit of operation. If constant cycling is to be prevented with the floating controller, some dead time must be introduced in the system. Dead time also tends to make the system stable.

Single speed action applies to a system in which the final control element operates at a constant rate while any deviation of the controlled medium exists. Two speed or multiple speed controllers are similar except that some arrangement is incorporated in the controller so that the final controller will operate at a different speed if the variation of the controlled medium exceeds a predetermined limit. Proportional-speed control is applied in such manner that the response of the final control element is proportional to the magnitude deviation of the controlled medium, and hence the dead time can be reduced or eliminated in the controller action. A comparison of the action of the three types of floating controllers is shown in Fig. 25.

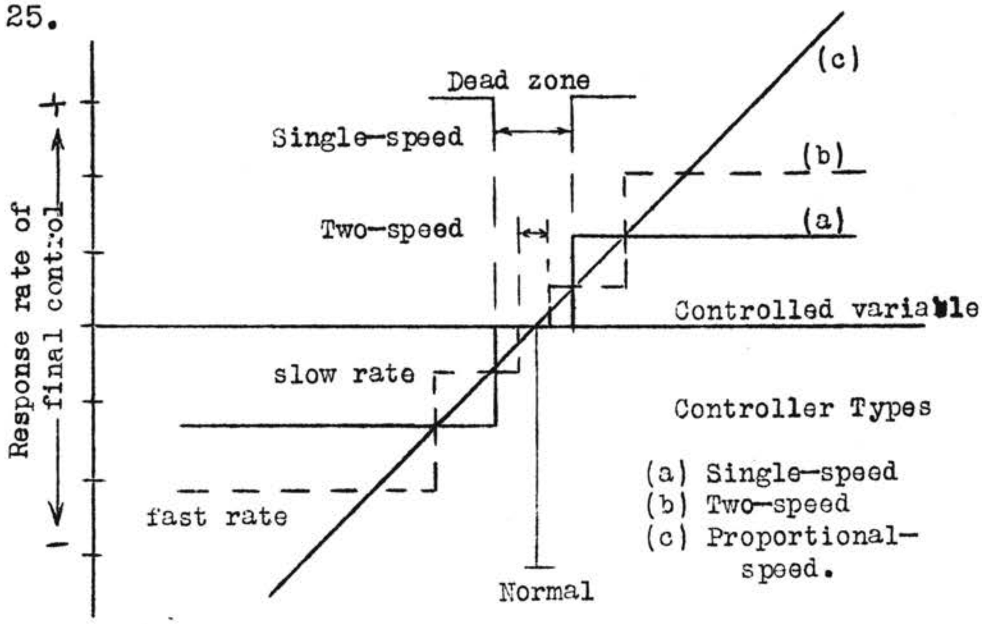


Fig. 25. Action of floating Controllers

Proportional-plus-Floating Controller

Proportional control is arranged so that the rate of change of the final control element is proportional to the rate of change of the deviation of the controlled medium from its normal state, while the proportional-speed-floating controller is arranged so that the rate of the final control is proportional to magnitude of the deviation of the controlled medium from normal.

By combining these two systems, the final control element will respond at a rate which is the sum of:

(a) a rate proportional to the deviation.

(b) the rate of change of this deviation.

The action of the proportional controller may be expressed in terms of the rate of deviation from normal. If δ represents the deviation and A is a constant for the system, then the controller action becomes

$$A \frac{d\delta}{dt}$$

The floating controller action is proportional to the magnitude of the deviation so if B represents this system constant, then the controller action becomes

$$B\delta$$

and the combined action may be expressed as

$$-\frac{dP}{dt} = B\delta + A\frac{d\delta}{dt}$$

where P represents the final control element position.

Such a system will have the stability of the proportional controller and the invariable control point of the floating controller. The dead-time required by the floating controller is not required since the proportional component produces the stabilizing action required to prevent oscillation.

A certain process has a sudden demand increase imposed on it, as shown in Fig. 26. The system is automatically controlled by a proportional-plus-floating controller. The proportional control produces a correction as in curve (b) while floating control action produces the correction of curve (c). The sum of these two corrective factors acting simultaneously produce a corrective action like curve (d) which is the sum of (b) and (c).

The combination of these two controller types results in a controller which will reset the control point automatically after some change in demand occurs. Incidentally, the combined process acts to eliminate the droop of the

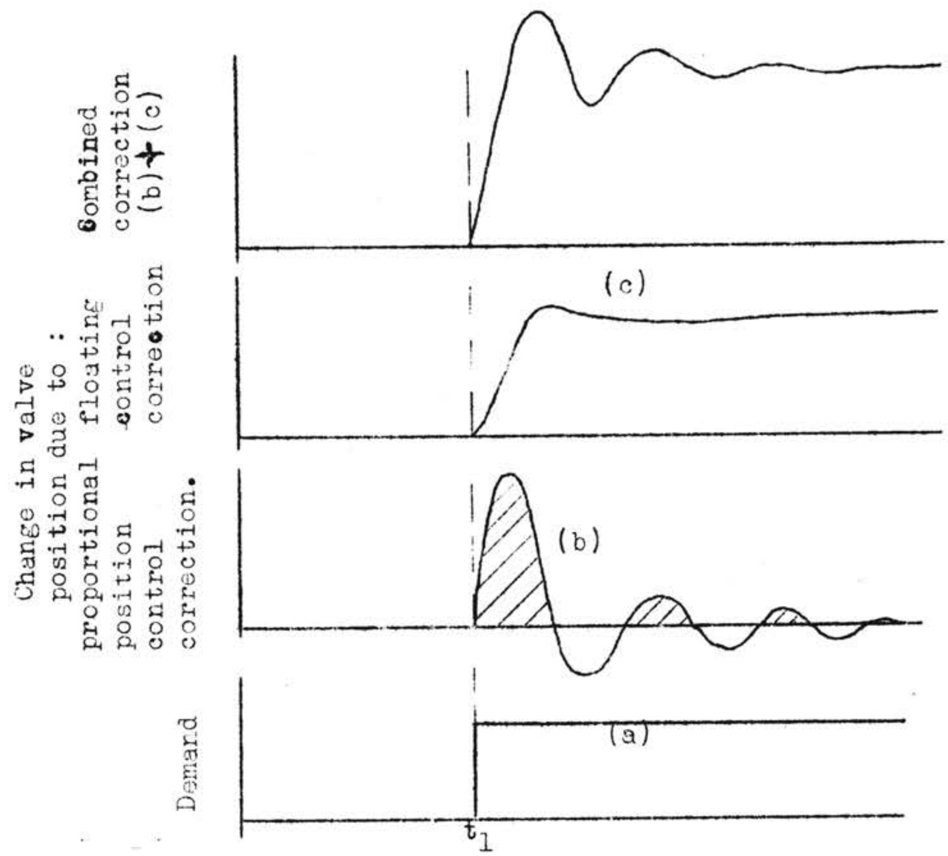


Fig. 26. Summation effect of Proportional-plus-floating control.

proportional controller with a minimum of cycling once the throttling range and floating time have been properly adjusted.

<u>Proportional-plus-floating-plus-second derivative Controller</u>

The proportional-plus-floating control process tends to overshoot the final controlled value when a sudden change occurs in the demand. If this is to be overcome, more energy must be rapidly added to the system but stability must be maintained. This can be accomplished if a large correction can be instantaneously added at the time of demand increase and then be made to swing farther in the negative direction before returning to a normal position, i.e., the final control element must be changed by amounts corresponding to the rate of change of the deviation from normal. Mathematically, this represents a second derivative action:

$$\frac{d}{dt}\left(\frac{d\delta}{dt}\right) = \frac{d^2\delta}{dt^2}$$

When such action is superimposed on the proportional-plus floating controller, the action becomes

$$-\frac{dP}{dt} = B\delta + A\frac{d\delta}{dt} + C\frac{d^2\delta}{dt^2}$$

This action is shown graphically in Fig. 27.

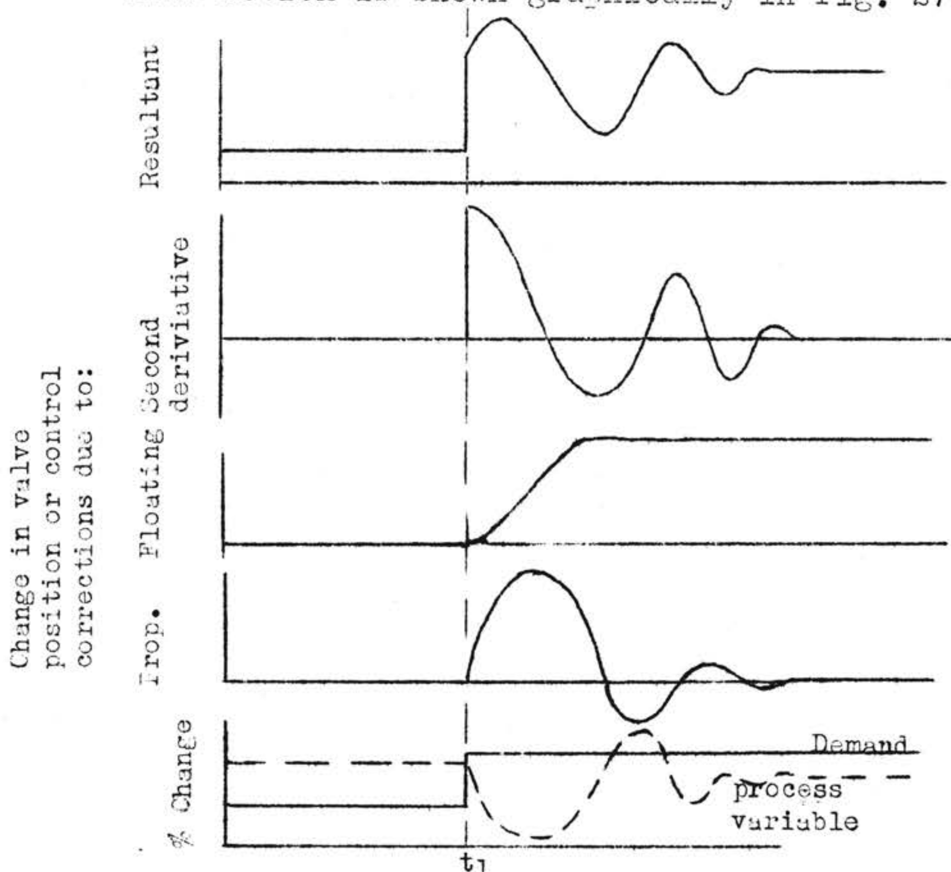


Fig. 27. Proportional Floating second derivative Control.

Neither the proportional control nor the second derivative contribute anything to the final correction, but is determined entirely by the floating control and ultimately determines the change required to stabalize any change in the demand side of the process. The rate of change of the controller, $\frac{dP}{dt}$, represents in effect a velocity term and depends upon the deviation of the process δ (process variable) and its derivatives. A, B, and C and constants which depend entirely upon the complete system of variable control. Obviously, the action of the floating control ($B\delta$) is independent of time variations. The proportional position control action represents a velocity change of the process variable while the second derivative control is, in effect, an acceleration term.

Fig. 27 shows that the floating control action changes in demand. The proportional control will vary, depending on the process variable and the rate of change of the process variable. Any oscillation of the variable will also be repeated in the proportional controller and the oscillation magnitude will depend on the throttling range (T.R.) of the proportional position controller. As soon as the fluctuations have been damped out, the proportional control returns to its initial position, i.e., the average effect is zero over a period of time and operates only during initial or momentary changes imposed on the process variable.

The second derivative controller operates in proportion to the acceleration of the process variable, or the rate of change of the proportional controller and has a slope like the process variable.

Electronic Control Systems

Automatic control of the process may be accomplished in a number of ways - some simple, some elaborate, some mechanical, some electrical. The discussion will consider electronic control methods, and the application of electronic systems to industrial processes. The electronic control system basicly accomplishes the same result as other controllers (see Fig. 1). The only difference comes in the methods of achieving the control. Fig. 28 indicates the general arrangement of an electronic control system as applied to a process. A comparison of Fig. 1 and Fig. 28 will indicate the general

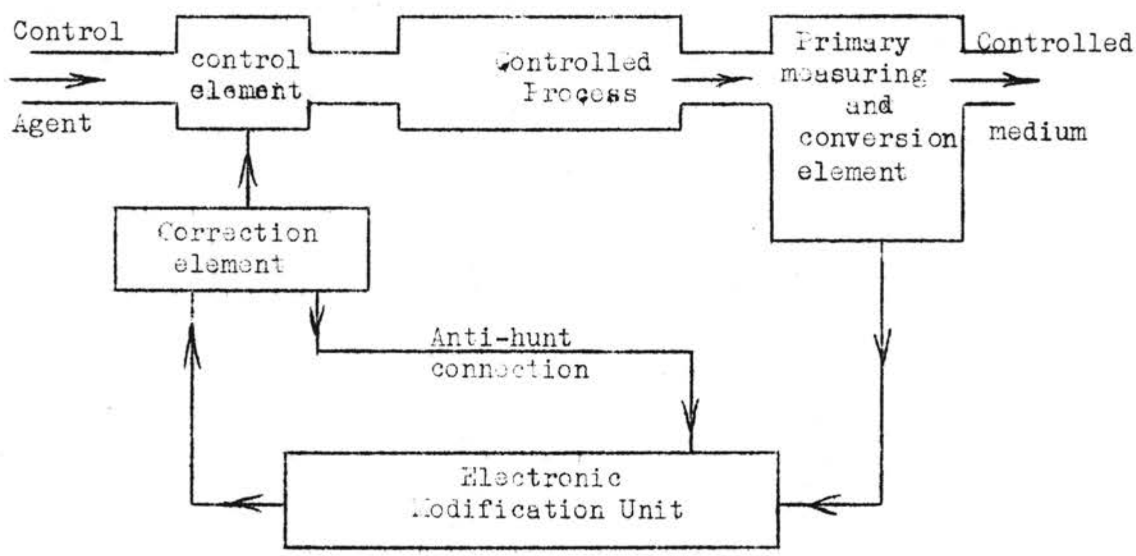


Fig. 28. Electronic Control System.

similarities of the two controller systems. The principle difference lies in the fact that the electronic control system depends upon electron tube action. Since the electron tube fundamentally requires a potential change at its input to "trigger" it, the primary measuring element must be so constructed that it will convert some change in the controlled medium to an electrical quantity. The conversion element, as it is called, may be so arranged that it will convert the process change to a voltage, a current, or a field (electrostatic or magnetic), which when properly applied, will activate the electronic modification unit.

The electronic modification unit consists of a vacuum tube circuit of such nature that the electrical quantity supplied by the conversion element will modify the static balance of the electronic unit and cause the correction element to operate upon the process to return it to a balanced state. The modification unit will consist of vacuum tubes arranged as amplifiers, oscillators, detectors, bridges, or some combination of these circuits. In any of these applications, the electronic modification unit must modify the output of the conversion element and in turn supply the correction element with activating energy.

The correction element may in some cases operate directly upon the control agent, and in other instances, the requirements may be such that the correction element serves as a coupling device between the electronic system and the final control element.

Several of the controllers previously discussed had a tendency to "overshoot" when acting to correct variations in the controlled medium. This poor stability proves particularly troublesome when employing electronic devices as a part of the control system. "Overshooting" the control differential, due to system lags, produces over corrective measures which in turn aggravates the already unsteady balance of the system and finally causes oscillation or "hunting". This fault may be readily corrected in electronic devices by using negative feedback corrections in the amplifier. Effectively, this anti-hunt correction has the effect of automatically desensitizing the unit by introducing equivalent damping resistance in the system. The equivalent damping resistance will be automatically controlled by the amount of "overshoot" or instability present in the system at any instant. There may be times when hunting can be damped by mechanical arrangements; however, the electrical feedback method is so simple and satisfactory that other methods are seldom used with electronic control methods.

Whenever balance of the controlled medium is disturbed the conversion element must respond in such a manner that the final correction produced on the control agent will act to counteract the disturbance; in effect 180° phase inversion must exist. If cause and effect are to act simultaneously all lags in the system must be eliminated. This is, of course, impractical but the lags in the electrical control system can be made to approach zero.

While electronic control devices represent over 50% of the applications of electronic devices in industry, numerous other applications exist also. According to a survey made by the Research Department of the McGraw-Hill Publishing Company, Inc. in 1944, eight major function groups of electronic devices were common in industry. This classification according to the function, or use, of the equipment follows:

Function	Present Use %	Potential Use %
Control	52.0	45.9
Electronic Heating	12.3	22.4
Regulation	8.7	14.4
Power Conversion	23.4	7.9
Counting, sorting, weighting inspecting	17.2	11.6
Molecular vibration uses		5.2
Measurement and analysis	46.4	30.2
Safety	19.0	13.7

Table IV - Present and Potential Use of Electronic devices in Industry[1]

While this tabulation is representative of only the larger industrial concerns, it does indicate a definite trend. The fact that these industries actually wanted electronic devices to perform many different new functions should not only encourage the electronic Engineer but should present a definite challenge to his ingenuity.

The chapters which follow will outline the principles and special applications of electronic devices as they combine to form complete electronic systems.

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CHAPTER II

CIRCUIT ELEMENT CHARACTERISTICS - COMBINATIONS

Industrial electronics is only one of several members of the large family of electronics, i.e., some electrical device which contains as one of its many elements the electron tube. Certainly there are many times when the application of electronic devices to industrial processes has decided merit over other methods. Electronic devices can be made extremely sensitive; remote control becomes a simple matter; response is essentially instantaneous; and in addition, great flexibility in design allows the electronic device to satisfy an extreme variety of physical demands. Because of the almost unlimited variations which may exist in electronic equipment, and still more or less completely satisfy given requirements, it appears undesirable to study specific pieces of equipment. In general, all electronic devices have certain common elements. Before attempting an analysis, or the design, or even servicing of industrial electronic equipment, it is necessary to consider some of the differences between industrial electronic and communication devices. Both contain vacuum tubes, resistors, condensors, etc.,; from there on they are usually quite different. Industrial electronic devices are often influenced by transient conditions, or non-sinusoidal waves, and include many special function devices. Hence, it is desirable to extend previous theory to include several new concepts.

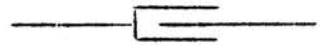
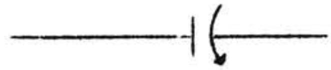
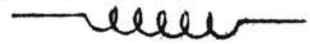
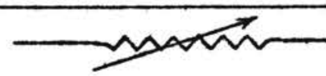
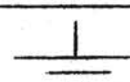
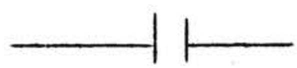
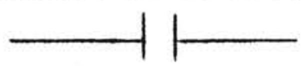
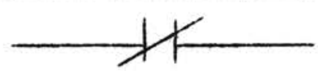
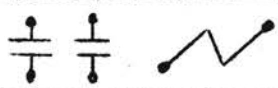
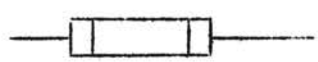
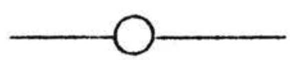
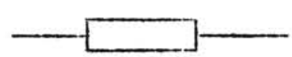
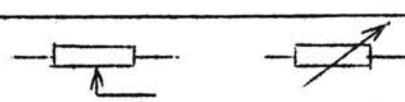
Without exception, components will display linear characteristics under <u>limited</u> steady-state conditions - even though this range may be only incremental - but under the influence of very wide changes and transient conditions the components may give surprisingly non-linear reactions. In fact, we might analyze component part action in terms of its linear and non-linear regions. The following paragraphs will briefly review the general nature of circuit elements and the variety of characteristics they may display. We are more interested in the characteristics of element combinations as they react in combination. However, it is desirable to briefly review outstanding pecularities of the various elements themselves.

<u>Industrial Symbols.</u>

Before investigating the characteristics and pecularities of component reactions, it is necessary to tabulate differences which exist in industrial symbol notation. Although the industrial symbols may tend to confuse the communication Engineer, and though there seems to be no good reason for conflicting notation, industrial wiring diagrams do use the following symbols.

<u>NOMENCLATURE</u>

ASA No.	DEVICE	STANDARD INDUSTRIAL SYMBOL
2.1	Battery	

3.4	Capacitor (fixed)	
3.5	Capacitor (variable)	
5.1	Reactor – (fixed) Transformer shown by two or more of these symbols.	
5.2		
5.8	Reactor (adjustable)	
7.1	Wires cross no connection	
7.2	Wires connected	
7.4	Ground (common)	
8.1	Contacts – Normally closed (N.C.)	
8.2	Contacts – Normally open (N.O.)	
8.3	N.O. contacts, time delay closing	
8.4	N.C. contacts, time delay opening	
8.8	Contactor, magnetic	
9.1	Fuse	
10.2	Lamp – letter shows color	
15.1	Dry plate Rectifier	
17.2	Resistor (fixed)	
17.3	Resistor (variable)	

Resistance

A unit which has resistance deliberately lumped is referred to as a resistor. The resistance, of course, represents an opposition to current flow. This might be stated in another way - the greater the number of free electrons in a given mass of a substance, the easier for current to flow and the measure of the number of free electrons per unit volume is its resistivity. The total linear resistance of a material mass is then

$$R = \rho \frac{l}{A} \qquad (1)$$

where R = total resistance of material in ohms.

ρ = resistivity, relative property of material.

l = length of material.

A = cross-sectional area of material.

Pure resistance always follows Ohm's law, and hence, there will be no electrical storage. This means that a potential gradient will appear across a resistor only when current is actually flowing.

then $e = Ri$

where e - instantaneous voltage drop

R - constant of circuit (Resistance)

i - instantaneous current flow

and no matter how simple or how complex the voltage wave may be, the above relation will hold. It must be kept in mind that commercial resistors may possess inherent inductance or capacitance due to construction. These effects are generally of little consequence in industrial applications, however.

Resistors are of more or less standardized construction. The physical size is limited by the power dissipation and the material constituting the unit. Carbon and carbon mixture resistors range from the tiny $\frac{1}{4}$ watt size up to large carbon stacks and may have a resistance range of but a few ohms up to several million ohms. Wire wound units likewise vary depending upon the dissipation requirements. Incidentally, the dissipation rating is based upon the allowable heat range of the resistor for constant resistivity when located in the center of a cubic foot of free air.

Temperature Coefficient

Temperature and resistance effects are so closely related that it often proves desirable to utilize the relation in electronic devices. Material is composed of atoms which in turn consist of positive and negative particles of basic electricity. Temperature changes cause atomic volume changes and simultaneously vary the restraining forces which hold the atom together. When the restraining forces acting on the individual electrons are altered, the ability of the atomic structure to oppose externally applied forces is also changed. This effect is defined as the Temperature coefficient of resistance and represents the change in resistance per degree per ohm at the initial temperature. If the temperature coefficient is constant, the temperature resistance-relation can be readily expressed as a linear proportion

$$\frac{R_2 - R_1}{R_1} = \alpha(T_2 - T_1) \qquad (2)$$

where R_1 - resistance at initial temperature, T_1.

R_2 - resistance at new temperature T_2.

α - temperature coefficient of material at T_1.

Many materials do not display such a simple linear relation at all or for only a very limited temperature range. However, the principle of resistance change with temperature change is advantageously employed in many auxiliary electronic devices. It must not be overlooked that reproducibility is perhaps the first requirement demanded of any industrial electronic application. Hence, great care must be exercised when choosing a temperature sensitive resistor. Platinum is highly dependable and repeating accuracties of 0.01% are readily obtainable, while carbon definitely lacks any permanent characteristics. Temperature sensitive resistors find wide application as primary sensing and conversion units in industrial control applications.

Deformation resistance

Whenever a material object is compressed or expanded due to changes in external forces, the dimensions will be altered. Suppose a thin resistance wire is stretched under tension (not beyond its elastic limit). The strain will cause the wire to become longer by a small amount Δe and also have its cross-sectional area reduced by an amount Δa. Hence, there will be a proportional increase in its resistance for

$$\Delta r = \rho\frac{\Delta l}{\Delta a} = \rho\frac{dl}{da} \qquad (3)$$

So long as wire material is chosen which has a very low temperature coefficient and a high elastic limit, a satisfactory unit may be assembled to display good resistance-strain characteristics. Before the unit can be applied to measuring or control devices, its reliability must be unquestioned.

Non-Linear Resistance

So far, we have considered resistance as a constant depending only on certain physical dimensions. Electronic circuits may contain many non-linear resistances as well as the linear type previously mentioned. The electron tube itself is seldom operating as a linear value, although there are many times we wish it would. Naturally, if a device is non-linear it no longer obeys the steady-state Ohm's law, but we must express non-linear resistance in terms of small changes so

$$r = \frac{de}{di} \qquad (4)$$

where r = instantaneous non-linear value of resistance.

de = incremental voltage change at operating point of resistor.

di = incremental current change at operating point of resistor.

This immediately indicates that the current-voltage characteristics of the unit is non-linear if plotted on regular coordinate paper, (Fig. 1). Some of the more common devices used in industrial electronic circuits are tungsten or carbon filament lamps, copper-oxide (or selenium) rectifiers, thyrite, thermistor, ballast tube, varistor, etc.

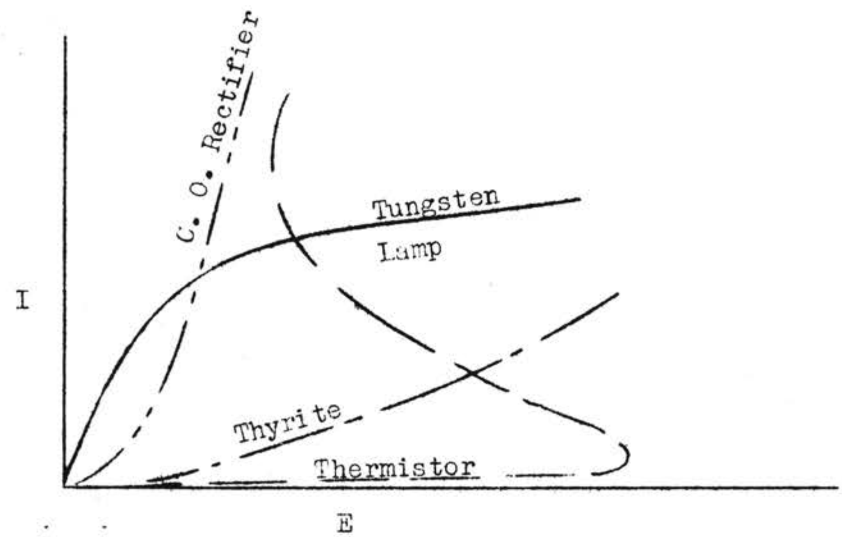


Fig. 1. Current voltage characteristics of typical non-linear resistors.

Negative-resistance

We certainly cannot go to the store and purchase a negative-resistance unit, but there are certain devices which, when carefully adjusted, do display a negative resistance characteristic, i.e., the current flow decrease as the applied voltage is increased (Fig. 2) and this would

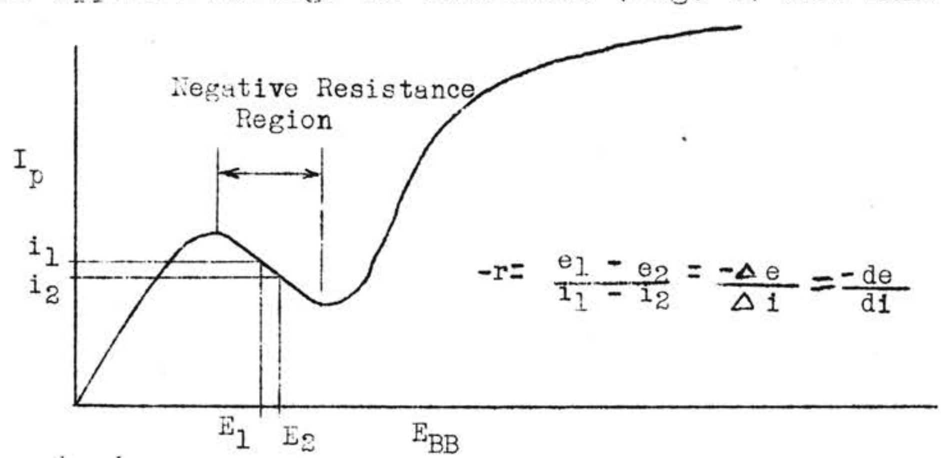


Fig. 2. Negative resistance characteristic of a Tetrode.

be expressed as

$$r = -\frac{de}{di}$$

but although seldom linear in nature, there are times when the device may display limited linear negative resistance characteristics.

There are several important negative resistances devices besides the specially operated vacuum tube. Certain chemical compounds, mainly metallic "ides" as oxides, carbides, sulfides, nitrides, etc., display a negative resistance characteristic. Several of these materials are readily available and reasonable in cost, and production methods are now extended so the materials can be made to display a high degree of reproducibility. Certain gaseous combinations likewise possess the above characteristics under ionization processes and, hence, can be utilized in properly constructed devices.

Capacitor

The capacitor is effectively an electrical storage tank for potential energy. The capacity of a condenser (as it is commonly called) is the factor indicating the quantity of charge which is stored in a dielectric field.

$$C = \frac{Q}{V}$$

where Q = total amount of charge transferred to the condenser plates.

V = potential difference required to transfer the charge.

Since the dielectric storage ability is a function of its atomic arrangement and its physical dimensions, capacity may be readily expressed in terms of these quantities.

$$C = \frac{kA}{4\pi t}$$

where C = capacitance in farads

A = area of active dielectric included between plates

k = dielectric constant (relative atomic nature of dielectric)

t = spacing between plates

The total energy stored in the condenser is

$$W = \frac{Q^2}{2C} = \frac{1}{2} CV^2$$

This stored energy will appear as an atomic stress of the dielectric material separating the plates of the condenser, and will tend to act as a stabilizing factor so as to prevent voltage change in its circuit. While current does not flow through the dielectric (except on breakdown), there is a definite flow of electrons to one set of conducting plates, and a corresponding flow away from the other set of plates whenever a condenser is being charged; and so long as the electron distribution on the two sets of plates is uneven, energy remains stored. The ideal condenser would remain in an energized state indefinitely, once it had been charged, but condensers are not ideal. Even though the dielectric is an insulator, it is not perfect and hence the unnatural stresses set up by the charge will ultimately equalize. This is another way of saying that some leakage (high parallel resistance) exists in the construction with attendant losses. These losses may be summarized as:

(a) Resistance loss - the condenser leads and plates are of metal, hence, an I^2R loss due to resistance.

(b) Leakage loss - the dielectric has a few free electrons, hence, some actual transfer may occur between atoms. This represents a resistive current with attendant I^2R loss.

(c) Absorption loss - the dielectric atoms do not instantly return to their original formation when discharged, i.e., the dielectric retains a certain amount of energy which appears as an absorbed charge and will not be recovered during rapid reversals (high frequency a-c).

(d) Hysteresis loss - absorption loss may be partly off-set by applying an opposed voltage for an instant. This represents an energy loss, for actually some energy on the reverse cycle (of applied a-c) is required to reverse the atomic formation.

It is common to express the imperfectness of the condenser in terms of its dissipating factor

$$D = R_s w C_s$$

where D = dissipation factor.

R_s = a series resistor equivalent to the leakage resistance of the condenser.

$W = 2\pi f$

C_s = capacity of equivalent perfect condenser in series with R_s.

likewise, the dissipating factor could be expressed in terms of an equivalent parallel impedance arrangement such that

$$R_p = \frac{1+D^2}{D^2} R_s = \frac{1+D^2}{DwC_s} = \frac{1}{DwC_p}$$

where R_p = a parallel resistor equivalent to the leakage across the condenser.

C_p = capacity of equivalent perfect condenser in parallel with R_p.

Condenser Current

The charge existing on the condenser was shown to be related to the potential producing it by $C = \frac{Q}{V}$.

Electronic circuits are seldom allowed to reach final conditions; but more often, time rates of change and transient conditions are active. Hence, the above factor must be expressed as an instantaneous condition. Let q be the charge on the condenser at any instant and v the corresponding potential drop. Then

$$q = Cv$$

and the rate of change with respect to time may readily be expressed as

$$\frac{dq}{dt} = C\frac{dv}{dt}$$

but by definition $\frac{dq}{dt} = i$, so the charging or discharging condenser current is proportional to the rate of change of the voltage

$$i = C\frac{dv}{dt}$$

The instantaneous voltage acquired by the condenser as it charges under the influences of an applied voltage can be readily expressed. Since $i = C\frac{dv}{dt}$ represents the charging current, it can be rewritten so $dv = \frac{1}{C}idt$ and if the expression is integrated, the back voltage at any instant will be

$$v_c = \frac{1}{C}\int idt$$

Suppose a sine wave charging voltage is applied to the condenser so $e = E_m$ sin wt. The charging current will then be

$$i = C\frac{d}{dt}\,(E_m \sin wt)$$

but since $\frac{d}{dt}\,(E_m \sin wt) = wE_m \cos wt$, the instantaneous charging current will be $i = wCE_m \cos wt$

but wCE_m is the maximum current which will flow during the cycle, for

$$I_m = \frac{E_m}{X_c} = \frac{E_m}{1/wC} = wCE_m$$

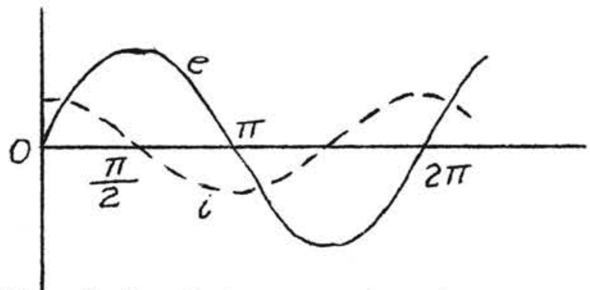


Fig. 3 Instantaneous charging current for perfect condenser with sinusoidal voltage applied.

From Fig. 3 it is apparent that the charging or discharging current is always 90^{o} ahead of the voltage for a perfect condenser.

Now consider the condenser under the influence of a triangular voltage. Again the relations hold as stated above, i.e., the instantaneous current is proportional to the <u>rate of change</u> of the voltage. Fig. 4 shows the applied triangular voltage. As the voltage rises from 0 to t_1 the slope remains constant, so the current will be of a steady value until t_1 when the voltage reverses its rate of change and steadily decreases to zero at a negative rate; hence, the negative pulse of current from t_1 to t_2. These same methods may be extended to include <u>any</u> type of surging or repeating voltage wave as encountered in electronic devices.

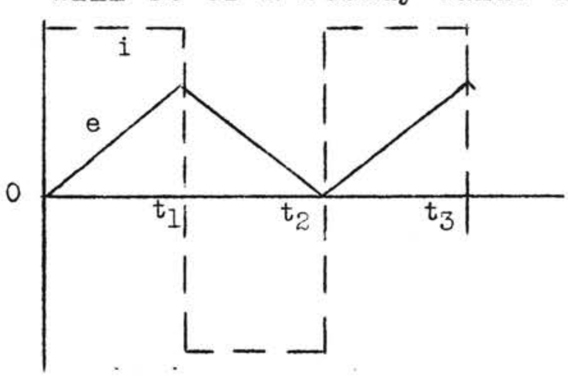


Fig. 4. Capacitive Differentiating Action.

Like the resistor, we find the condenser normally displays linear characteristics for any given frequency or capacity is a circuit constant so long as no physical change occurs in its construction. Of course, we have variable condensers, as well as fixed condensers, electrlytic as well as dry types, etc. However, like the resistor, we do find that capacity can be made to vary with temperature, pressure, etc., by arranging for relative physical movement of the plates. We find these types of construction sometimes used in industrial control application.

Self-Inductance

Another form of electrical storage device is the inductance coil. Its action can be readily determined by Lenz's law - merely a restatement of the law of conservation of energy. The Law says that whenever changing flux links a wire or coil, an opposing potential will be established in the coil. This might be considered as cause and effect. Something first causes a change of current flowing in a conductor; but when current changes, the attendant magnetic field also changes in time phase with the current change, but 90° in space phase. Whenever flux changes occur about a conductor, there will be voltage induced which opposes the action causing the initial current change, i.e., opposed in time phase, or mathematically

$$e = -N\frac{d\phi}{dt}$$

where N = number of times flux change cuts the current (number of coil turns).

$\frac{d\phi}{dt}$ = rate of change of flux linking the current.

The induced voltage may also be expressed in terms of the change in current causing a flux change

$$e = -K\frac{di}{dt}$$

where K = a proportionality constant

$\frac{di}{dt}$ = rate of change of current

These relations express the same condition so

$$K\frac{di}{dt} = N\frac{d\phi}{dt}$$

or

$$K = N\frac{d\phi}{di}$$

and K is simply a proportionality factor of the physical wire arrangement known as the inductance of a coil, hence

$$L = N\frac{d\phi}{di}$$

but L represents the physical arrangement of the current path (or wire) so L can also be expressed as a function of physical dimensions of the wire

$$L = \frac{0.4\ N^2 A}{10^8 l}\mu \text{ henries}$$

where N = number of turns in coil

A = cross-sectional area of flux path

l = length of flux path

μ = relation of permeability (μ of air = 1)

These conditions assume an ideal situation, the arrangement of the current path and the linking flux must be perfect if no flux is lost due to leakage.

<u>Inductance Current</u>

Since $Nd\phi$ is equal to Ldi, this substitution may be made in the above expression so that the opposing voltage may be expressed in terms of the coil inductance and the rate of current change or

$$e_i = -L\frac{di}{dt}$$

Rearranging so $di = \frac{1}{L} e_i dt$, i may be determined by integration

$$i = \frac{1}{L}\int e_i dt \; C$$

and for steady-state conditions C is zero.

The $\int e_i dt$ represents the area under the e-t curve and may be readily found either analytically or graphically.

Suppose that a sinusoidal voltage is acting upon a pure inductive air cored coil ($\mu = 1$). The charging current flowing to maintain the field will then be readily determined.

Let $e = E_m \sin wt$ be the applied voltage acting on the inductor L.

$$i = \frac{1}{L}\int e \; dt = \frac{1}{L}\int E_m \sin wt \; dt$$

$$i = -\frac{E_m}{wL}\cos wt = \frac{E_m}{wL}\cos(-wt)$$

but $\frac{E_m}{wL}$ is the maximum current that will flow since

$$I_m = \frac{E_m}{X_L} = \frac{E_m}{w_L}$$

When these time relations are plotted, we have the characteristics of an ideal inductor as shown in Fig. 5 illustrating the typical current lag of the inductance coil.

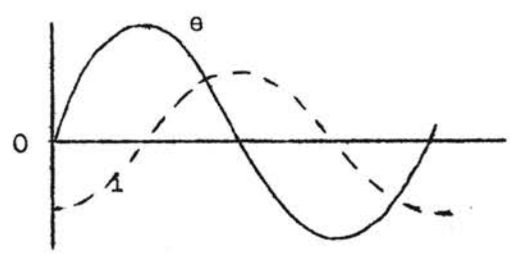


Fig. 5. Instantaneous current-voltage characteristic of an inductor.

If this same coil should be subjected to a square wave voltage as shown in Fig. 6, the resulting current flow will be of a sawtooth nature. This will become apparent if the integration process is carried out either mathematically or graphically. Consider the positive voltage pulse E lasting from t_o to t_1 or ΔT

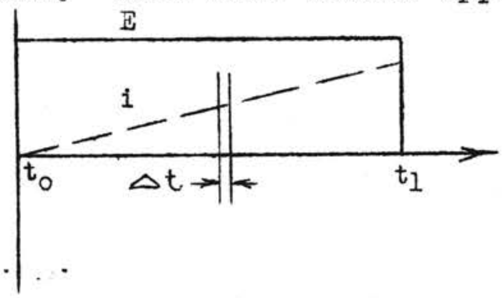


Fig. 6. Current flow in inductance coil.

$$i = \frac{1}{L}\int e\ dt = \frac{1}{L}\int E\ dt = \frac{E}{L}\Delta t$$

$$= \frac{E}{L}t$$

which is a linear equation in i and t with a slope of $\frac{E}{L}$.

The same result will be obtained graphically by considering some time interval Δt and measuring the area under the voltage curve up to the time t. When plotted, we obtain a stepped current curve as shown in Fig. 7, but as the interval Δt is made smaller, the final curve will approach the current curve of Fig. 6. This sort of analysis may, of course, be extended to include any kind of voltage condition.

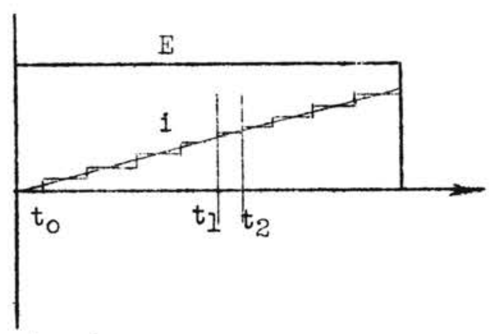


Fig. 7. Graphical determination of inductive current.

The Practical Inductor Characteristics

So far, we have considered the fundamental action of only an ideal inductance coil which never exists in practice. Any coil of wire must have resistance distributed through the winding. In addition to the distributed resistance of the coil, there will be core losses present so long as the inductor has a magnetic core. The core losses consist of both hysteresis and eddy current losses. There is always some flux leakage, too, for no matter how careful the construction, some few flux lines will fail to completely encircle the current path. These losses tend to absorb energy and hence may be considered as additional equivalent resistance acting in conjunction with an ideal inductance. This resistance results in some energy dissipation (as heat) whenever current flows through the inductor and is usually treated as a lumped quantity acting in series with an ideal coil. The relative merit, or Q, of a particular coil is simply a way of comparing the actual coil to the ideal, for

$$Q = \frac{wL}{R_s}$$

Obviously, the ideal coil would have an equivalent series Resistance R_s of zero or its Q would be infinite. The actual coil will have some finite resistance, hence, the coil Q will be definite and usually in the order of 100 or less. There may be times when it is desirable to express Q in terms of an equivalent parallel resistor and an ideal series or parallel coil.

$$L_p = \frac{1+Q^2}{Q^2} L_s$$

$$R_p = (1+Q^2)R_s = \frac{(1+Q^2)wLs}{Q} = QwL_p$$

where L_p = ideal parallel coil

R_p = equivalent parallel resistance

$Q = \frac{wLs}{R_s}$ = merit of coil

L_s = ideal series coil

R_s = equivalent series resistance

The included resistance of the coil will modify the resultant circuit current when a voltage wave is acting on the practical coil. Consider a coil which has a definite quantity of resistance distributed through its winding and acted upon by a positive voltage pulse as shown in Fig. 8.

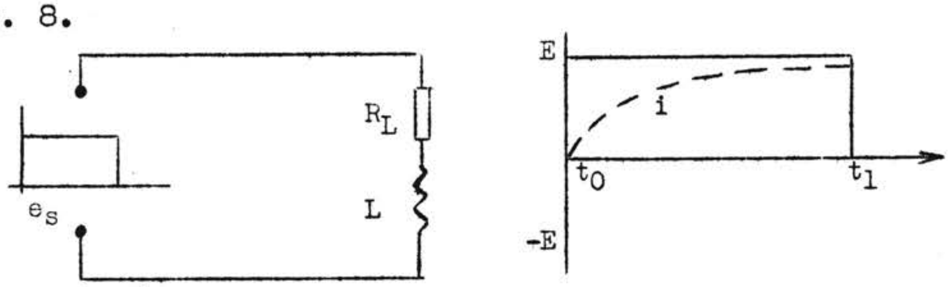


Fig. 8. Current-voltage characteristic of impure inductance.

By Kirchoff's voltage law

$$e_s = R_L i + L\frac{di}{dt}$$

rearranging gives a linear differential equation

$$\frac{di}{dt} + \frac{R}{L} i = \frac{e}{L}$$

applying the integrating factor $\mathcal{E}^{\frac{Rt}{L}}$ and solving the equation yields the following value of i:

$$i\,\mathcal{E}^{\frac{Rt}{L}} = \frac{e}{L}\int \mathcal{E}^{\frac{Rt}{L}}\,dt + C$$

$$i\,\mathcal{E}^{\frac{Rt}{L}} = \frac{e}{L}\frac{L}{R}\,\mathcal{E}^{\frac{Rt}{L}} + C$$

$$i = \frac{e}{R} + C\,\mathcal{E}^{-\frac{Rt}{L}}$$

and, if the time reference is chosen so that i = 0 when t = 0, then we can evaluate the constant of integration, or $C = -\frac{e}{R}$, hence

$$i = \frac{e}{R}\left(1 - \varepsilon^{-\frac{Rt}{L}}\right)$$

We chose a type of voltage wave so $e = +E$ from t_0 to t_1. Considering the current change during the interval t_0 to t_1, the instantaneous current will be

$$i = \frac{E}{R}\left(1 - \varepsilon^{-\frac{Rt}{L}}\right)$$

The current exponentially approaches a limiting value of $\frac{E}{R}$, for as t becomes large compared to the value of $\frac{L}{R}$, the exponential term $\varepsilon^{-\frac{Rt}{L}}$ approaches zero.

Suppose the voltage supply is suddenly interrupted at t_1. The energy which has been stored in the inductance field by the current flow must dissipate itself. The collapsing current will induce a high voltage ($L\frac{di}{dt}$) which tries to oppose the sudden change and sustain current flow. This induction voltage must be dissipated through resistance in the form of heat. Obviously, if the resistance discharge path is high, tremendous voltage may be induced and cause arc over in the switch or between turns of the coil. Fig. 9 shows the voltage current conditions during this energy decay period. When the inductance is very large, compared to the resistive discharge path, it may be necessary to provide some auxiliary low resistance discharge path to protect the inductance. A resistor might

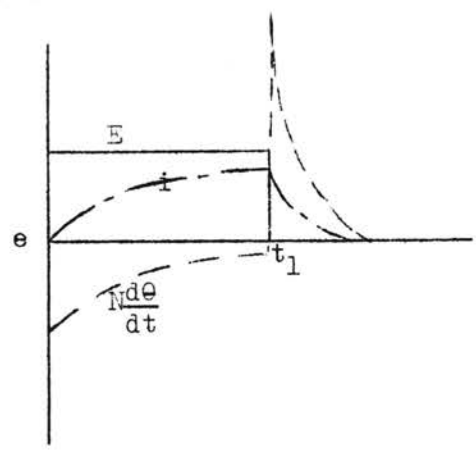


Fig. 9. Inductive decay period.

be shunted directly across the coil but this calls for wasted supply energy and a lowered circuit Q. Switches may be arranged to insert resistance across the coil before the supply circuit is opened. Sometimes special resistors, such as thyrite, display the correct negative resistance characteristic to be left permanently connected across the coil without excessive lowering of the circuit Q under normal excitation.

If the applied voltage had been of such a nature that it also was a time function, the resulting current expression is much more complex. Consider the case of a sinusoidal voltage when suddenly applied to the circuit.

Let $e_s = E_m \sin(wt + \alpha)$ where is the fixed angular displacement between e = 0 and t = 0 and measured positively as e passes through 0 in the positive sense. This notation is familiar from previous circuit studes. Kirchoff's voltage Law then allows us to establish the instantaneous voltage relations in the circuit as:

$$L\frac{di}{dt} + Ri = E_m \sin(wt + \alpha)$$

This is a linear differential equation whose general solution may be written for the dependent variable.[1]

$$i = \frac{E_m}{(R^2 + w^2L^2)}\left\{R \sin(wt + \alpha) - wL \cos(wt + \alpha)\right\} + C_1 e^{-\frac{Rt}{L}}$$

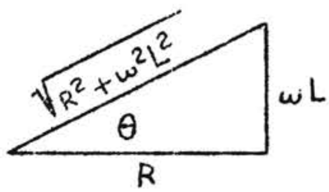
Rewriting this expression yields

$$i = \frac{E_m}{\sqrt{R^2 + w^2L^2}}\left\{\frac{R}{\sqrt{R^2 + w^2L^2}} \sin(wt + \alpha) - \frac{wL}{\sqrt{R^2 + wL^2}} \cos(wt + \alpha)\right\}$$

$$+ C_1 e^{-\frac{Rt}{L}}$$

1. Kells - Elementary Differential Equations, pp. 49, 50.

Applying the familiar impedance triangle to the expression within the brackets, and making equivalent substitutions, the current equation can be simplified.



$$\sin \phi = \frac{wL}{\sqrt{R^2\ w^2L^2}}$$

$$\cos \phi = \frac{R}{\sqrt{R^2\ w^2L^2}}$$

$$i = I_m \left\{ \cos \phi \sin(wt+\alpha) - \sin \phi \cos(wt+\alpha) \right\} + C_1\ e\ \varepsilon^{-\frac{Rt}{L}}$$

$$i = \frac{E_m}{Z} \sin(wt+\alpha-\phi) + C_1\ \varepsilon^{-\frac{Rt}{L}}$$

In view of the superposition theorem, we find the current is composed of two components each of which vary with time. The first component is the usual steady-state expression and varies sinusoidally with time, while the second component is an exponential time variation representing a transient current.

We must yet evaluate C_1 (the integration constant) before we can completely define the current conditions in the circuit. If we consider the voltage as suddenly applied to the circuit, no current will be flowing prior to this instant, so

$$i = 0 \text{ when } t = 0 \text{ and}$$

$$C_1 = -\frac{E_m}{Z} \sin(\alpha - \phi)$$

and the current will flow according to

$$i = \frac{E_m}{Z} \sin(wt+\alpha-\phi) - \frac{E_m}{Z} \sin(\alpha-\phi)\ \varepsilon^{-\frac{Rt}{L}}$$

or i total $= i_s - i_t$ as shown in Fig. 10. The initial conditions imposed on the circuit were that $i = 0$ when

when t = 0. The steady state current at the instant of

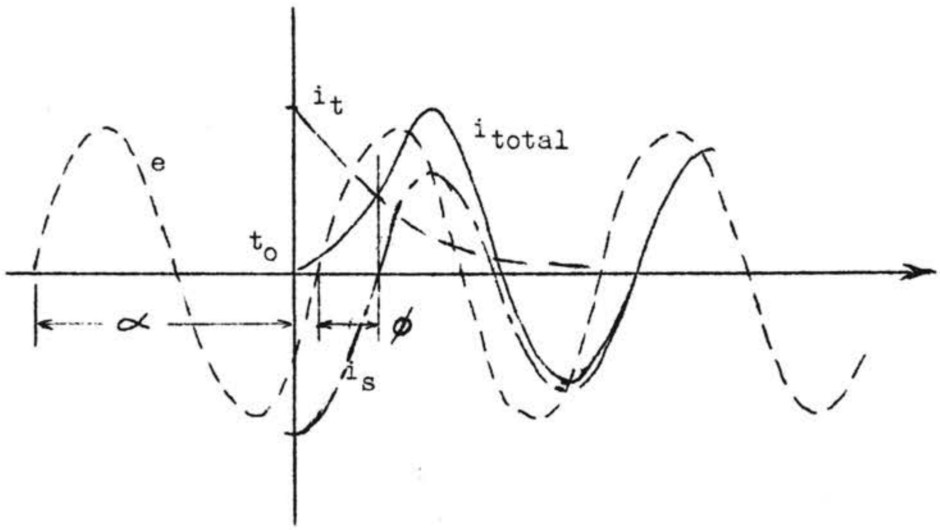


Fig. 10. General graph of transient current period.

switch closure will be $\frac{E_m}{Z}$ sin $(\alpha - \phi)$ and the transient component will be $-\frac{E_m}{Z}$ sin $(\alpha - \phi)$ indicating that the two components will be equal but cancel one another as the switch is closed.

It will be interesting to note the effects of switching upon the circuit current. If the instant of switching, t_o, is chosen so $(\alpha - \phi)$ is either zero or 180 degrees, there will be no transient. This can be readily shown by letting $\alpha = \phi$. Then

$$i = \frac{E_m}{Z} \sin wt$$

which is the steady-state current that will flow. This condition is shown in Fig. 11.

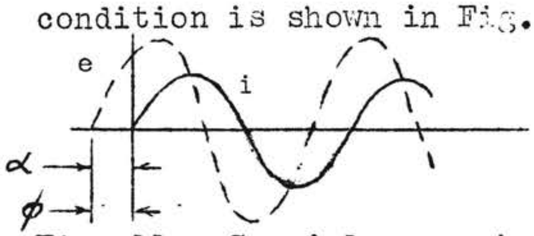


Fig. 11. Special case when $\alpha = \phi$.

If on the other hand, sin $(\alpha - \phi) = 1$ when t = 0, the <u>maximum</u> transient and steady-state current will surge as the switch is closed. But if sin $(\alpha - \emptyset) = 1$, then the angle $(\alpha - \emptyset) = \frac{\pi}{2}$ or some multiple thereof. If the circuit has a high Q, then the largest transient will occur as α approaches zero or 180 degrees. If the circuit is very low Q, then $\emptyset$ will approach zero degrees so the maximum transient would then occur as α approaches $\frac{\pi}{2}$ or some multiple.

An interesting case occurs when the switching action takes place at the instant the applied voltage is also zero. Under this condition, $\alpha = 0$ and i also must be zero as the circuit is first energized at t = 0. Inserting this limitation in the current equation gives

$$i = \frac{E_m}{Z} \sin (wt - \emptyset) - \frac{E_m}{Z} \sin (-\emptyset)\ e^{-\frac{Rt}{L}}$$

At the instant of switching the steady-state and transient current will be equal and opposite. Now, if the circuit Q is high the phase angle $\emptyset$ will approach 90 degrees and the instantaneous current will appear as in Fig. 12. The steady state component will rapidly approach the current flow for the ideal coil ($-I_m \cos wt$) while the maximum transient current at t = 0 will approach I_m of the steady state component as a limit. This can be easily shown if it is recalled that sin (wt-90) =

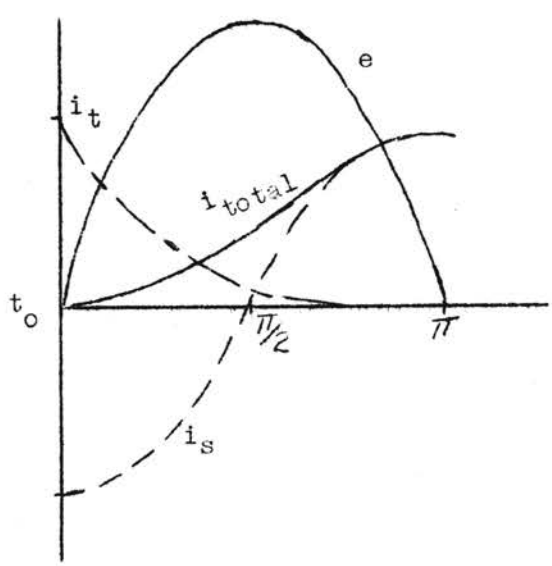


Fig. 12. Switching Transient.

- cos wt, and high Q implies very low resistance, hence,

$$i = \frac{E_m}{Z} \cos wt + 0$$

This method of analysis may be extended to include any form of complex voltage wave encountered in practice, provided an expression involving time can be set up for the voltage. This can then be inserted for e in the general expression

$$\frac{di}{dt} + \frac{Ri}{L} = \frac{e}{L}$$

and a solution similar to the above will be necessary. In practice, it is often more convenient to analyze the circuit response by using oscillographic records of circuit current and applied voltage. These oscillograms may be obtained using a two element electromagnetic oscillograph or an electron switch and cathode ray oscilloscope designed for transient studies.

<u>Non-linear Inductance</u>

We have based the previous discussion on an air core inductance which may always be considered sensibly constant regardless of current magnitude. Whenever we have an iron cored inductance, there is no longer a linear current-voltage characteristic, but the effect of changing permeability causes the inductance to vary proportionally, for

$$L = \frac{0.4\pi N^2 A}{10^8 L} \times \Delta\mu$$

where $\Delta\mu = \frac{\Delta B}{\Delta H}$

ΔB = an incremental change of flux density in the core.

ΔH = an incremental change of the magnetizing force (proportional to change of current).

The magnitization curve, Fig. 13, for any iron has a changing slope ($\Delta\mu$) as different operating points are chosen. If two operating conditions happen to be chosen, as indicated in Fig. 13, it is obvious that the values of incremental permeability will be quite different. Either of the operating conditions could be readily established by allowing enough d-c current flow in the coil to establish a static operating point as H_o. Should a-c then be imposed on the d-c current, a small change in H may then produce either large or small changes in B, depending entirely upon the choice of H_o and the relative magnitude of the a-c current. This characteristic is often advantageously employed when it is desirable for an inductance to display a non-linear characteristic. Such devices as saturable reactors and peaking transformers are designed so they have non-linear characteristics dependent upon the non-linear change of permeability. The "swinging" choke, often used as the input to a filter system, displays this non-linear characteristic. It is so designed that it displays high inductance with low values

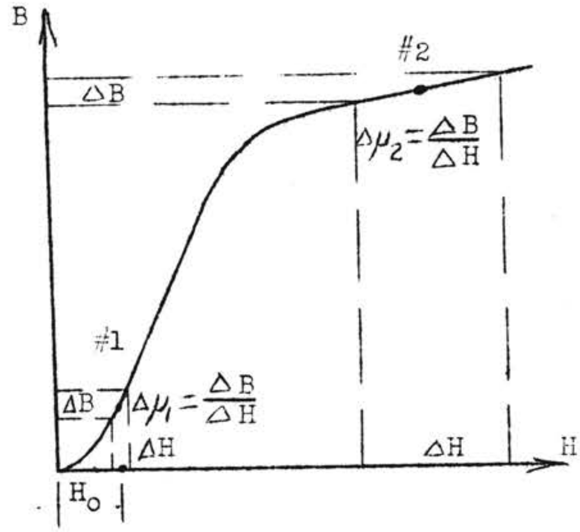
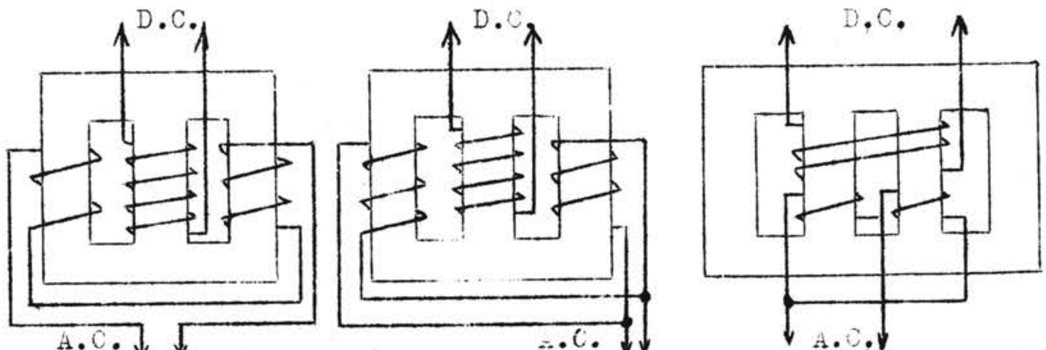


Fig. 13. Typical magnetization curve for iron.

of d-c current and low inductance with high d-c current flowing in the winding, and if the d-c component is increased too much, the core becomes saturated. Under these conditions the choke will have minimum inductive characteristics.

The saturable reactor is another magnetic controller which utilizes core saturation effects to control wide load demands. Several methods of common construction are shown in Fig. 14.



(a) Series a-c Winding (b) Parallel a-c Winding (c) 4 Legged core

Fig. 14. Types of Saturable reactor Construction

Simply applying d-c to one winding of a transformer will give some control of the a-c inductance but with a large decrease in effective primary inductance as the d-c winding acts effectively as a short circuit to the a-c on another winding. This would result in large losses. By properly arranging the windings, with reference to the flux path, this objection is readily overcome. In Fig. 14, the a-c windings are polarized on the core so that all a-c flux cancels in the middle leg of core a or b and the two central legs of core c - this calls for careful a-c balance magnetically. When d-c is applied to the auxiliary winding, there will be a definite steady flux set-up in both a-c flux paths, and due to the non-linear permeability of the iron, the a-c inductive effect will be made to vary as the d-c control flux is varied. Reasonable design will easily allow a 20 to 1 inductive change. The three-leg core construction has a rather high flux leakage. The core windows have to be quite large to accommodate the necessary windings and so do not form a very complete magnetic screen for either internal or external field. The four-leg core shown in Fig. 14 (c) gives a better magnetic construction with lower losses, better shielding from external fields, and greater coupling between the a-c and d-c fields.

The magnetic change causing inductive variation is slow, although the series connection, Fig. 14 (a), is faster acting than the parallel connection, and speed can only be obtained by sacrificing efficiency. The saturable reactor normally acts as a series controller, Fig. 15. The magnetic characteristic, being non-linear, cause considerable distortion in the a-c current (high 3rd harmonic content) with attendant change in wave shape of the load voltage.

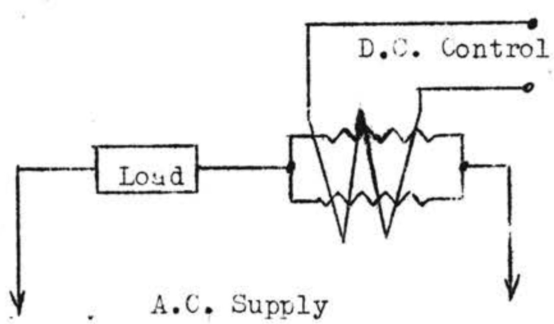


Fig. 15. Saturable reactor control of loading.

The flux distortion is greatest about the knee of the magnetization curve, which represents the mid-range of d-c control.

The saturable reactor allows a very small amount of d-c power to control large blocks of a-c power flow, and furthermore, the a-c and d-c paths are completely insulated from each other which is highly desirable from both the control and operational standpoint.

There are times when one reactor alone does not yield the desired range of control. If two or more saturable reactors are connected in tandem, a very small amount of d-c energy may control a very large a-c load. There are other times when several independent a-c loads may be simultaneously controlled by a single d-c supply control.

Mutual Inductance

When varying current flows in a coil, we have shown that a self induced voltage will be generated which opposes the applied emf to limit the current to some value dependent upon the coil construction.

$$e = -N\frac{d\phi}{dt} = -L\frac{di}{dt}$$

The changing flux caused by the current change may be readily expressed in terms of the coil construction from the above relation

$$\frac{d\phi}{dt} = \frac{L}{N}\frac{di}{dt} = \left(\frac{.4\pi N^2 \mu A}{Nl}\right)\frac{di}{dt}$$

and by lumping the fixed dimensions of the coil in a constant the change in flux might be expressed as

$$\frac{d\phi}{dt} = KN\mu\frac{di}{dt}$$

where $$K = \frac{0.4\pi A}{l}$$

Suppose this flux change occurred in the core of the coil arranged as in Fig. 16, and assuming constant permeability, then the voltage induced in the second winding due to current change in the first coil could be written for

$$e_2 = N_2\frac{d\phi}{dt}$$

but if the previous expression for $\frac{d\phi}{dt}$ is inserted, then

$$e_2 = K\,N_1N_2\mu\frac{di}{dt}$$

Mutual inductance (L_m) is defined as the ratio of voltage (e_2) induced in one coil to the current change in another coil producing the mutually changing flux

$$M = L_m = \frac{e_2}{\frac{di}{dt}_1} = K\mu N_1N_2$$

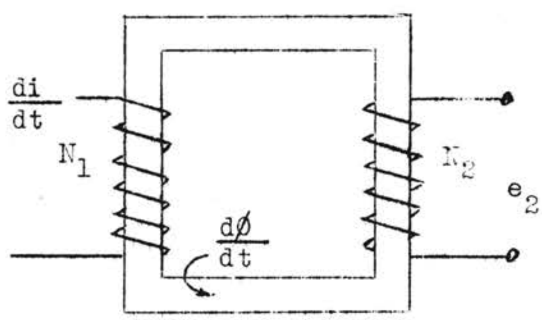


Fig. 16: A mutually coupled Circuit.

So long as we consider leakage flux negligible, as may be the case for an unloaded iron core transformer, the secondary voltage may be readily expressed in terms of the turns ratio

$$e_2 = N_2\frac{d\phi}{dt}$$

$$e_1 = N_1\frac{d\phi}{dt}$$

$$\frac{e_2}{e_1} = \frac{N_2}{N_1}$$

This expression will hold so long as no load is active on the secondary and the voltage-current relations are as shown in Fig. 17. Actually, there are losses in the transformer and though the primary current is small, it will be definite. Furthermore, the iron path through which the flux is being forced is not linear and its magnetization characteristic tends to flatten off toward the saturation point. This action will result in the generation of a definite third harmonic current in the primary. If the supply source were ideal - no internal resistance - this would be of little consequence perhaps; but the supply source resistance allows a definite third harmonic current to flow in the primary circuit. As a result, the secondary voltage will tend toward distortion. The farther the iron is worked toward saturation and the greater the source resistance, the more third harmonic voltage is induced in the secondary until finally a distorted, peaked secondary voltage results.

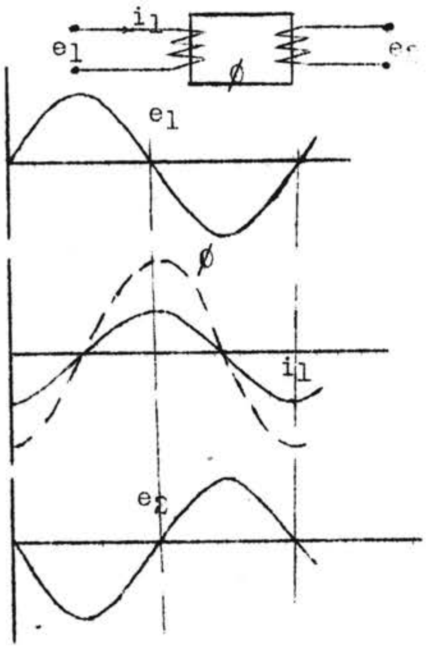


Fig. 17. Phase relations of the mutually coupled circuit.

An interesting application of the saturating action of iron is the peaking transformer. If the unit is so designed that the primary current far exceeds the saturation current required by the core, there will be no flux change except during current reversals. And, since the secondary voltage is determined by $-N\frac{d\phi}{dt}$, there will be only sudden short pulses of developed voltage as shown in Fig. 18. Some series limiting resistor (or inductance) is generally connected in the primary circuit to control the peaking action and limit the transformer heating. This type of

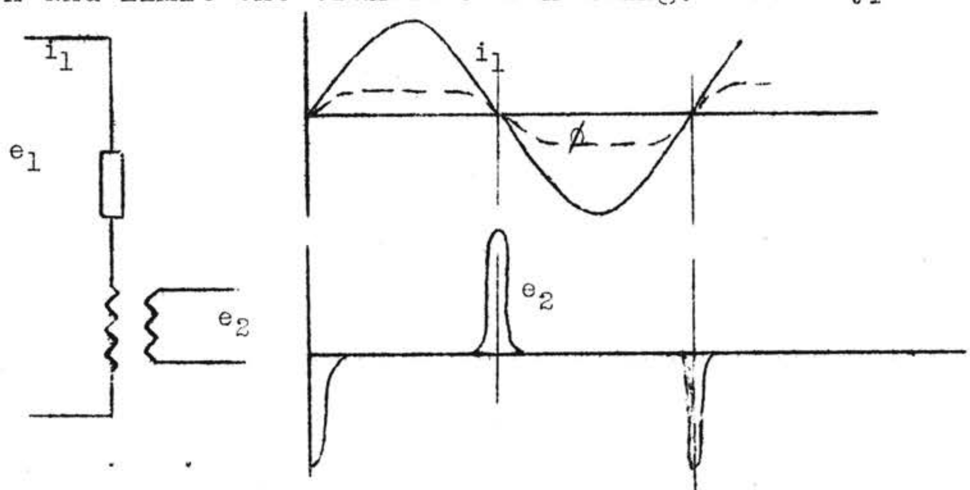


Fig. 18. Peaking transformer Action

transformer action is very inefficient but when a peaked voltage is needed, it serves admirably. Such transformers are often used to supply control firing pulses to thyratron circuits.

The transformer may also be used as a coupling transformer between tubes in an amplifier and, when so connected, there will be practically no loading imposed on the secondary, that is, minimum secondary current will flow. Many other industrial applications, however, require that the secondary carry heavy loads with heavy secondary current flowing. The secondary current will produce a counter flux in the core so that the self induced primary voltage becomes proportionally smaller. The equivalent net voltage then acting on the primary will increase. This is only another way of saying that the energy supplied to the primary increases proportionally to the increase in secondary loading.

Mutual inductance devices prove extremely versatile and serve in many industrial electronic devices.

Inductance-Capacitance Circuits

The L-C circuit is one of the most interesting and the many possible variations result in a variety of applications. The elements may be either connected in series or in parallel and the circuit reactions will vary depending on the proportioning of L and C. The actual circuit will always include some distributed resistance in the inductance but additional resistance may also be included due to loading and other effects. The complete RLC circuit may be so proportioned that at the operating frequency

(a) $X_L > X_c$

(b) $X_L = X_c$

(c) $X_L < X_c$

Each circuit proportion will result in different relative values of instantaneous voltage and current relations, and the effects of varying the resistance will still further modify the reactions. Thus, the circuit reaction to an applied voltage cannot be numerically predicted until the relative proportions of R, X_L and X_c for the operating conditions are known. We may, however, generalize on the circuit action.

If either X_L or X_c predominates at the operating frequency, the resulting current will be controlled by the predominating reactance, and will either lead or lag depending upon predominance and circuit connections. The general reactance curve will help in predicting current-voltage relations. Consider the series connected circuit where $X_1 > X_c$ at the operating frequency. Fig 19 shows this condition at f_1 for a specified value of L and C.

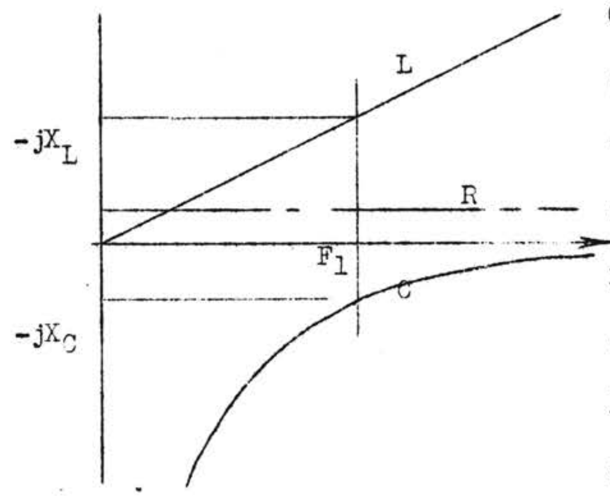


Fig. 19. Reactance vs frequency characteristic.

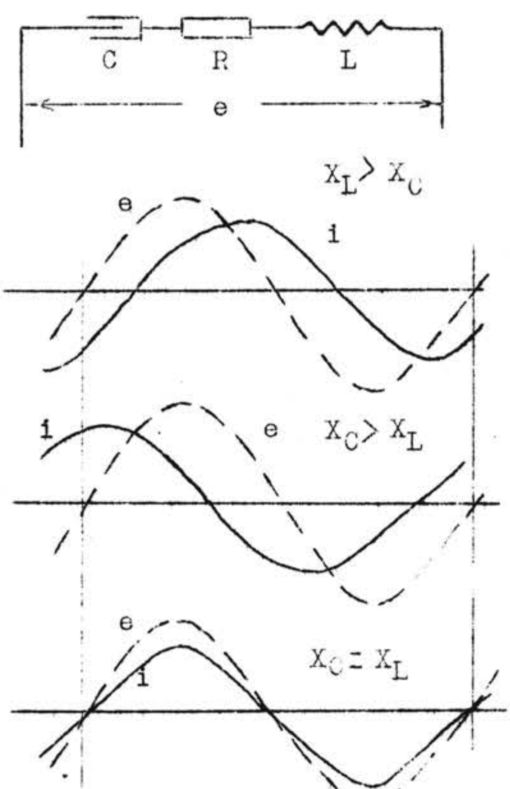


Fig. 20. Steady-state action of a series circuit.

Obviously, the current demand will be limited by the resistance and the predominant reactance $(X_L - X_c)$ for the circuit; hence, the current will be predominately inductive. The general steady-state current voltage characteristic of the series circuit are shown in Fig. 20, as X_L and X_c are proportioned differently. On the other hand, if R, L, and C are connected in parallel, the resistance and capacitive reactance being smaller magnitudes than the inductive reactance, the predominating current will be controlled by R and C. Then the circuit will demand principally capacitive current - just the opposite of the series circuit.

The general steady-state action of the parallel circuit when connected across an a-c supply is shown in Fig. 21. A more interesting case occurs (Fig. 21) when $X_L = X_c$ at the operating frequency. The applied voltage will attempt to charge and discharge the capacitor field, but at the same time the inductance is demanding a decrease and increase in its electromagnetic field. Hence, the discharging capacitor, being series connected locally will supply charging energy to the inductance and the discharging inductance will in turn supply the condenser with charging energy. If the resistance of the local circuit is small, very little of this exchanging energy is lost as heat and the local current flowing will be extremely high. When the exchange of energy takes place at the same rate as the supply frequency ($X_L = X_c$), the circuit is in resonance. Since the local series resonant circuit demands only a small current flow to supply the losses of the circuit,

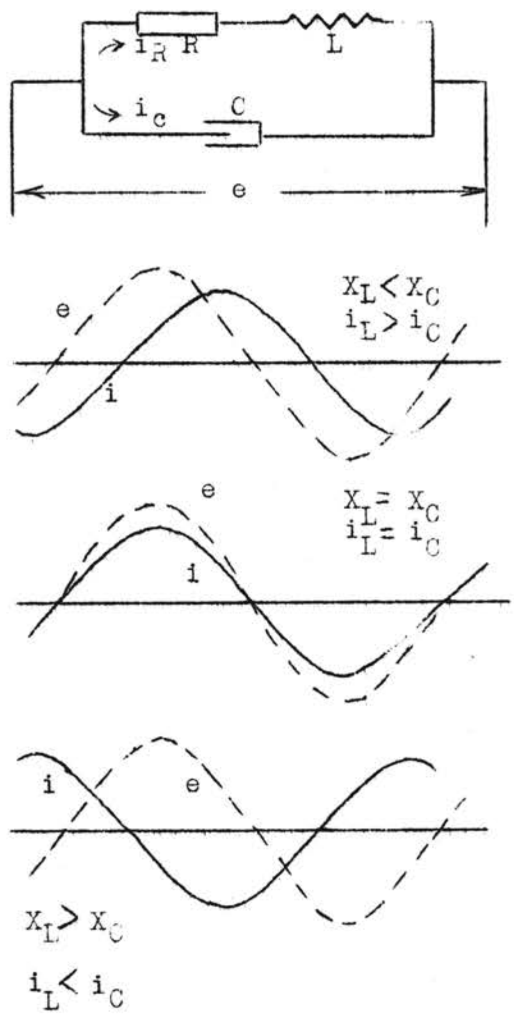


Fig. 21. Steady-state action of a parallel circuit.

it is the equivalent of a high resistance load to the supply source. It is interesting to note that all the supply source needs to do is simply kick the circuit with a power pulse to start the energy exchange process, and with little resistive loss, the energy will continue to oscillate in the circuit for some time. This condition is referred to as underdamping.

Suppose a pulse of voltage is suddenly applied to the series circuit of Fig. 22. The charging condenser momentarily acts as a short circuit, but the series inductance will try to prevent this current surge from flowing. Hence, the current will start to rise as an

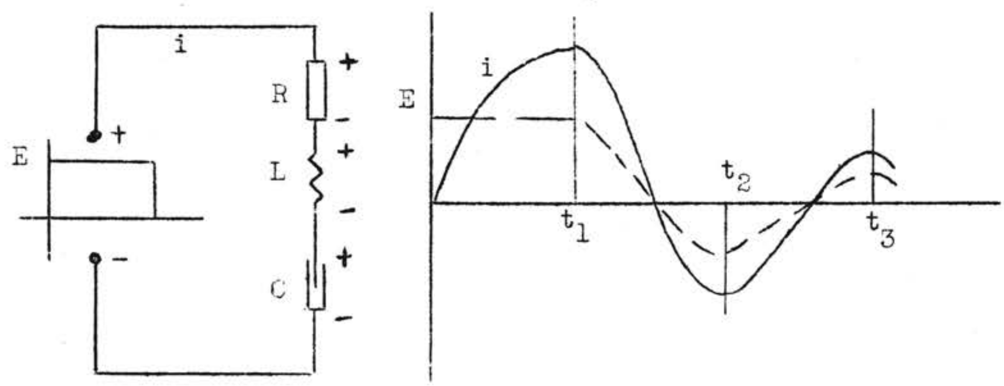


Fig. 22. Transient state of series circuit

inductive current but will rise much more rapidly due to the charging demand of the condenser. The pulse suddenly drops to zero at t_1 and leaves a short circuit across the source. The energy in the magnetic field will start to dissipate itself and will charge the condenser still higher due to a reversal of current from t_1 to t_2. But, as the condenser potential becomes higher than the decaying inductance voltage, the condenser will begin to discharge to maintain voltage equilibrum and current will again flow from t_2 to t_3. This process will continue until the energy initially stored in both fields has dissipated itself as heat in the resistor. The current reversals will take place at regular time intervals corresponding to a definite frequency such that $X_L = X_c$, the natural resonant frequency of the circuit.

If the resistance had been large so that it dissipated essentially all of the exchange energy, the circuit could not continue to oscillate and would be referred to as overdamped. Since the current surging in the series circuit is high, the inductive and capacitive voltage drops will be much higher than the source voltage; the higher the circuit Q, the greater this voltage amplification. This will become more obvious when the circuit is analyzed. The maximum current of the resonant series circuit will be

$$i = \frac{E}{R}$$

but $$e_L = e_c = iX_L = iX_c = E\left(\frac{wL}{R}\right) = EQ$$

hence, the inductive and capacitive drops will be Q times the applied voltage, E_m.

The parallel resonant circuit behaves somewhat differently. The parallel elements exchange large amounts of energy through their local circuit - this is, in fact, a localized series resonant branch. However, the source needs only to supply the losses in the local circuit which normally are made quite low; thus, since the parallel circuit demands only small current flow, it may be considered as presenting a very high equivalent impedance to the supply. As long as the circuit Q is reasonably high, wL may be considered essentially equal to $\frac{1}{wC}$ and the parallel impedance may be readily evaluated

$$Z = \frac{Z_c Z_L}{Z_c + Z_L} = \frac{wL/wC}{R} = \frac{1}{wC}\left(\frac{wL}{R}\right) = \frac{L}{CR} \qquad \text{or}$$

$$Z = wL\left(\frac{wL}{R}\right) = wLQ$$

However, the higher the circuit Q, the greater the exchanging current in the L-C circuit. This localized current would represent an equivalent current amplification in the local circuit. It can be shown that the branch currents will be Q times the current supplied by the source for a high Q circuit.

The above characteristics of series and parallel circuits are wholly true only after the circuit has reached steady-state conditions. The current demands will vary somewhat just at the instant the supply is initially connected to the circuit. Quite large amounts of transient energy must flow if the electromagnetic and electrostatic fields are to be established. Only as soon as inductive-capacitive energy exchange has been equalized do the preceding conditions prevail.

When an a-c supply is connected across an RLC circuit, the concepts previously mentioned will still hold. The current supplied to the capacitor by the source reaches its positive maximum just as the supply is changing most rapidly in a positive sense, so the voltage is passing through zero and a quarter cycle ahead of its maximum positive peak. The current in the inductance is maximum just at the end of the half cycle in which the source has been working to force current flow in its direction. At this instant, the voltage is just going through zero in a positive sense, so the inductive current is at its maximum negative value. Thus, at this instant we have both a positive and negative current demand. The difference between these currents (the Ri drop) must be supplied by the source. If the frequency of the supply does not agree with the natural resonant frequency of the circuit, the supply current will be either leading or lagging depending upon the direction of frequency disagreement.

The Electron Tube

The electron tube, as applied to industrial electronics, may be required to satisfy any one of several basic functions - it may act to rectify, amplify, clip, or mix various voltages involved in the process. Basically the current-voltage characteristic of the tube is non-linear and resistive in nature. Since it is a non-linear device, its characteristics are considered as differential ratios. The more important characteristics determined by its construction features may be summarized as plate resistance, mutual conductance, and amplification factor. The tube may be thought of as an electrostatic check valve arranged so some potential change on the tube elements control the amount of power (or current) flowing in the controlled circuit. The tube will function much as a check valve, i.e., there can be only unidirectional current flow through the tube circuit. There are numerous methods of classifying the hundreds of available tubes, but one satisfactory method may arrange them as vacuum tubes, gas-filled tubes and special tubes. This is a very broad general classification which may then be subdivided in terms of the number of elements included in the tube construction as the diode, triode, tetrode, etc.

The Vacuum Tube

The number of elements, their relative positions, and the applied operating potentials, combine to form an electrostatic field within the vacuum tube. Any variations caused in the field will result in control over the electron stream trying to flow across the field. Since the electrostatic field is determined by applied potentials, while the electron flow depends on the field, the differential form of Ohm's Law may be applied, so the instantaneous plate resistance may be expressed as

$$r_p = \left.\frac{\partial E_p}{\partial I_p}\right] E_g \text{ is constant}$$

So long as the tube has more than two elements and one of its elements is arranged in the construction so that any small potential change, and its resulting change of the electrostatic field in the tube, has a controlling influence on the electron flow, the tube will have an amplification factor and mutual conductance. The amplication factor is thus a ratio showing the effectiveness of the element potentials in controlling the current flow.

$$\mu = \frac{\frac{\partial I_p}{\partial E_g}}{\frac{\partial I_p}{\partial E_p}} = -\left.\frac{\partial E_p}{\partial E_g}\right] \; I_p \text{ is constant}$$

Mutual conductance indicates the relative ability of the <u>grid</u> to control the current flow in the tube so

$$G_m = \left.\frac{\partial I_p}{\partial E_g}\right] \; E_p \text{ is constant}$$

These so-called constants really tell very little of the tubes action for they simply represent the slope of the characteristic at any one operating point. Before a complete story of the tube can be told, we must refer to a set of characteristics of the tube. These are usually shown graphically over a wide range of operating conditions. Fig. 23 shows the grid, plate, and constant current characteristics for a triode.

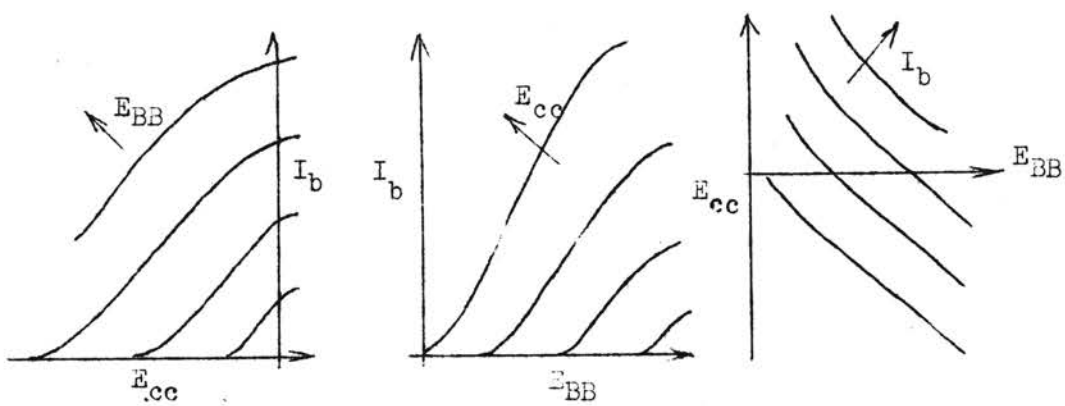


Fig. 23. Typical triode characteristics

When the slope of these characteristic curves are plotted, the "constants" are quite variable, especially over certain parts of the operating range.

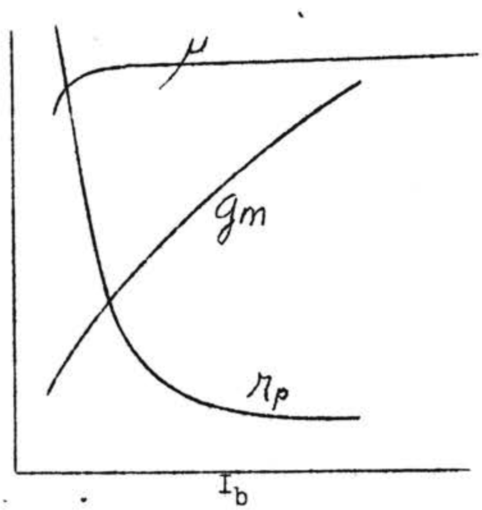


Fig. 24. Variation of the "constants" of a triode tube.

Since the vacuum tube is a non-linear resistive device, it does not always have the same proportional current change for a given potential change. Many applications of tubes in industrial devices require nearly linear response. When a circuit is so arranged that a linear and non-linear resistance are connected in series, the non-linear effect can be minimized by proportioning the two resistors so the ratio of the non-linear to linear resistor approaches zero. Operating limitations prevent the ideal condition from being realized, but the series linear resistor (plate load) can be made several times greater than the non-linear plate resistance.

The internal electrostatic control field of the vacuum tube is proportioned according to relative spacing of the elements. A high-mu tube would have a small mesh control grid located very near the cathode so a very small change in its relative potential would have a large effect upon the tube current, and a large swing in plate potential results in rapidly increasing non-linear action. Practical limitations on the electrostatic field control prevent the triode from having an amplification factor over 100.

By introducing a "screen grid", between the control grid and the anode, the anode can be effectively isolated from the control grid. The screen grid operates at a <u>constant</u> positive voltage and establishes a constant accelerating force upon the electron stream. So long as this screen is maintained at a constant potential below that of the plate, it effectively screens any changes in plate potential from the control grid. Thus the tube will display the characteristics of an equivalent constant current generator. If the plate potential drops below the screen potential, the tube displays a negative resistance effect due to secondary emission at the plate (See Fig. 2).

Secondary emission effects can be overcome if the field effect from screen to anode could be nulified. By introducing a suppressor grid between the screen and plate, and connecting it so it is at the same potential as the cathode, the electrons which break through the screen and suppressor region will now be attracted by the positive plate even though the plate potential may be lower than the screen potential. The elemination of secondary emission results in the absence of the negative resistance region and, hence, the operating range of the pentode may be extended to include a greater portion of the supply voltage.

By proper physical placement of the grids with reference to each other, the electrostatic field may be so established that the constant current pentode characteristic may be extended over still a greater portion of the supply voltage. This type of construction may actually require no suppressor grid. The control grid structure is adjusted so it is exactly in line with the screen grid and the electron flow is "beamed" to the plate. Beam forming plates near the anode are held at cathode potential and not only help in the beaming action but also suppress secondary anode emission. The electrostatic control action is even better than in the pentode field. The screen current will be less than for a corresponding pentode, so beam tubes form excellent power amplifiers.

<u>The Gas filled Tube</u>

The construction of the gas filled tube may upon first inspection appear to be essentially the same as a vacuum tube. One outstanding difference exists. As the name implies, some gas or gas forming material has been purposely introduced in the tube construction. Very different characteristics result.

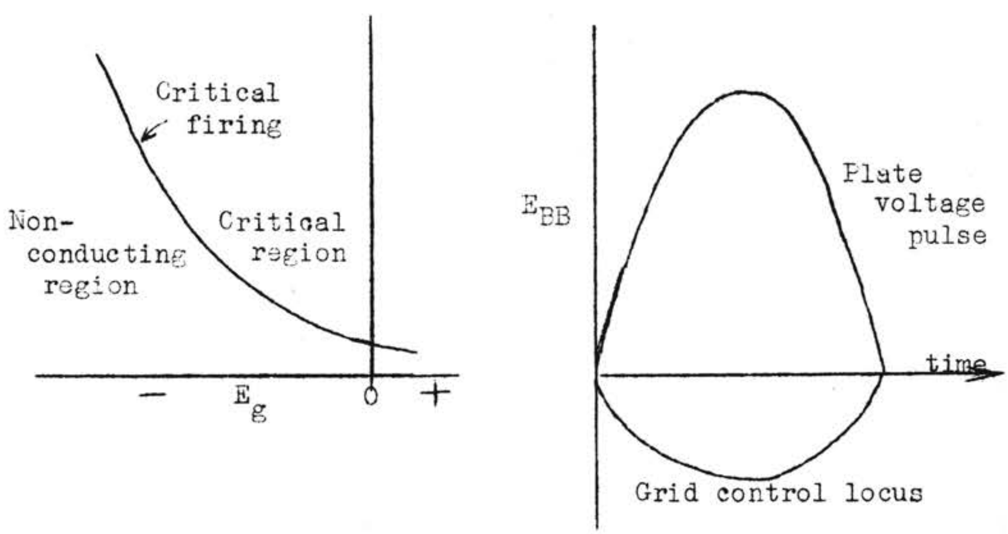


Fig. 25. Gas Tube Control Characteristic

Once the gas is ionized, the positive particles float in toward the negative control grid and completely blank out its controlling effect. Furthermore, the gas forms a very low resistance path for the electrons to travel through from cathode to plate with the result that tube resistance has little effect upon the circuit. The ionization effect results in an effective neutralizing of the space charge in the tube, thus the constant internal drop of the tube is approximately equal to the ionizing potential of the gas for any current within the cathode emission range. Relatively little energy is lost within the tube, and consequently, large currents can be tolerated by the plate. The maximum emission characteristic of the cathode material will be the limiting current factor.

The gas tube is slow in its action. Time is required to ionize or deionize gas and, hence, the plate current will not instantly follow control grid impulses. Grid control of the tube firing may be accomplished by biasing the control grid with a d-c voltage. Fig. 27 shows how variation in this control bias may be used to control the firing angle of the tube. Notice that the minimum time of power flow will be 1/4 cycle of the applied plate voltage pulse. Furthermore, as the firing point approaches

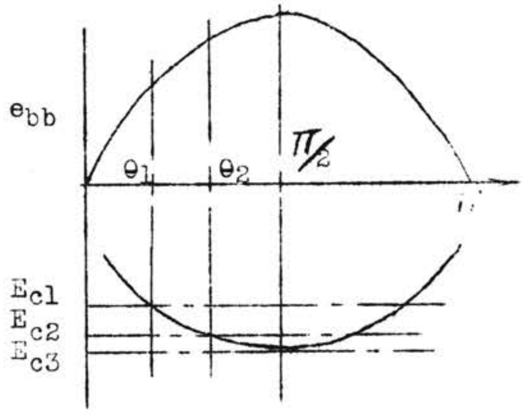


Fig. 27. D-C control of the firing angle of a gas tube.

this value the slope of the grid control locus is not much different than the bias voltage slope; hence, the exact firing point becomes uncertain as E_c approaches a value corresponding to $\pi/2$ of the plate voltage pulse. If the bias is increased beyond this critical bias toward E_{c3}, the tube cannot fire during the cycle.

Firing control may also be accomplished by applying an a-c grid voltage having the same frequency as the plate voltage. As the relative phase of the grid and plate voltages are shifted the firing angle may be readily controlled over nearly the full 180° of the plate voltage pulse. Fig. 28 shows how the applied control

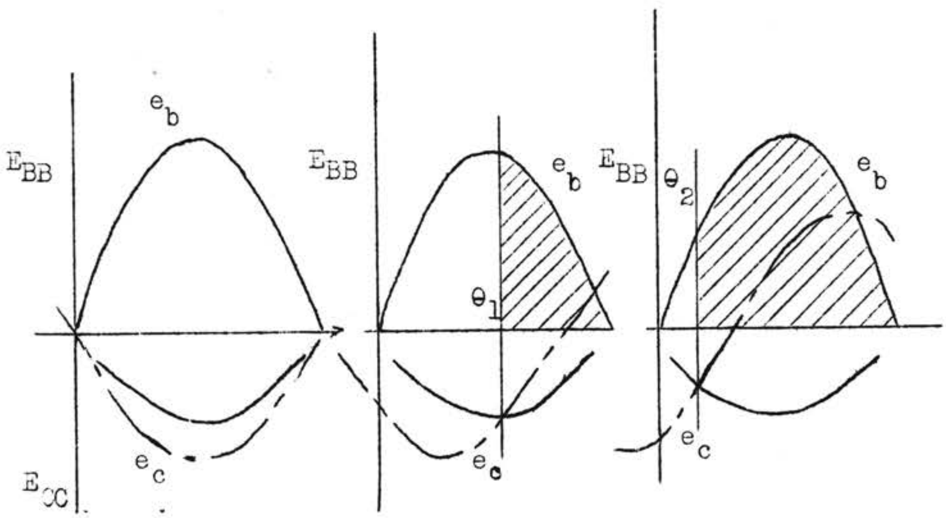


Fig. 28. A-C control of firing angle of gas tube (a) tube will not fire (b) tube fires at θ_1 (c) tube fires at θ_2.

voltage may be shifted to intersect the control locus of the tube at any desired firing angle. Note that e_c must always be greater in magnitude than the corresponding control locus. Furthermore, the grid will at times be forced positive by the a-c grid voltage; hence, grid current must flow even though the tube might be completely cut off for the full cycle. This is not desirable for certain types of grid control gas tubes. Whereas the d-c control became uncertain, as the bias forced the firing angle close to $\pi/2$, the a-c control becomes uncertain as the a-c bias forces the firing angle toward 0° or 180° because the slope of the control locus and the grid voltage approach each other.

A combination of d-c and a-c gives much better control for now the amplitudes of each voltage may be independently adjusted as well as the relative phase of the a-c grid component and the plate voltage. This control is illustrated in Fig. 29. As e_c is shifted, in phase, there can still be some uncertainty of control as 0 or 180° is approached due to slope similarities of the control locus and the instantaneous grid voltage.

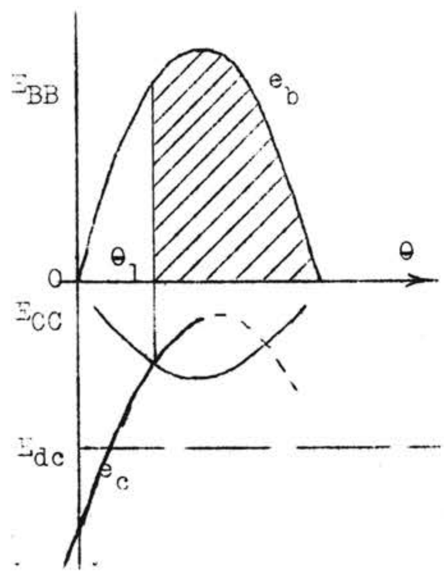


Fig. 29: A-C D-C firing Control.

When it is necessary for the thyratron to fire at exactly the same instant in each successive cycle, it may prove best to superimpose a sharp positive pulse voltage on a d-c bias component, Fig. 30. This type of control pulse may be obtained in several ways which will be discussed later. The more common circuits utilize one of the following devices; saturable reactor, peaking transformer, differentiating network, or some impulse generator in combination with a phase shifting network to control the relative time when applying the positive pulse. This type of control also aids deionization of the gas and helps clear the grid of emitting material deposited there during the conduction time of the firing cycle.

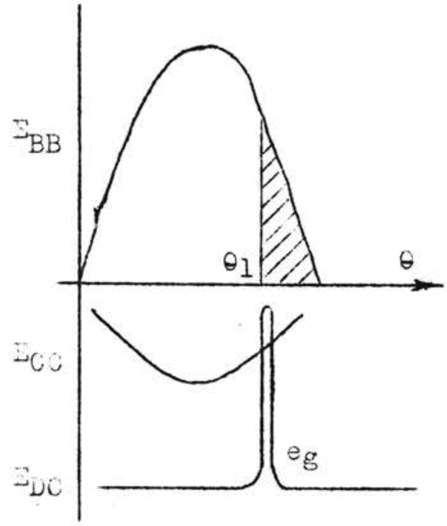


Fig. 30. Impulse firing control of thyratron.

Industrial processes utilize the gas filled tube to advantage when larger currents are demanded than the vacuum tube will carry. Some of the more important gas tubes include the gas filled rectifier, the thyratron, the ignitron, the mercury arc rectifiers, and regulator tubes.

Special Tubes

There are many tubes which may be considered as special types. Photoelectric tubes depend upon the ability of a specially coated cathode to emit electrons when influenced by an impinging light beam. Photoelectric tubes may be either vacuum or gas types depending upon the desired characteristics. Photoelectric multiplier tubes are quite useful and increase the effect of the few photoelectrically emitted electrons many times. Multiplier tubes require extremely high voltages and this may prove disadvantageous. Other tubes, as the cathode ray tube, the "magic eye" and electrometer tubes are often used in industrial applications.

Resistance-Capacity circuits

Consider a circuit composed of lumped capacity and resistance suddenly connected across a steady voltage source as shown in Fig. 31.

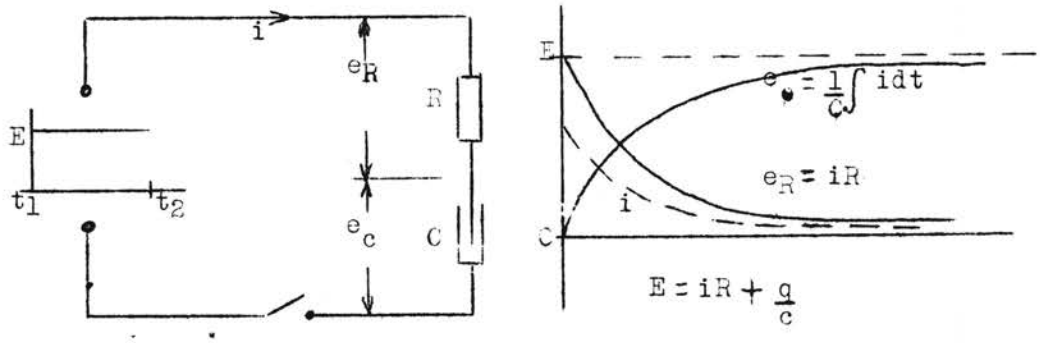


Fig. 31. Transient RC Action.

Kirchoff's law allows us to write the instantaneous voltage equation of the circuit, so

$$e_s = e_r + e_c$$

Substituting instantaneous voltage drops for the period from t_1 to t_2, when the voltage is of constant value E, the voltage equation becomes

$$E = iR + \frac{q}{C}$$

We are interested in instantaneous rate of change conditions in the circuit. Differentiation of the voltage equation with respect to time will describe this condition

$$0 = R\frac{di}{dt} + \frac{1}{C}\frac{dq}{dt}$$

but $\frac{dq}{dt} = i$ so the equation becomes

$$R\frac{di}{dt} + \frac{i}{C} = 0$$

rearranging the equation gives a linear differential equation similar to the equation of the L-R circuit.

$$\frac{di}{i} = -\frac{dt}{RC}$$

This equation when integrated gives the instantaneous current flow

$$\text{Ln } i = -\frac{t}{RC} + \ln K$$

$$i = K\varepsilon^{-\frac{t}{RC}}$$

The integration constant will be evaluated in terms of the circuit constants when it is remembered that $q = 0$ at the instant the switch is closed ($t = 0$).

$$E = K\varepsilon^{-\frac{t}{RC}}R + \frac{q}{C} \quad \text{when} \quad q = 0, \ t = 0$$

$$K = \frac{E}{R}$$

Substituting the value of K then gives an expression for current at any instant

$$i = \frac{E}{R}\varepsilon^{-\frac{t}{RC}}$$

The current is maximum ($\frac{E}{R}$) at the instant the switch is closed, i.e., the condenser acts as an instantaneous short circuit with R alone limiting the current, and then exponentially decreases until, after a relatively long period of time, the current exponentially approaches zero as shown in Fig. 31.

The voltage across the resistor at any instant is Ri so

$$e_r = Ri = R(\frac{E}{R}\varepsilon^{-\frac{t}{RC}})$$

$$= E\varepsilon^{-\frac{t}{RC}}$$

and by Kirchoff's law, the voltage drop across the condenser at any instant must be the difference between the steady applied voltage and the resistor drop so

$$e_c = E - iR$$

$$= E(1-\varepsilon^{-\frac{t}{RC}})$$

The instantaneous condenser voltage has been already expressed as an integral of the current $e_c = \frac{1}{c}\int idt$, and since the charging current has been found to be $i = \frac{E}{R}\varepsilon^{-\frac{t}{RC}}$ the condenser voltage could be readily determined for integrating $e_c = \frac{E}{RC}\int \varepsilon^{-\frac{t}{RC}} dt$ shows that

$$e_c = \frac{E}{RC}\ (-RC\,\varepsilon^{-\frac{t}{RC}}) + K$$

The integration constant K may be evaluated when we remember that $e_c = 0$ at the instant the switch is to be closed ($t = 0$) and hence,

$$K = E$$

Hence, the potential across the condenser at any instant exactly checks with the previous method of evaluation,

$$e_c = -E\,\varepsilon^{-\frac{t}{RC}} + E$$

$$= E(1-\varepsilon^{-\frac{t}{RC}})$$

If it so happened that the product of RC was equal to the time chosen to investigate the circuit conditions, then

$$e_c = E(1-\varepsilon^{-1})$$

$$= 0.632E_B$$

Other time intervals could be investigated for the above value of R and C and a time per-cent voltage curve could be drawn as in Fig. 32.

If the circuit had become completely stabilized

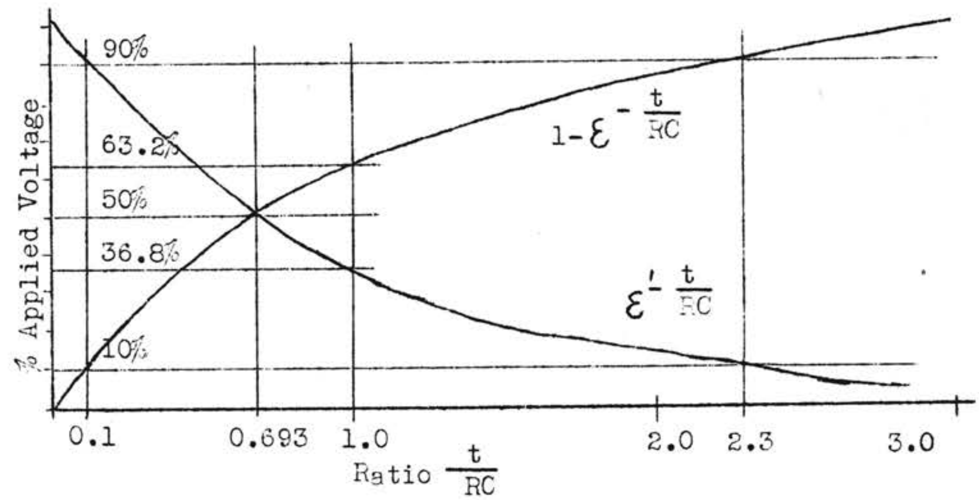


Fig. 32. Instantaneous potentials of an RC Circuit.

(i reduced to zero), and the circuit suddenly connected to discharge the stored condenser energy through the resistor, the instantaneous discharge voltages would be

$$e_r = e_c = E\,\varepsilon^{-\frac{t}{RC}}$$

so the curves of Fig. 32 will still be applicable by choosing the corresponding exponential curve.

The product of RC is generally referred to as the <u>time constant</u> of the circuit and represents either the time required to discharge a condenser 63.2% of its original charge or to charge the condenser to 63.2% of its final value. The time constant must be related to some chosen time interval so that either

(a) $RC < T_o$
(b) $RC = T_o$
(c) $RC > T_o$

The three possible conditions are shown in Fig. 33

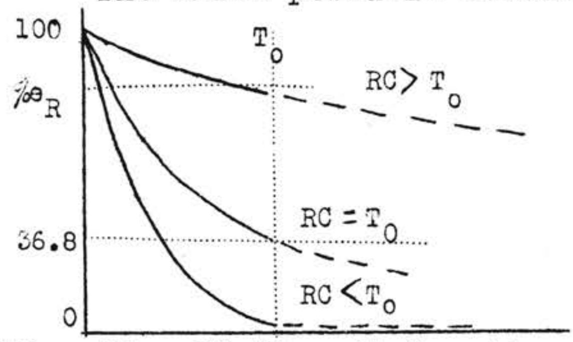


Fig. 33. RC Circuit Reaction.

and in relation to the given period considered, the circuit is said to have a short time constant when RC T_o, an equal time constant when RC = T_o, and a long time constant when RC T_o. It is interesting to observe that if the circuit has a short time constant, the current has decreased to practically zero by the time the period considered (T_o) has become 10 times as great as RC. But, if the circuit has a longer time constant, the condenser is only partially charged at the end of the period considered. Now if the applied voltage is suddenly changed to some new value at the end of T_o seconds, the condenser will have already acquired an initial charge Q_o, and the current flowing after this change will be governed by two voltages. Suppose, for illustration, the voltage is suddenly increased at time T_o. The back voltage already acquired by the condenser is $\frac{Q_o}{C}$ and the current which flows will be due to the difference of the new potential E_1 and the condenser voltage $\frac{Q_o}{C}$. The current at the instant after the sudden voltage increase has no relation to the current just prior to the change and must be equal to the voltage change plus or minus (depending on an increase or decrease) any back voltage due to initial charge on the condenser, hence

$$I_o = \frac{E_1 - \frac{Q_o}{C}}{R}$$

Hence, this is the new integration constant of the previous analysis and

$$K = \frac{E_1 - \frac{Q_o}{C}}{R}$$

making this substitution in the general current expression gives the instantaneous current after the change

$$i = \frac{E_1 - \frac{Q_o}{C}}{R} \, \varepsilon^{-\frac{t}{RC}}$$

Fig. 34 shows the action of an RC circuit under these conditions.

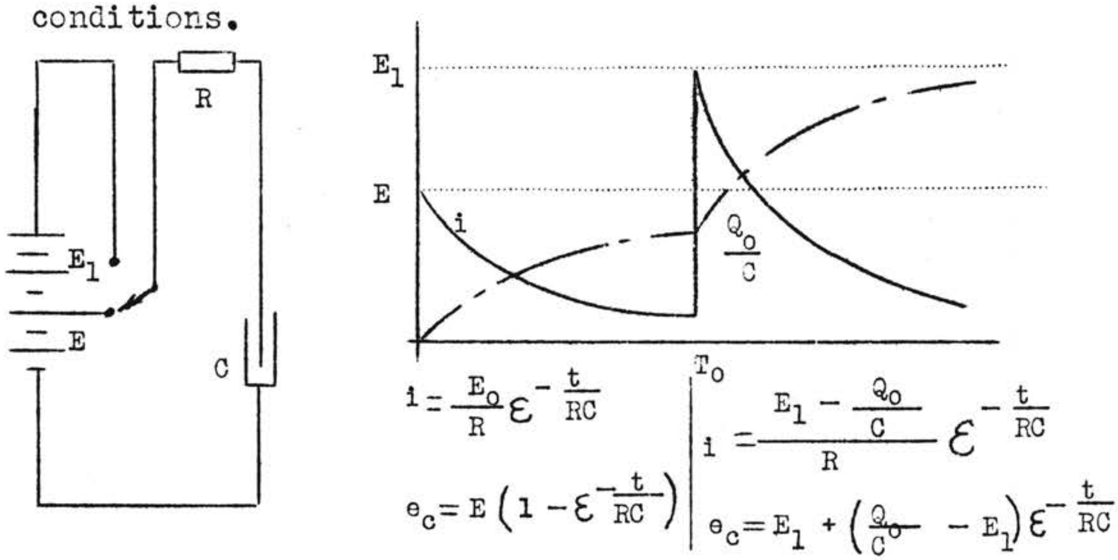


Fig. 34. Instantaneous relations in an RC circuit when the supply is suddenly increased.

The same results could be obtained by a rather simple graphical method which will be illustrated in the following:

Let us analyze a long RC circuit when acted upon by a pulse type of voltage. The generator voltage is varying between +150 volts and +300 volts with respect to ground, holding each value steady for 100 microseconds. In effect, we have a square wave of 75 volts amplitude superimposed on a d-c voltage of 225 volts. We will choose the resistor and capacity so they have a time constant of

200 microseconds. The complete circuit reaction is shown in Fig. 35.

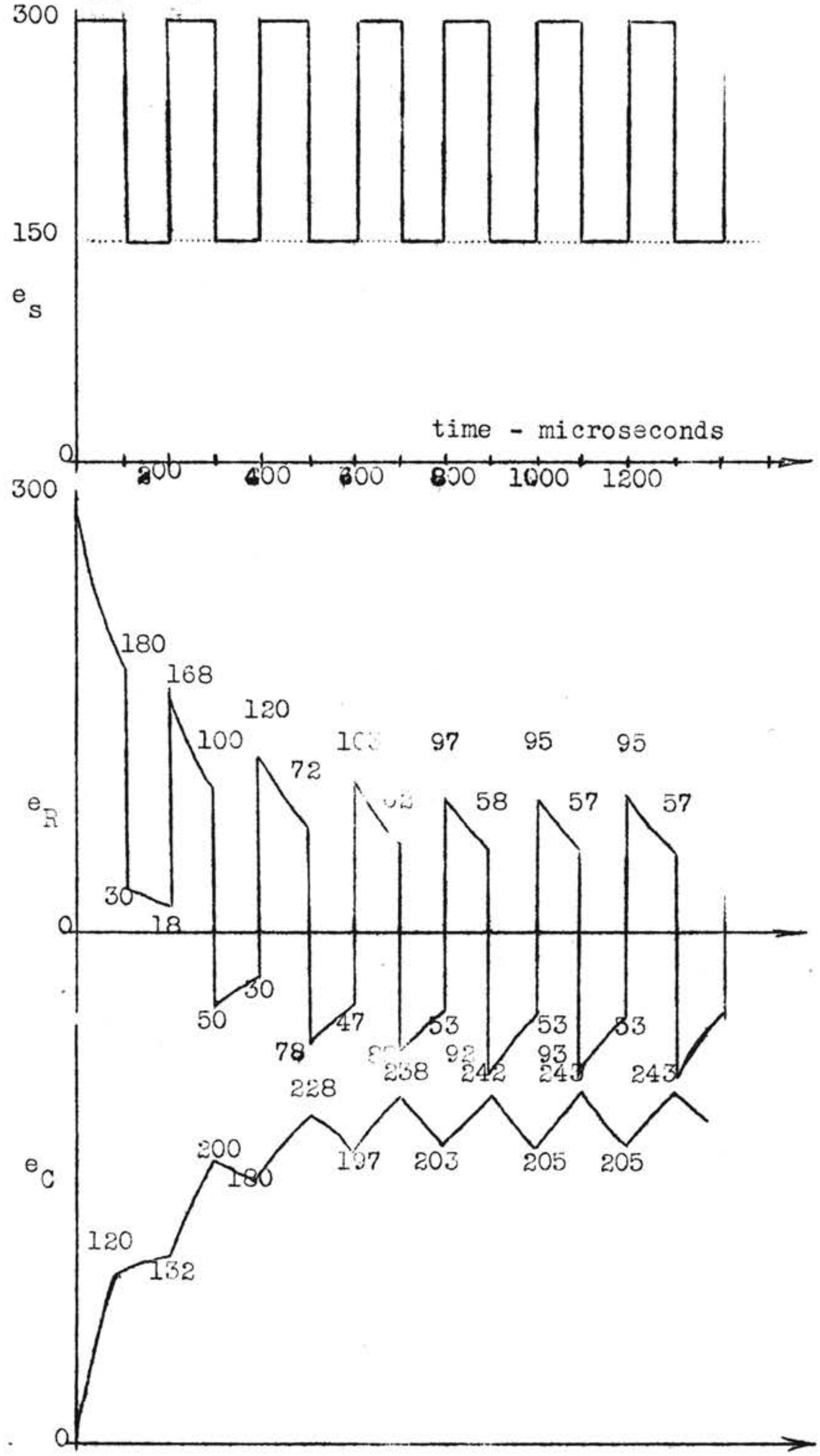


Fig. 35. Action of a long RC Circuit

The circuit is suddenly energized at t = 0. Since there is no difference of potential across the condenser plates at this instant, the full 300 volts appears across the resistor due to electron flow. The condenser begins to charge exponentially. The applied voltage remains constant for 100 microseconds, during which time the condenser acquires a charge Q such that its back voltage $\frac{Q}{C}$ is 40% (See Fig.32) of the applied 300 volts, while the drop across the resistor has dropped to 180 volts. At the end of the first pulse period the voltage suddenly drops to 150 volts. Since the condenser had only reached 120 volts difference across its plates, it will continue to charge but toward 150 volts not at 300 volts, and from 120 volts, not zero as during the first 100 microseconds. Thus the effective charging voltage is 30 volts at the instant the pulse voltage changed from 300 to 150 volts. After 100 microseconds more, the condenser will assume 40% of the effective charging potential, and the total voltage difference across the plates will be 132 volts at the end of 200 microseconds.

When the applied voltage dropped from 300 to 150 volts at the end of 100 microseconds, this represented an instantaneous change of 150 volts in the negative direction. Since this change occurred in zero time, the voltage across the condenser could not change, and all of this change had to appear across R and in the same direction, so the voltage dropped from 180 volts to 30 volts. During the following time that the condenser is charging from 120 to 132 volts, the resistor potential across the resistor will drop from 30 volts to 18 volts.

At the end of 200 microseconds, the applied pulse voltage instantaneously increases to 300 volts again. C cannot charge instantaneously so the change must be off-set by a potential rise across R - to 168 volts. C charges from 132 volts towards 300 volts, an effective charging voltage of 168 volts for 100 microseconds, leaving the potential across the condenser at 200 volts at the end of this pulse period. During the same interval the potential drop across R must change from 168 to 100 volts. At the end of 300 microseconds the condenser voltage will be 200 volts and the resistor voltage will be 100 volts. At this instant, the supply suddenly drops again from 300 to 150 volts, another change of 150 volts in a negative direction. By reference to Fig. 35 , it will be seen that e_r drops to <u>negative</u> 50 volts, although nothing but positive voltage has been applied to the circuit. During this period the condenser discharges slightly, since the polarity across R has reversed, and reverse current flows in the circuit. C discharges 20 volts from 200 volts toward 150 volts during this period, and the resistor voltage rises to negative 30 volts.

Notice that C is always charging as long as e_r is positive and that as C charges e_r becomes less positive; but when e_r is negative C discharges and e_r becomes less negative. As time progresses the condenser continues to increase its charge every cycle until the average voltage has shifted down far enough that C will discharge as much as it charges each cycle. The area below the reference line is the same as the area above for each cycle, hence the condenser no longer takes energy from the source.

Actually, a long RC would be relatively much greater ($RC = 10T_o$ or more) and would require longer to become stable. Suppose it required 1000 cycles to reach equilibrum, this would be only one second after the signal was applied in the case of a 1000 cycle per second voltage. It is apparent then, that if the condenser voltage does not change much during a cycle, the resistor voltage will tend to vary exactly as the applied voltage regardless of the actual wave shape applied.

This characteristic of the RC circuit leads to one of its most important applications - the coupling device between amplifier tubes. The multi-tube amplifier commonly requires that the <u>changes</u> of plate voltage on one tube be passed to the grid of the succeeding tube without placing the grid at the same quiescent potential as the preceeding plate. With the coupling arrangement shown in Fig. 36, any variations in the plate voltage of VT-1 will affect the grid of VT-2 as a potential drop across R. These variations occur as e_r varies but R, and hence the grid of VT-2, is isolated from the plate potential of VT-1 by the condenser C.

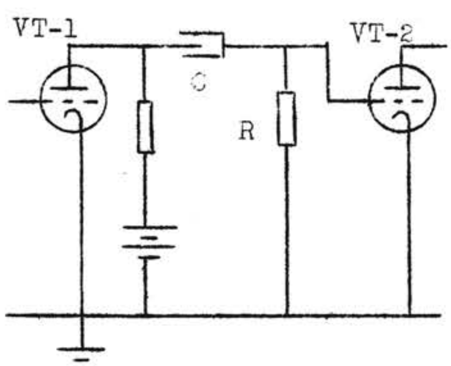


Fig. 36. RC Coupling in an Amplifier.

Variations of the basic circuit will be discussed later when we consider differentiating and integrating circuits.

Rectifier-Inductance Circuits

Industrial electronic circuits often include a rectifier tube connected in series with some simple R, L, or C combinations. Suppose a half wave rectifier is in series with an R-L circuit and energized from a sinusoidal voltage source of negligible impedance as shown in Fig. 37.

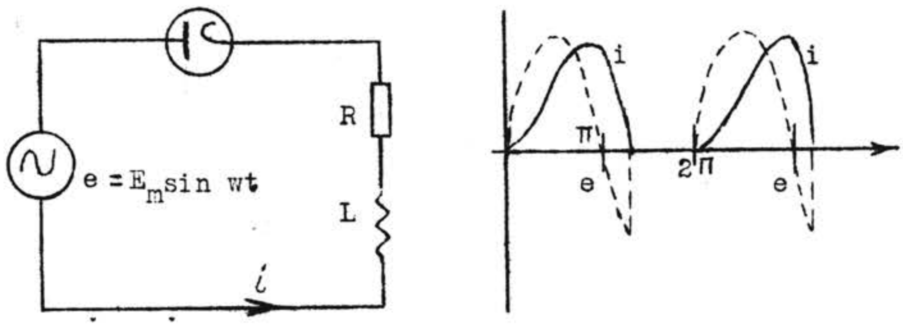
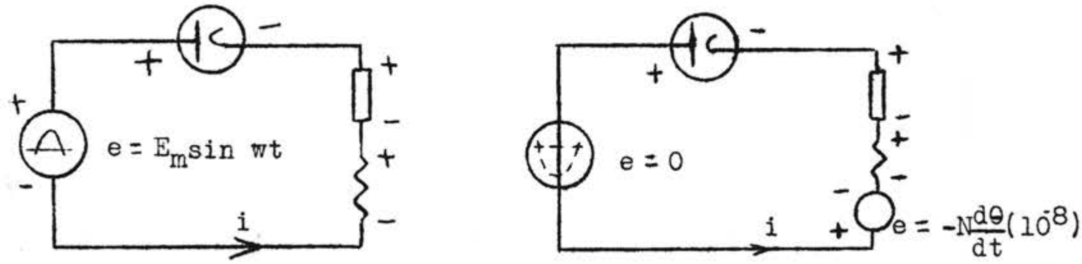


Fig. 37. Transient characteristics of a simple rectifier.

The rectifier tube can, of course, pass current only so long as its anode is positive. As the voltage starts positively from zero, as indicated in Fig. 37, the current must also start from zero as indicated in the previous discussion of an R-L circuit and will consist of a transient and a steady-state term. As the applied voltage continues through its positive excursion and finally back to zero, the tube effectively opens the supply circuit, i.e., the plate is forced negative by the negative supply pulse. But at the same time, the energy which has been stored in the magnetic field must collapse. This means that a voltage will be induced in the coil which is $-N\frac{d\phi}{dt} \times 10^{-8}$, and its polarity is of such nature as to maintain the rectifier plate positive even though the supply source has reversed polarity. Current will continue to flow until the energy has been dissipated by the resistor. These conditions are indicated in Fig. 38.



(a) Charging relations. (b) Discharging relations.

Fig. 38. Half-wave rectifier, inductance, and resistance in series.

When the self-induced inductor voltage drops below the corresponding instantaneous value of the applied voltage, the rectifier no longer conducts and the circuit remains idle until the next positive pulse from the supply initiates the process again. This action is typical of any practical inductor for the distributed resistance may be considered as a lumped quantity. The same action is just as true for a circuit composed of separate resistor and inductance. The duration of the current pulse is always greater than 180° for any practical inductance circuit and the "overhang" depends upon the length of time required for the resistor to dissipate enough energy to cause the self-induced voltage to become equal and less than the increasing negative value of the applied voltage. This may be expressed as the ratio of $\frac{wL}{R}$ or the Q of the circuit. A high Q circuit will allow the current pulse to flow for 90% or more of the applied voltage cycle, while a low Q circuit will limit the current pulse to slightly over

50% of the voltage cycle.

An analysis of the current pulse by any of the common methods (Fouriers, etc.) will reveal that the peak current will be greater than if no rectifier tube had been included, and if iron is present some tendency toward saturation exists, with still higher peaks resulting. Like the peak current, the effective and average currents will also be higher for the rectifier circuit. More heating will result for a given average flux density condition. This must be kept in mind when choosing magnetic devices to operate in such a circuit.

If an additional resistor is paralleled across the inductor of Fig. 37, the inductor current becomes unidirectional. Consider the action of this circuit shown in Fig. 39.

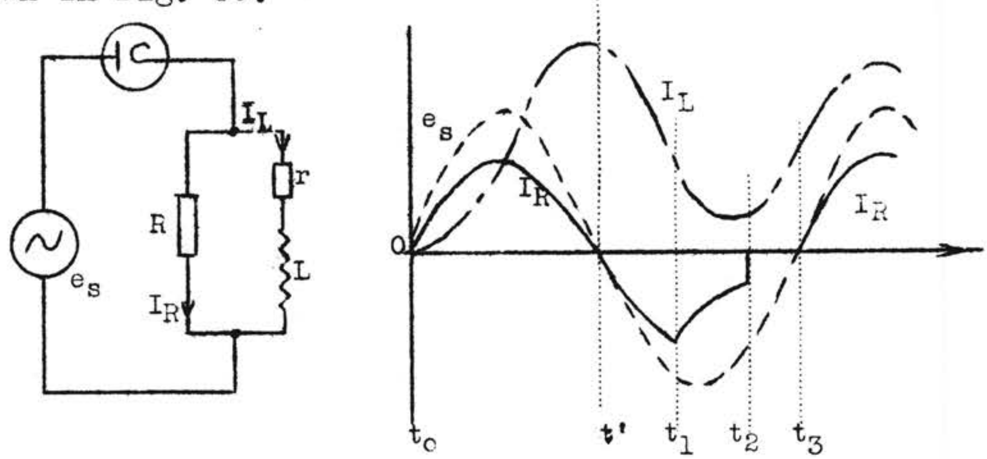
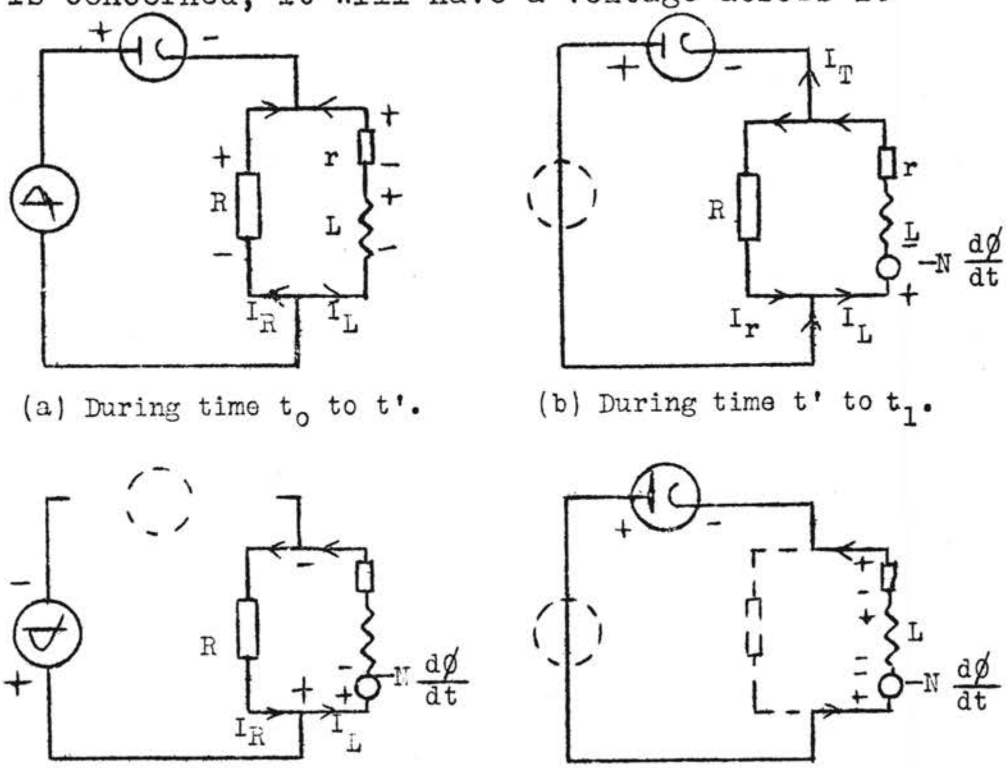


Fig. 39. A Series parallel circuit action.

As the supply voltage increases positively from t_o the tube will conduct and its current will divide in the two parallel branches. The current in the resistor branch will exactly follow the change in voltage while the current in the inductive branch will behave exactly as in the previous circuit. When the supply voltage reverses polarity, the energy stored in the inductance field again sets up a potential to force current back through the supply; but since R is in parallel with the inductor, current will also be forced to flow through it but in a reverse direction. When the negative supply potential equals the drop across the parallel circuit (at t_1) the tube can no longer conduct since the supply voltage continues to increase more negatively, and holds the rectifier plate at a negative potential with respect to its cathode. However, the remaining energy stored in the inductance field will continue to discharge through R and r along an exponential path. So long as this resistance path is not too low, the inductor energy will not have been completely dissipated before the next positive pulse of the supply voltage begins (at t_3) and the inductor current will proceed to rise from this residual value resulting in unidirectional inductor current after a few cycles, until the circuit losses during the negative voltage half cycles, balance the gain during the positive voltage half cycle.

Another interesting part of the circuit action occurs between t_2 and t_3. The rectifier ceased conducting at t_1 but current continued to flow in the parallel circuit. The drop across R continues for some time depending upon the length of the time constant. Polarity conditions are shown in Fig. 40a, b, c, and d. So far as the rectifier tube is concerned, it will have a voltage across it



(a) During time t_0 to t'. (b) During time t' to t_1.

(c) During time t_1 to t_2. (d) During time t_2 to t_3.

Fig. 40. Series Parallel Circuit Action.

which is the sum of the supply voltage and the drop across the resistor R. Obviously, if the resistor R is made very small, the discharge energy during t' to t_1 will be dissipated almost instantly and the time interval will become very small, or t_1 will occur much earlier in the voltage cycle. Furthermore, very little energy could be stored in the inductor during the charging time since a small value of R would effectively by-pass most of the rectifier current around the inductor. With little energy stored in the inductor it could not force energy to flow back through the line against the supply source. This circuit should have rather a long time constant if this condition is to be avoided.

The supply voltage is rapidly decreasing toward zero between t_2 and t_3 while the resistor voltage is exponentially decreasing to zero but of reversed polarity so far as the rectifier tube is concerned. From the instant t_2 on the resistor drop exceeds the supply voltage in magnitude, hence the rectifier, being influenced by the positive drop across R, will conduct <u>before</u> the supply voltage returns to zero (t_3). But as soon as the tube conducts it effectively short circuits R and so the inductor must dissipate its remaining energy in r (so long as r_p is neglected or small). There will then be no current in R until time t_3 when the supply again takes control of the circuit. This type of circuit may be employed in connection with thyratron tubes for control applications.

It was pointed out that the previous circuit must have a fairly high value of R if the losses are not too excessive, and reverse current is to flow during the negative voltage cycle. If the resistance across the inductor could be made infinite during the energy charging period and zero during the discharging period, the current in the inductor will approach a steady d-c current flow. This ideal circuit can be readily approached by employing the circuit of Fig. 41, often referred to as the "free-wheeling" circuit.

When the supply voltage is increasing positively from t_0 the inductor is charging according to previous discussion, and if the inductor has high Q, the coil current will approach an instantaneous value of

$$i = I_m\ (1-\cos wt)$$

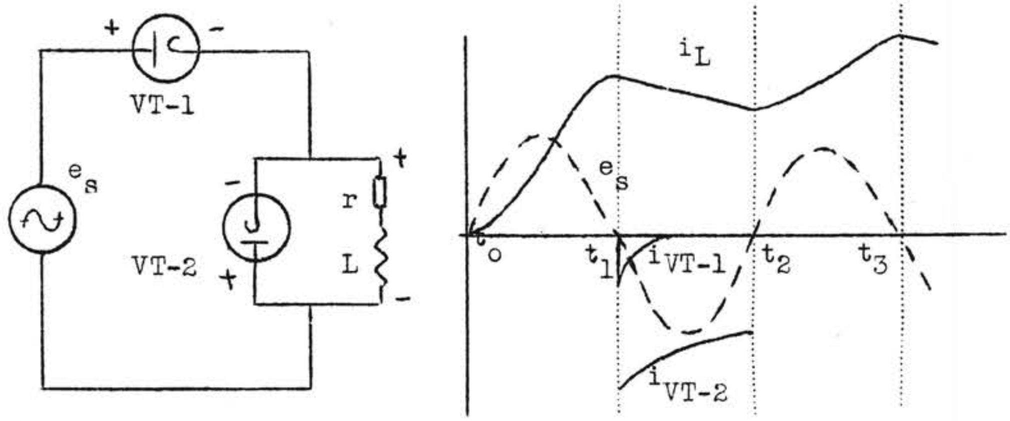
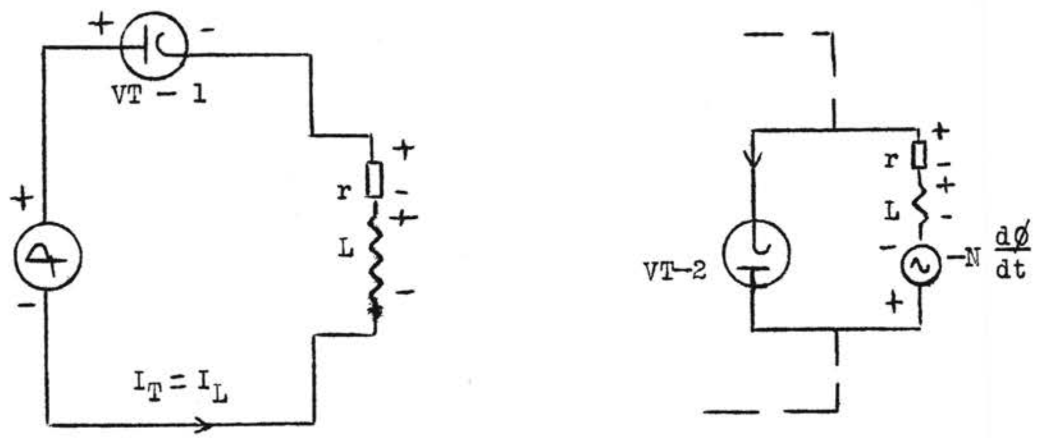


Fig. 41. The "freewheeling" circuit.

The rectifier VT-1 will be carrying the charging current during this period but VT-2 will have reverse polarity on its elements and will act as an open circuit, Fig. 42(a), thus giving the circuit a very high Q so long as r is small. When the supply voltage reverses polarity, the energy stored in the inductor field will establish a back emf as in Fig. 42(b), which makes the anode of VT-2 positive and it will begin to conduct. Its internal resistance will be small so we may think of it as a short circuit across the inductor terminals resulting in a low resistance discharge circuit; hence, the current will decrease slightly during this period from t_1 to t_2. Unlike the previous circuit, the voltage drop across the tube VT-2, while of correct polarity, will be very small due to the low resistance of the tube VT-2. Hence, the current flow back through VT-1 will be only an instantaneous pulse.

When the potential of the supply again reverses the current flow will be added to the residual current, so



(a) Charging current t_0 to t_1. (b) Discharging current t_1 to t_2

Fig. 42. Equivalent circuit action.

that after a short "pyramiding" effect, the current will approach a steady-state condition such that the positive half cycles supply just enough energy to offset the losses of the negative half cycles.

This sort of circuit has received considerable attention in connection with saturable reactors. Such a circuit normally uses a grid controlled thyratron in place of VT-1 (Fig. 43) so that smooth simple control of the d-c magnetizing current in the saturable reactor may be established. This circuit may be applied when the load demands such control. Theatre dimming of lights might be readily accomplished by such a circuit.

Rectifier-Capacitance Circuits

If a rectifier is connected in series with resistance and capacity and supplied from a sinusoidal source, the current flowing in the circuit may be used to supply timing pulses to industrial electronic devices. Timing

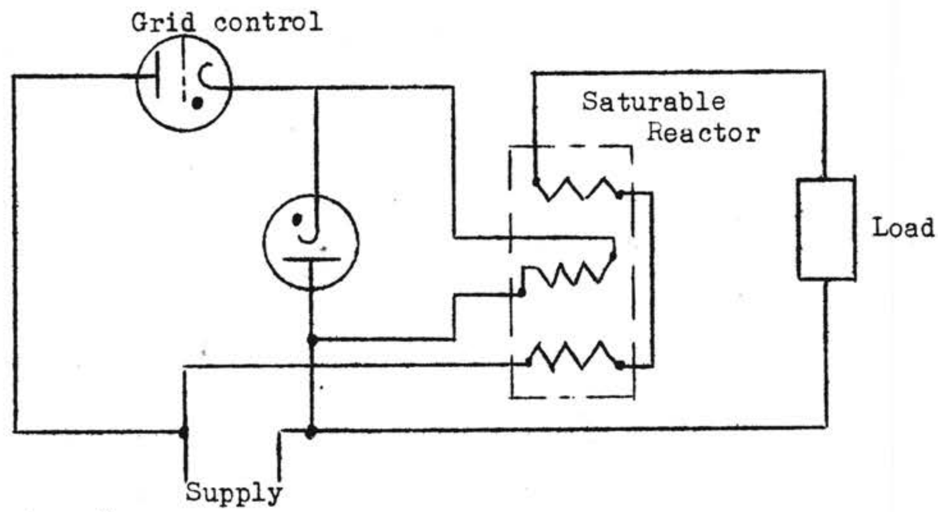


Fig. 43. Simple circuit to control energy flow to load.

devices are very important in process control. Consider the action of the circuit in Fig. 44.

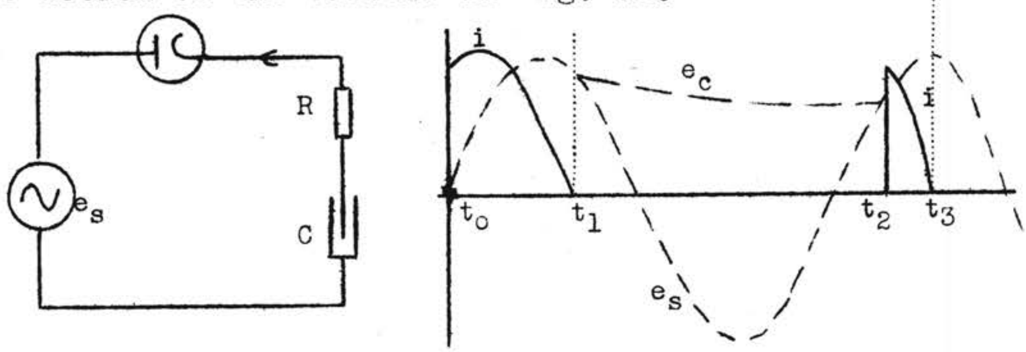
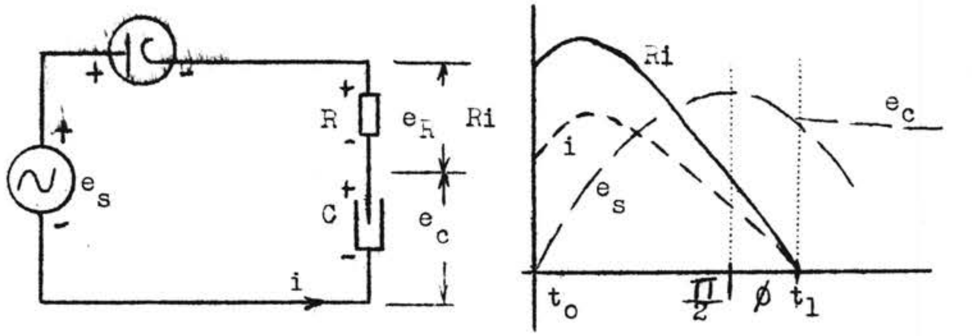


Fig. 44. Series circuit action.

As the supply source starts from zero in the positive direction, the tube will allow current to flow in the circuit to charge the condenser. The series resistor tends to retard the current flowing into the condenser but as the voltage decreases back to zero some charge will be left in the condenser and it will have the polarity indicated in Fig. 45(a). As soon as the supply potential decreases below the potential, due to the charge stored in the capacitor, the anode of the tube becomes less



(a) Charging period t_o to t_1.

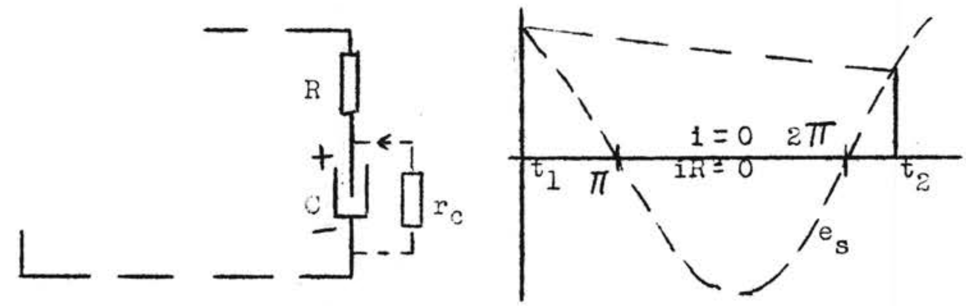


Fig. 45. Potential conditions of Fig. 44 during initial charging.

positive than the cathode and will no longer conduct. This potential condition will exist until the supply potential again becomes positively equal to the "stored potential" in the condenser (time t_2). It is important to notice that as the supply potential swings through its maximum negative voltage an inverse voltage approximately equal to $2xE_m$ will appear across the anode-cathode of the rectifier tube. If the tube is not carefully chosen it may not be able to withstand this high peak inverse voltage. The tube is really acting as an insulator during its non-conducting periods to prevent arc-back current in the circuit. If arc-back should occur, serious damage to the tube would likely result. If the condenser were perfect it would hold this potential exactly while the circuit is idle, but, of course, in practice some small dielectric loss is always present so the condenser potential will decrease slightly during this period.

When the supply voltage again starts to increase positively, the condenser will again assume a potential equal to the increasing voltage supply as it exceeds the condenser potential. From the instant when these two potentials are equal, the tube anode will become increasingly positive and the condenser will demand additional charging current. This process will continue for several cycles until the condenser potential has become equal to the maximum supply potential. From then on, only very sharp current pulses will flow in the circuit allowing the supply to furnish positive energy to off-set the dissipation occurring in the practical condenser.

If the resistor had been connected in parallel with

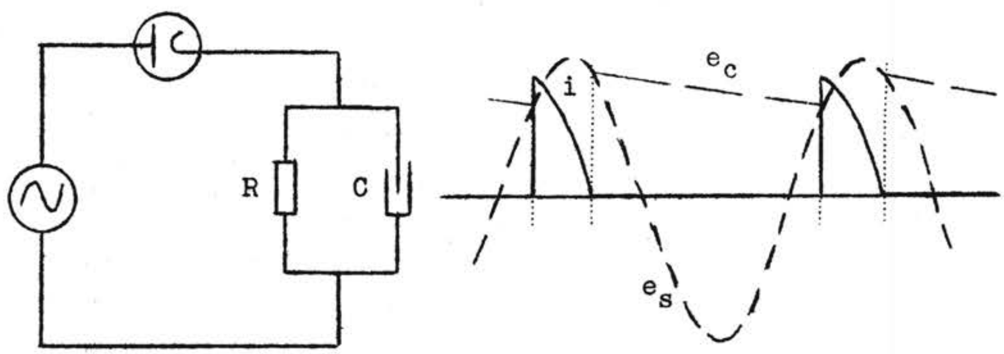


Fig. 46. Simple Rectifier-filter System

the condenser, a common form of low pass filter results. The circuit is shown in Fig. 46. When the circuit is first energized during the positive swing of the supply voltage, the rectifier will allow charging current to flow. The current in each branch of the parallel load will be determined only by their constants. These currents are shown in Fig. 47(a). The condenser current continues

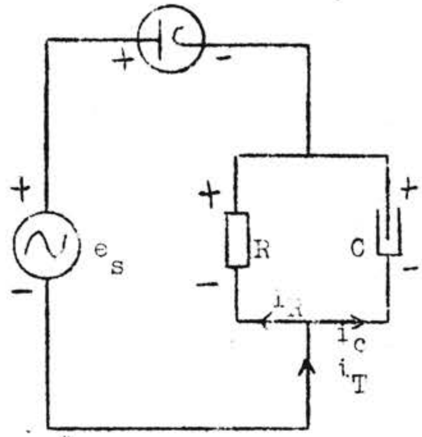


Fig. 47(a) Firing Circuit from t_0 to t_1.

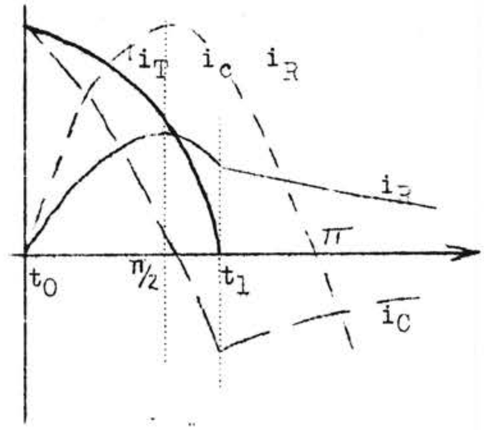


Fig. 47(b) Instantaneous charging relations of Circuit

to flow for $\frac{1}{4}$ cycle, or until it is charged to the peak value of the supply voltage. Beyond this peak, the supply is decreasing toward zero so the higher potential of the condenser will begin discharging through the parallel resistor. But the resistor will continue to draw current from the supply as long as the tube will conduct. At time t_1 the drop in r due to the capacitor discharge current begins to exceed the instantaneous supply potential which makes the anode of the tube negative with reference to its cathode (Fig. 48) and it will no longer conduct until its anode-cathode potential is reversed. The condenser continues to discharge exponentially through the resistor. If the resistor is small enough to completely discharge the condenser before the supply voltage again starts on its positive swing, the above process will repeat each cycle. However, if the resistor is large, the condenser will still retain a part of the charge from the first cycle, and charging current cannot again flow until the anode of the tube has been forced positive, i.e., the instantaneous supply voltage must exceed the stored potential of the condenser. The condenser will be charged as before once current begins to flow, and after a few cycles, the voltage and current will appear as in Fig. 46. So long as R is large, the voltage across the capacitor approaches a condition where there is little difference between the peak and average values. This type of circuit may be very satisfactorily employed as a filter circuit for a d-c supply so long as the load current is very small.

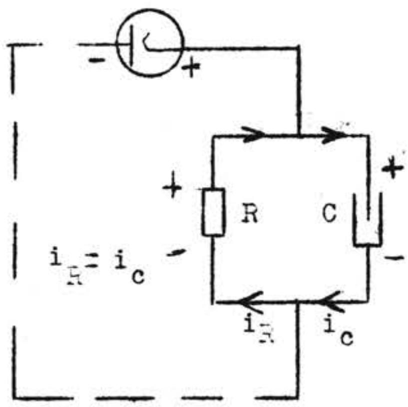


Fig. 48. Equivalent Circuit from t_1 to t_2

Rectifier-Inductance-Capacity Circuits

The number of variations possible with these circuit elements is great. Each variation will result in modified current and voltage characteristics. The practical inductor, of course, always includes some resistance and there may be times when we purposely introduce additional resistance in the circuit. Hence R, L, C, and the rectifier may be connected in series with the supply, or R, L, and C may be connected in parallel and then in series with the rectifier and supply. These two general circuits may then be modified so the reactions will be quite different depending on the relative proportions of R, L, and C.

Consider first the arrangement shown in Fig. 49.

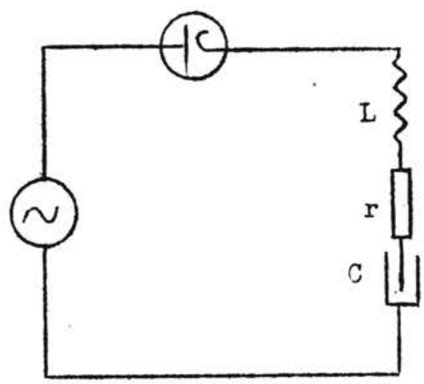


Fig. 49. A rectifier-filter system.

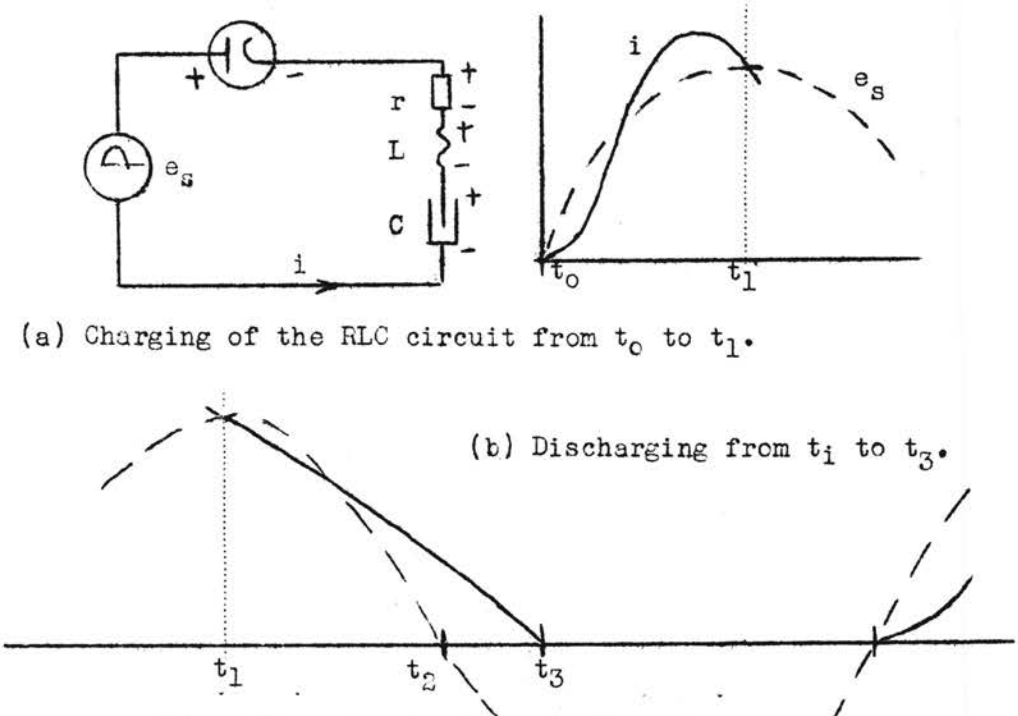
R will be considered as small but representing the distributed resistance of the inductor. The constants L and C may be proportional so that

(a) $X_L > X_C$

(b) $X_L = X_C$

(c) $X_L < X_C$

Each circuit proportion will result in different relative values of instantaneous current and voltage values. Suppose we consider the first case where $X_L > X_C$. As the applied voltage rises in a positive sense from zero, the tube will allow charging current to flow through the circuit. The inductance of the circuit requires that the current be zero at $t = 0$ and momentarily the condenser will act as though short-circuited, so the current will start to rise following a typical rectifier-RL current characteristic. Simultaneously the condenser will begin a high charging current demand but the series inductance-resistor combination will delay and limit the current surge demanded by C. But as the inductance begins to allow current flow the condenser will gradually assume a charge until its back voltage will become equal and greater than the instantaneous supply magnitude and will try to prevent further current flow until the next corresponding value of the cycle. In the meantime, the inductance was left in an energized state which must try to collapse. The self-induced voltage of the decaying inductive energy will attempt to maintain the rectifier plate positive after the supply starts decreasing in magnitude. This must be done against the opposing condenser voltage, so



(a) Charging of the RLC circuit from t_o to t_1.

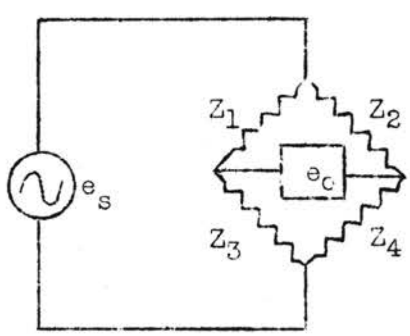
(b) Discharging from t_i to t_3.

Fig. 50. Analysis of Fig. 49.

the inductive discharge will be delayed. If the condenser is quite large ($X_c \rightarrow 0$) the inductive current surge can display only a momentary effect, hence, the condenser will tend to retain its "stored potential" until the supply source has again reached an equal potential in the next cycle so the tube may again conduct to supply the inductance with its discharged energy. This type of circuit proves quite satisfactory as a smoothing filter for rectifier supplies, provided L and C are effectively large while R is kept as small as consistent with inductance design. This combination results in rather constant voltage across the condenser, so if the load is connected to utilize the capacitor voltage, it will receive fairly smooth power flow. When several such sections are connected in tandem, the final load voltage will approach a steady d-c value.

Bridge Circuits

The bridge circuit is normally considered as a measuring device so arranged that balance will indicate the value of an unknown. When the bridge is balanced (Fig. 51) some applied voltage, e_s, has been balanced out so that no voltage appears across the opposite bridge diagonal.



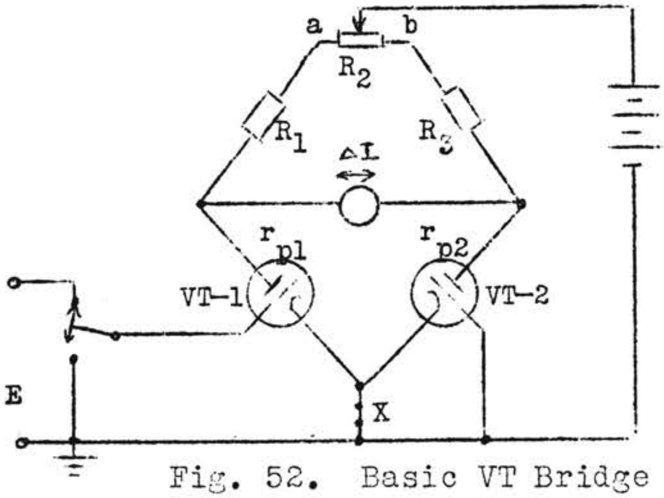
Balance equation :

$$Z_1 \cdot Z_4 = Z_2 \cdot Z_3$$

Fig. 51. The fundamental bridge Circuit.

The bridge may operate from a direct current source if all of the arms happen to be pure resistors, or it may operate from an a-c source if the arms include reactance. The a-c bridge is perhaps more versatile in that it may be arranged so that it is insensitive to the frequency of the applied voltage (single angle type) or it may be arranged to balance at a selected frequency (opposite angle bridge). The frequency selective bridge may be arranged to indicate (1) direction of unbalance (2) phase unbalance. While the balanced bridge may be readily employed for measurement purposes, the unbalanced bridge finds wide application in industrial electronics devices. So long as one of the arms can be made to vary proportionally to the change of the controlled process medium, the bridge may conveniently serve as the coupling circuit between the primary sensitive element and the controller. Such devices that change their resistance or reactance under temperature, displacement, or pressure changes may satisfy the above unbalance condition.

The vacuum tube bridge has received wide attention in the industrial field both as a metering device and as a controller. Two tubes are arranged so that their plate resistance replaces two of the bridge arms. One of the tubes has its grid returned to ground as shown in Fig. 52. For preliminary adjustment, the other grid is also temporarily grounded and R_2 is balanced so the bridge satisfies the basic bridge equation. If some small voltage, for instance $+\Delta E$, is then applied to the grid of VT-1 its plate resistance will decrease by a proportionate amount. Since no change occurred on VT-2, the bridge output will be no longer balanced and the indicator M will show both direction and magnitude of



$$(R_1 + aR_2)r_{p2} = (R_3 + bR_2)r_{p1}$$

Fig. 52. Basic VT Bridge Circuit

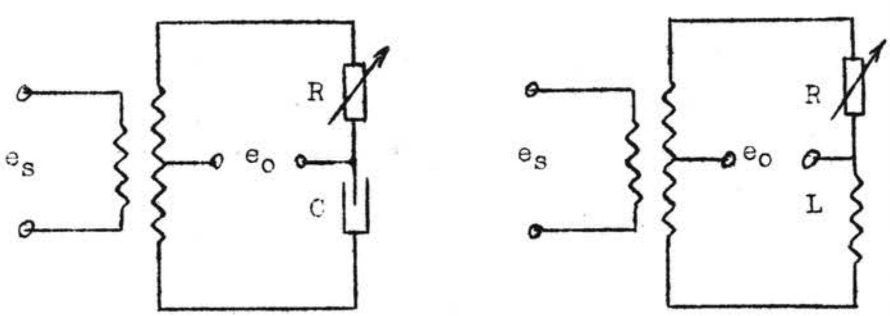
unbalance. The vacuum tube bridge may be made very stable and essentially independent of power supply voltage variations if degenerative resistors are included in the cathode circuit of the tubes. The bridge, of course, has the advantage of some amplification due to tube action. Extreme changes in ΔI can be limited by saturation, and cut-off characteristics so that the indicating device will not be damaged.

It is interesting to notice that when a common cathode resistor is inserted at X, Fig. 52, a "push-pull" action results. When the $+\Delta E$ was applied, a decrease was indicated in plate resistance of tube VT-1. This means an increase in plate current with a corresponding increase in drop. But an increased cathode voltage is the equivalent of biasing VT-2 negatively, hence, its plate current will decrease making the plate resistance of VT-2 greater with a somewhat greater potential active across the indicating device M. Many interesting vacuum bridge applications may suggest themselves to the reader.

Phase Shift Circuits

A variety of applications of this general circuit are found in industrial electronic devices. The particular application requirements will usually determine the particular phase-shifting circuit employed, although there may be several methods of achieving the same result. The phase-shifting circuit may be arranged to give a predetermined phase shift, or it may be adjustable so a particular phase relation may be chosen at will. Most phase-shifting networks are arranged to produce definite shift between the output and input voltages. One of the important applications is grid control of the thyratron tube.

One of the simplest and most useful phase shifting bridges for thyratron control is shown in Fig. 53. A



(a) Capacitive shifter. (b) Inductive shifter.

Fig. 53. Common types of phase Shifters.

center-tapped low impedance transformer feeds the load circuit consisting of R and C (Fig. 1a) or R and L

(Fig. 1b). The circle diagrams for the two load circuits are shown in Fig. 54. The current flow in the

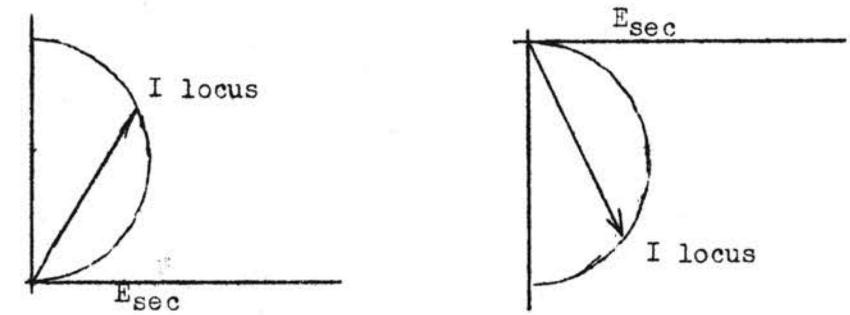


Fig. 54. Current locus as R is varied.

variable resistor will produce a proportional voltage drop. Now, if the voltage is picked off at the junction point of the resistor-reactance with reference to the mid-tap of the transformer winding, the phase relation of this voltage to the secondary voltage will be as indicated in Fig. 55.

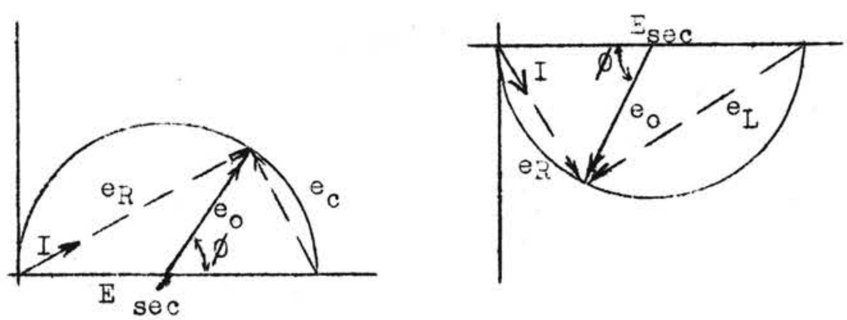


Fig. 55. Output voltage vector as R is varied.

It is interesting to note that e_o has constant magnitude as its phase is varied with respect to the secondary voltage. Furthermore, the inductive portions of the circuit always contains some distributed resistance so complete 180° control is never possible with this circuit. One other important limitation of the circuit should be noted. So long as the circuit connected to e_0 draws essentially no current, the phase control indicated above will hold, but if we begin to load the circuit output the phase relations will become quite different depending on the nature of the load. The impedance of the network should be kept reasonably small at the operating frequency if loading effects and voltage changes are to be minimized. Likewise, the voltage will no longer remain constant in magnitude. When the circuit is applied to the control grid of a thyratron, a limiting resistor should be connected in series with the grid in order to minimize any loading effects caused by grid current.

We have considered the control element as a variable resistor. This is perhaps the simplest method for manual control. There are times when this method of control may not prove desirable, particularly, when automatic control is desired. The manually controlled resistor might be replaced by an "electronic" resistor. If the circuit is arranged so the plate resistance of a vacuum tube replaces the resistor element, manual control may be dispensed with and the phase control could be made to automatically follow any control grid variation impressed on the tube. While a tube connected in this manner (Fig. 56) will be limited in its range of resistance variation, remote and automatic control may still be achieved. However, the circuit is difficult to apply as the control tube circuit introduces high d-c potentials which must be isolated from the thyratron grid circuit by very low reactance. Any sudden control transients readily pass through the capacitive circuits causing false responses.

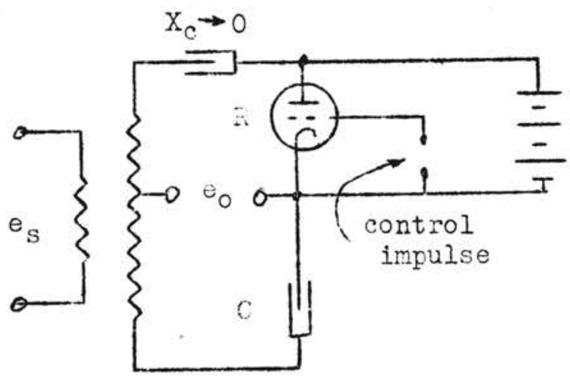


Fig. 56. Electronic control of phase shifter.

Capacity variation may be employed under limited conditions. When operating at the low power frequencies, very large values of capacity are required if the circuit impedance is to be kept reasonably small. Continuously variable capacitors in large sizes are neither available nor economically justifiable. However, if the frequency is quite high, or if the network impedance can be high (zero current demand), conventional types of variable air condensers may be used.

Inductance variation, on the other hand, is easily achieved by employing a saturable reactor. This method of phase control has proven very desirable. It becomes a simple matter to electronically control the effective a-c reactance, and furthermore, inductance does not readily respond to sudden control transients which might be active in the circuit. The separate a-c and d-c circuits of the saturable reactor allow complete d-c isolation between the controlling tubes and the controlled tube grid.

Perhaps the simplest arrangement of the saturable reactor circuit is shown in Fig. 57. The circuit shows reasonably fast response, the entire inductance range being covered in 2 to 4 hundredths of a second.

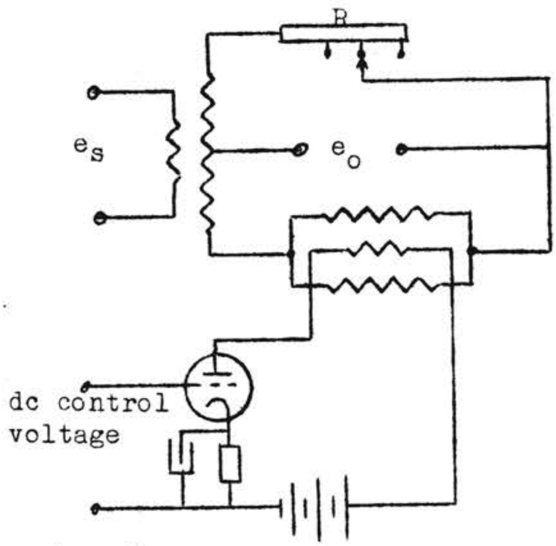


Fig. 57. Electronic Control of Phase Shifter.

Many other electronic phase shift circuits may be used in industrial electronic devices. Some of these will be discussed in later sections.

One other increasingly important method of obtaining phase shift for control purposes is the employment of a selsyn phase shifter. This requires that either two or three phase power be available, but phase shifts are no longer limited to less than 180 degrees. The construction of the selsyn is similar to that of the three phase alternator, in a fractional horsepower size. However, the action is quite different. When a three-phase supply is connected to the distributed three-phase Y-connected stator windings, a rotating three-phase field is established with 120 degree displacement. The rotor consists of a single winding arranged to rotate with respect to the stator structure. Fig. 58 shows the three fluxes resulting from the application of a three-phase voltage on the stator at a particular instant during their cycle. The relative angle of the stator winding is indicated as θ. The voltage induced in the rotor at any instant is $-N \frac{d\theta_T}{dt}$, where θ_T is the vector summation of the three fluxes actively cutting the rotor winding at any particular instant during the voltage cycle. The three coil currents required to establish the field may be expressed as:

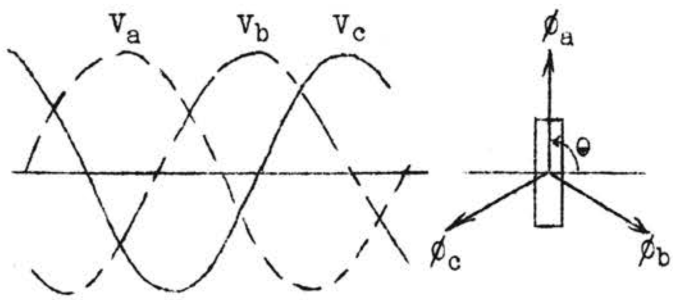


Fig. 58. Time and space phase relations of the selsyn stator.

$$\phi_a = \phi_m \sin wt$$

$$\phi_b = \phi_m \sin (wt + 120) = -\tfrac{1}{2}\sin wt + \tfrac{\sqrt{3}}{2} \cos wt$$

$$\phi_c = \phi_m \sin (wt + 240) = -\tfrac{1}{2}\sin wt - \tfrac{\sqrt{3}}{2} \cos wt$$

By the proper choice of rotor references, the summation of the rectangular flux components of the resultant field is effectively

$$\phi_T = \frac{3}{2}\phi_m \sin wt$$

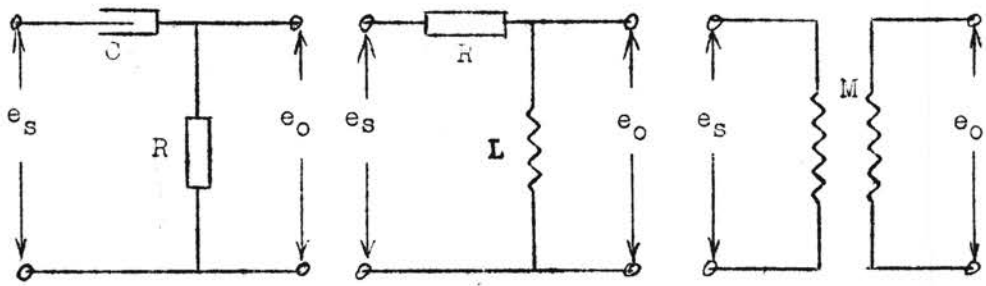
Thus the resultant field is of constant magnitude and revolving with constant angular velocity.

The flux cutting the coil is proportional to $\cos (wt - \theta)$ and the induced voltage to $\sin (wt - \theta)$ so the time-phase displacement of the induced rotor voltage is equal to the angular displacement, θ, of the rotor from its zero position. The selsyn may be connected in several other conventional ways to afford remote indication of position.

The Differentiating Circuit

The instantaneous voltage drop across the resistor of an R-C circuit has already been shown to be $e_r = iR$ but also the rate of change of the resistor voltage was expressed as $R \frac{di}{dt}$, or it could be said that the instantaneous change in voltage across the resistor is proportional to the rate of change of circuit current. But the circuit current is always proportional to the driving voltage, hence, the rate of change of current must be proportional to the rate of change of the component drop or we could say that $e_r = K \frac{dv}{dt}$, i.e., the drop across the resistor is proportional to the differential of the active voltage. If the R-C circuit is so connected that the instantaneous voltage drop across the resistor is used, the circuit is known as a differentiating circuit. It can also be shown that the drop across the inductance of an L-C circuit, or the secondary voltage of a transformer, is proportional to rate of change. There is one limitation, we must yet impose on these circuits to make true differentiating circuits. The duration time of the applied voltage pulse must be considerably greater than the circuit constant. (Fig. 59).

In a previous discussion, it was shown that the resistive drop of a long RC circuit almost exactly followed any changes which occurred in the supply voltage. However, if the time constant is very much smaller than the pulse duration time, the condenser will have sufficient time to completely charge during the pulse period, and likewise, it will completely discharge during the recovery period.



$e_o \doteq \frac{de_s}{dt}$ $\qquad$ $e_o \doteq -L\frac{di}{dt}$ $\qquad$ $e_o \doteq -M\frac{di}{dt}$

$RC \ll T$ $\qquad$ $L/R \ll T$

Fig. 59. Typical differentiating Networks.

Fig. 60 will illustrate the analysis of a short RC circuit. Referring to Fig. 32, it will be found that if $T = 10\ RC$ the charge or discharge voltage of the condenser will have reached about 99.9% of its final value. So, practically speaking, the condenser will have reached stable voltage conditions by the end of the pulse period, while the resistive drop will have dropped to zero. At the end of this pulse period, the supply voltage suddenly drops to zero. This sudden change must appear across R as a negative voltage since e_c cannot change instantaneously. But considering the supply impedance as zero, the condenser will discharge through R during this period which is just long enough to allow e_c to reach zero. Remembering that e_c and e_r must be equal at all times during discharge, the resistive voltage will also return to zero at the end of this period. As the supply repeats its cycle, the charge-discharge cycle will repeat.

Fig. 61 will further illustrate the action of a short RC circuit. The same RC combination was used as before (Fig. 60) but the pulse period has been doubled (T = 20 RC). C will charge completely before the pulse

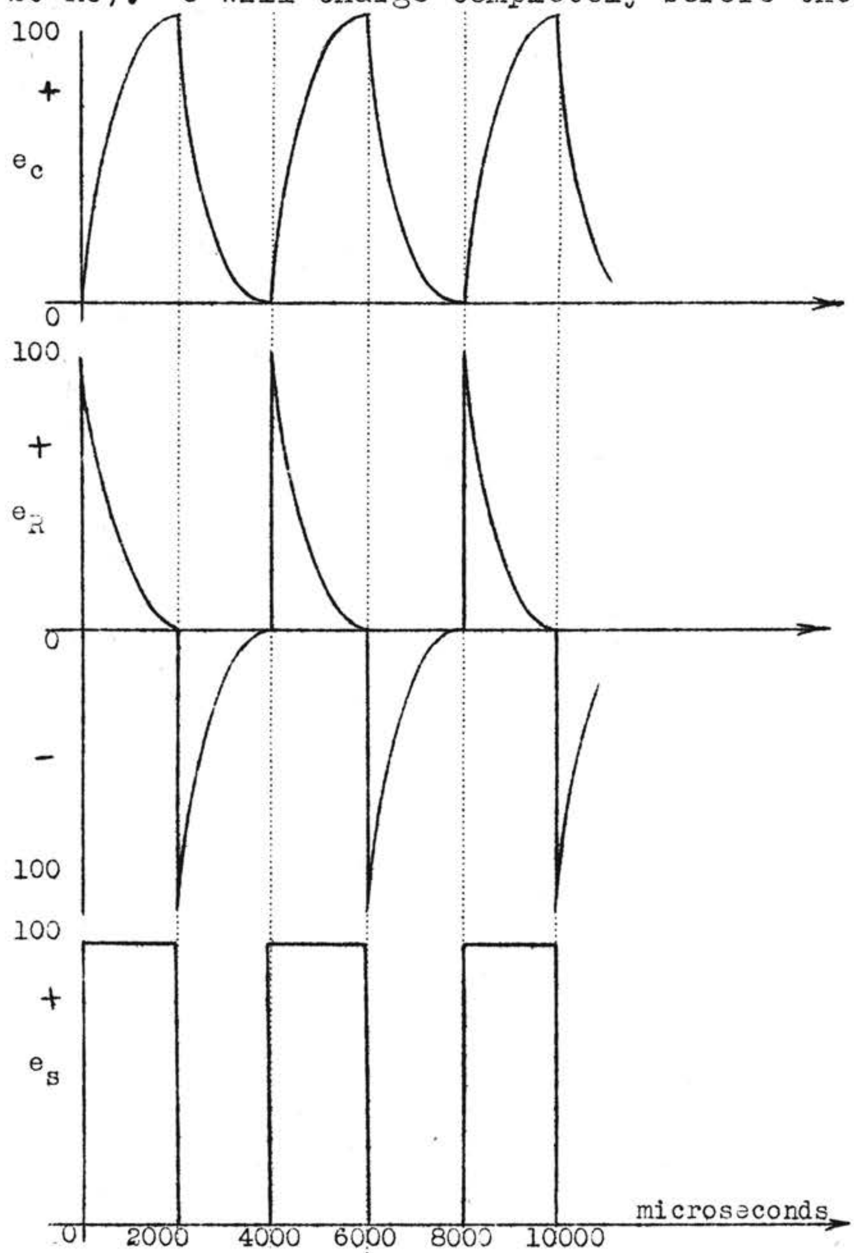


Fig. 60. Characteristics of short RC Circuit.

is removed so there is a period of time during which e_c remains constant and equal to the applied pulse magnitude, while e_r remains at 0 during this same period. At the end of the pulse time, e_r drops negative to offset the sudden change in pulse voltage. C then discharges completely through R before the beginning of the next pulse.

It will be observed that the smaller the RC product,

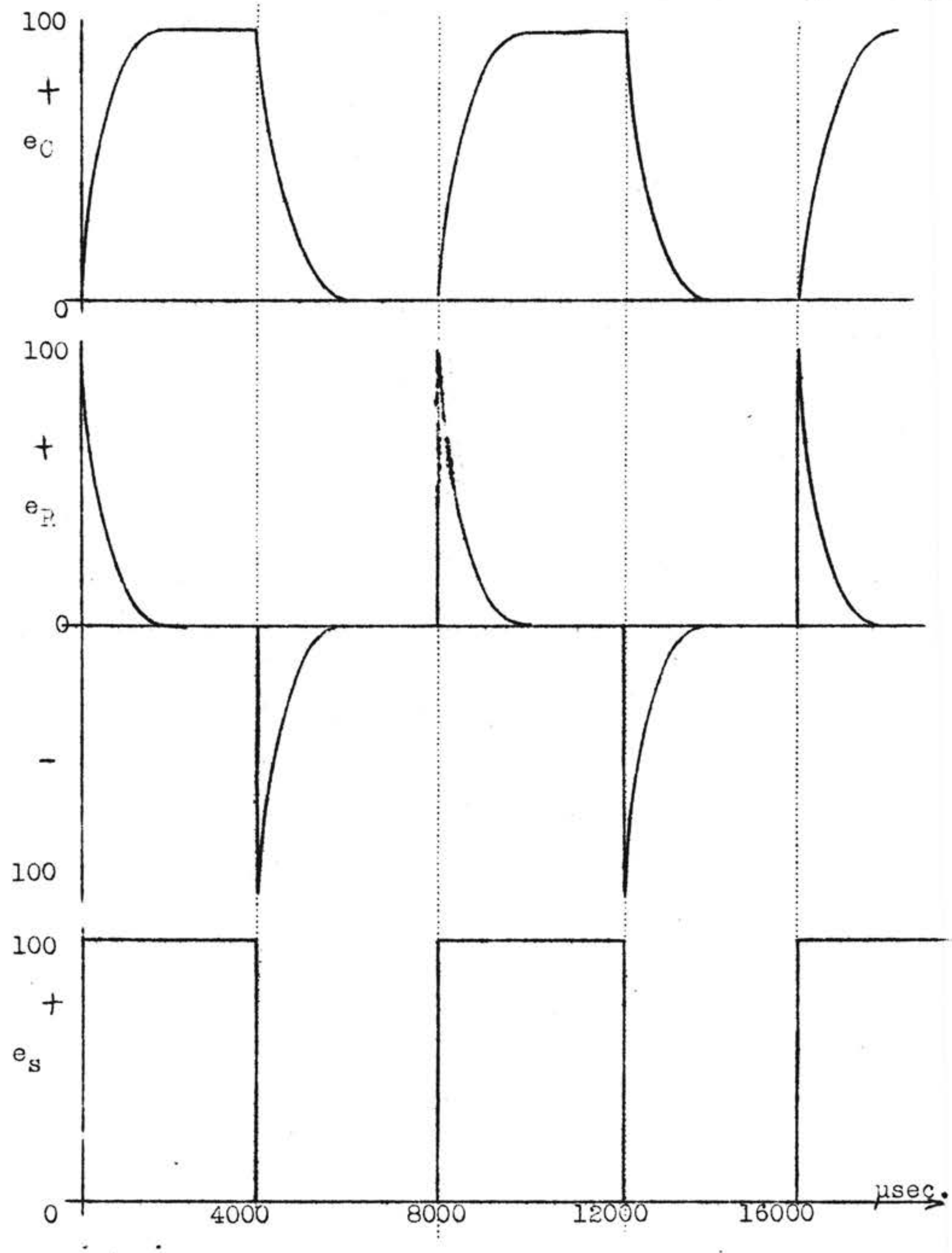


Fig. 61. Very short RC circuit Action.

compared to the pulse time, the more nearly the resistor drop approaches the derivative of the applied voltage pulse; or, saying it in another way, the shorter the time constant, the sharper the pulse across the resistor.

A similar analysis of the other two general types of differentiating networks will reveal that they react in essentially the same manner as the RC differentiating circuit. Several important applications will be found in industrial electronic circuits. It has been already indicated that thyratron firing circuits may be controlled by sharp firing pulses. This type of network is also often used to initiate timing and counting impulses. Differentiating circuits may also be used to discriminate between various signal pulses, allowing different control actions to be initiated as the wave shape of the pulse signal is varied.

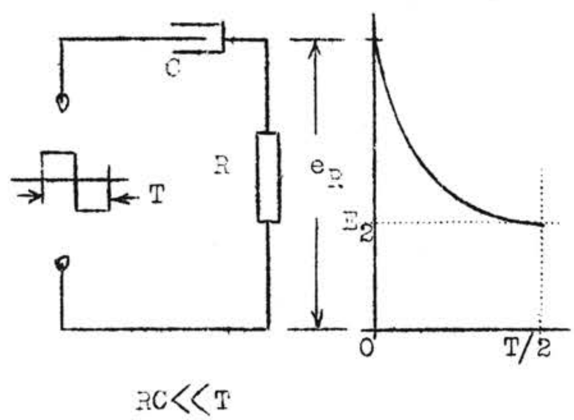


Fig. 62. Action of a simple Differentiating Circuit

Analysis of differentiating networks is easily accomplished by oscilloscopic traces. The instantaneous voltage magnitudes can be readily measured and calculations can then be made based upon these measured values. The output voltage of the differentiator (Fig. 62) is

$$e_r = E_1 \varepsilon^{-\frac{t}{RC}}$$

The voltage at the end of the half-period $(\frac{T}{2})$ is E_2; insert this in the general equation so

$$E_2 = E_1 \varepsilon^{-\frac{T/2}{RC}}$$

and knowing the time of the repetition cycle allows RC to be readily calculated.

The Integrating Circuit

Just as the drop across one of the elements of the networks, shown in Fig. 59, approaches the differential of the applied voltage as the time constant becomes very small, so the condenser voltage approaches the integral of the applied voltage as the period of the voltage becomes very long. This will become more apparent after a comparison of the condenser drops of Figs. 60 and 61 are made. The more common integrating circuits are shown in Fig. 63. The output voltage will become approximately

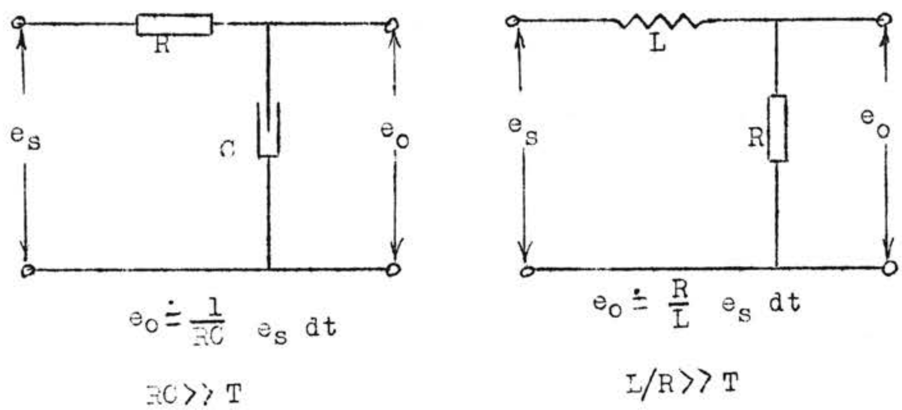


Fig. 63. Integrating networks

proportional to the duration and repetition rate of the supply pulse as the time constant becomes great compared to the duration period. Analysis of the integrator shows that the exponential rise of the capacitor voltage is

$$e_c = E_1 \left(1 - \mathcal{E}^{-\frac{t}{RC}}\right) \text{ where } E_1 = \frac{E_o}{2} + \frac{E^1}{2}$$

This is illustrated in the oscillogram of Fig. 64. If the integrator is energized by some irregular type of pulse voltage, the action over some time interval is such that

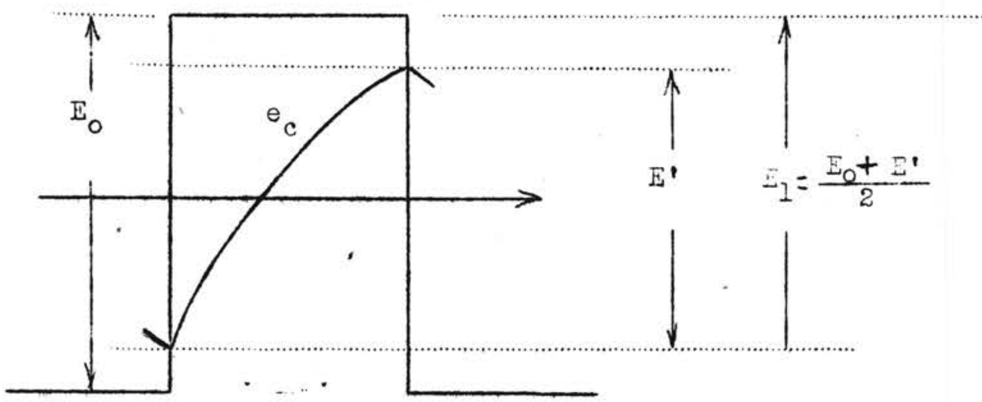


Fig. 64. Integrator Analysis

the integrating circuit "sums up" the energy of the pulses and develops an output voltage which averages the varying pulse voltage over the time interval considered.

Integrating networks find application in industrial electronic devices. For example, certain types of primary measuring elements respond to produce voltage proportional to acceleration (piezoelectric pickup element). If this output is integrated once, a voltage proportional to velocity is obtained, integration a second time gives a voltage proportional to displacement, thus allowing complete velocity or displacement studies to be carried out.

In certain applications, it is desired to operate a control element some definite time after the operation of the primary measuring element. One of the several ways in which this can be accomplished is outlined in Fig. 65.

A sine wave is applied to the input of a square wave generator. The square wave output is arranged so it is inverted with reference to the applied signal. The

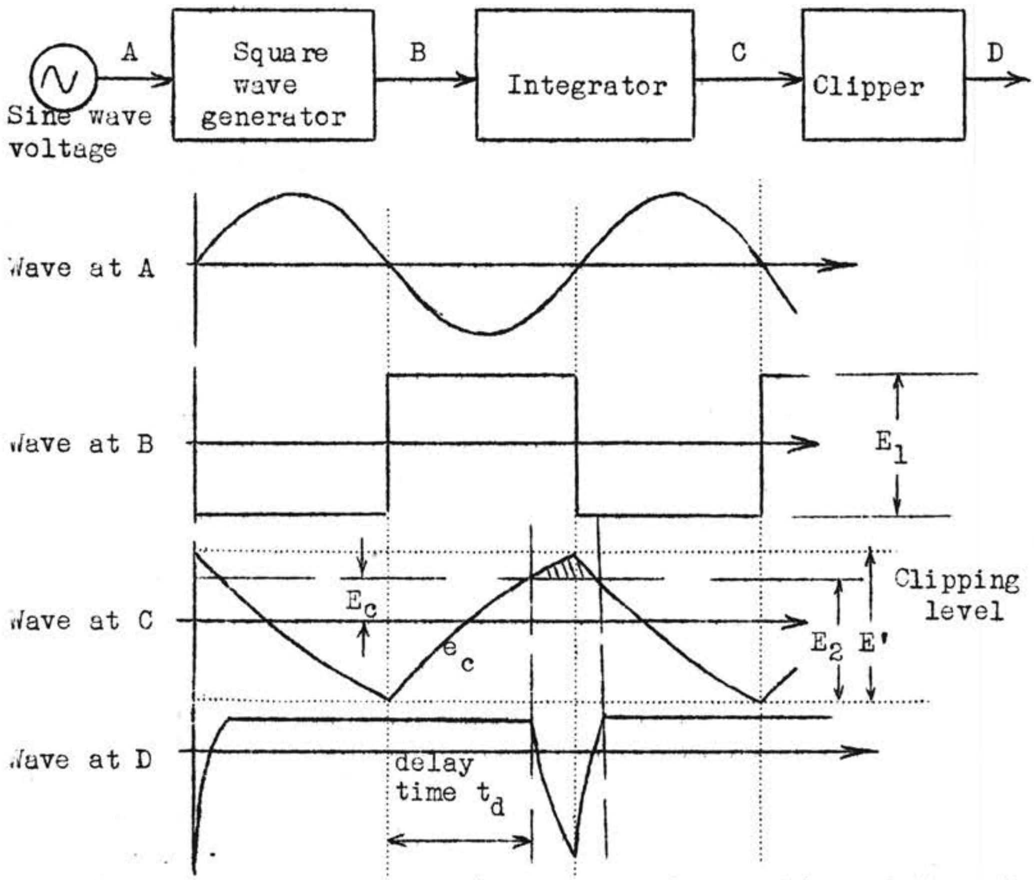


Fig. 65. Controller incorporating a time delay System.

square wave is then applied to an integrating circuit and the integrator output is then fed to a "clipper" tube. The output of the clipper corresponds to the shaded portion of the integrated square wave. The delay time is the time by which the leading edge of the output wave is delayed with respect to the leading edge of the original sine wave.

The output of the integrator circuit is

$$e_c = E_1 \left(1 - \varepsilon^{-\frac{t}{RC}}\right) \text{ where } E_1 = \frac{E_o}{2} + \frac{E^1}{2}$$

This voltage is then clipped so

$$E_2 = E_1 \left(1 - \varepsilon^{-\frac{t_d}{RC}}\right) = E_c + \frac{E^1}{2}$$

Oscilloscopic analysis will allow the voltages, E_c, E_o and E^1 to be measured, and knowing RC, the delay time can be readily calculated. Note that if E_o is decreased, then the delay is increased; if RC is increased the delay will be increased; or, if the clipping level is decreased the delay will decrease.

Additional applications of integrating as well as differentiating circuits will suggest themselves.

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CHAPTER III

CONVERSION METHODS

The electron tube is fundamentally a voltage operated device. The various tube constructions determine just how the tube and its associated circuits will respond to the controlling voltage which is to operate the electronic device. Table IV, Chapter I, gave an indication of the functions of electronic devices. With but few exceptions these functions are initially dependent upon some process variable. Even the exceptions are likely to include some control arrangement in the system. Since these electronic devices must respond to the process variation, it is necessary that some "coupling" arrangement must be established between the process and the electronic device. The primary measuring and conversion element (Chapter I) must serve this purpose. Some arrangement must be devised which will change the information about the process deviation into an electrical signal. Just how this signal voltage is made to vary, or how it is initiated, depends upon the ingenuity of the designer. In any event, it must be generated and controlled by the process variable in such a way that it represents definite predetermined information. The design of the actual device used to couple the process to the electronic circuit seems almost unlimited, but so long as the variable of the process can be measured, some device can be built to convert the measured quantity into a controlling voltage for the electronic device. No matter whether the conversion device operates directly from the process variation, or from some incidental part of the process, the information sent to the electron circuit must have some predetermined relationship to the process itself. All conversion methods are based upon the fundamental physical laws of science.

There may be a temperature or pressure change, a displacement or a time variation, a frequency or flow variation, but in any event, the conversion element must interpret this information for the electronic system as a voltage change. To attempt a complete discussion of all available conversion elements would only represent a complete review of all the basic physical laws of science and their ingenious applications to equipment.

<u>Fundamental Variables</u>

One of the immediate effects of temperature change is expansion or contraction of an object. Several other important material changes resulting from temperature changes are:

(a) resistance or conductivity change
(b) permeability change
(c) voltage generation
(d) optical and sound effects
(e) Piezoelectric effects
(f) dielectric or capacitive change
(g) chemical change
(h) electronic emission

Pressure changes resulting from a process variation may, likewise, cause any of the above variations, or combinations of several of these changes may result. Displacement changes may result directly from pressure or temperature changes of the variable or some indirect part of the process may be utilized to produce changes proportional to the final product. Many of the effects are so interrelated to the cause - and, incidentally, to the final product - that the measuring-conversion element is arranged to respond to some secondary effect of the process. This secondary effect may be quite unimportant to the final product but so long as a conversion element may be made to respond in the desired way, it may be utilized. As a continued study of electronic applications is made, it becomes increasingly difficult to classify converters under a few simple isolated headings, especially in view of the variety of control systems common in industry. A simple on-off control converter may be easily designed but the process may call for proportional control. In other words, each process has its own peculiar characteristics and calls for a specially developed system. Too often, there is a tendency to try to adopt existing electronic equipment rather than devise equipment with characteristics to exactly satisfy the process requirements.

The literature [1.] affords ample discussion of the measuring instruments themselves; however, it is desirable to review the fundaments of conversion methods. The

1. Instruments for Measuring and Controlling Process Variables - Staff - Chemical and Met. Eng., 50-1,5,108. (1943).

methods of application and the choice of auxiliary mechanisms is limited only by the ingenuity of the designer. Thus the conversion element may assume a variety of forms. For example, it could be a piece of resistance wire so arranged that it changed resistance when the surrounding temperature changed. If a current was flowing through this conversion element, a variation in voltage across the resistor terminals would develop as the surrounding temperature changes. This changing voltage could then be applied to the input of the electronic device. Or the converter could be a thermocouple so arranged that, as the surrounding temperature changed, voltage would be generated by the thermocouple in proportion to the change in temperature. This voltage could then be applied to the electronic circuit to obtain exactly the same control as with the resistance variation of the converter. Other methods of obtaining the same electronic control might be utilized. Ultimately, the choice of the converter would depend upon the ease of application to the process and the reproducibility possible.

Resistive Converters

One of the simpler converters consists of a resistor element arranged so that its resistance will change in some predetermined manner as the process changes.

Temperature effects upon various resistance elements have already been mentioned. Table V gives the physical constants of some of the more common materials used in

TABLE V[1]

Material	Resistivity μ ohms/cc	Temperature Coefficient
Aluminum	2.688	.00403
Brass	8	.002
Bronze	17.8	.0005
Carbon	3500 at 0°	— .0009
Copper	1.724	.00393
Gold	2.44	.0034
Graphite	800 at 0°	—
Iron	9.8	.0065 (0–100)
Iron Cast	79 – 104	—
Lead	22.0	.0039
Mercury	5.08 at 0°	.0047 (0–100)
Platinum	9.83 at 0°	.003
Silver	1.629 at 18°	.0038
Steel (soft)	11.8	.004
Steel (hard)	45.6	.0016
Steel (nickel)	30 – 85	.0007
Tin	11.5	.0042
Tungsten	5.5	.0047 (0–100)
Zinc	5.75 at 0°	.0037
Values related at 20° C level unless otherwise specified		

1. Compiled by Westinghouse Electric Company

temperature sensitive units. The resistance thermometer is suitable for measuring temperatures from the lowest range to the highest. The thermometer element is a carefully constructed coil of wire usually made of nickel or platinum. The coil is often wound with very little wire to have only low resistance. This results in fast action as the thermal lag has been reduced to a minimum. The choice of this resistance element material, however, will be determined by the temperature range and the desired response to the process variation. It is a problem of design ingenuity to couple this thermometer element to the process. But in many instances, the resistance element must be remotely located to the electronic circuit. The long connecting leads may have resistance of the same order as the temperature element and may introduce large errors. The circuit and measuring element must be so arranged and installed that the effects of the lead resistance is minimized. Perhaps the simplest circuit utilizing the thermometer element is shown in Fig. 1.

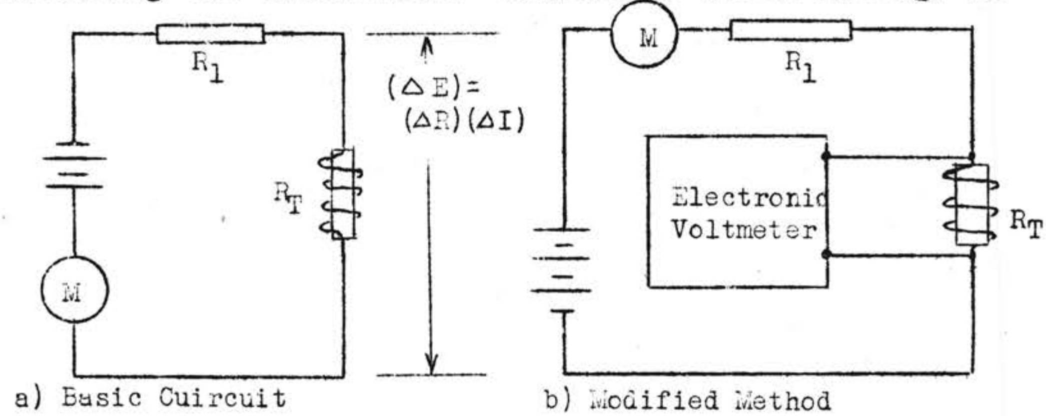


Fig. 1. Simple resistance converter connections.

Ohm's Law applies directly to the circuit. Any change in temperature will cause the special resistor coil

R_T to change by an amount ΔR which results in a current change ΔI. R_1 may represent the lumped lead resistance and calibrating resistor. Incidentally, the series resistor R_1, if large compared to R_T, will minimize any slight non-linear temperature-resistance characteristics of R_T, but at the same time, may introduce relatively large thermal lags. The circuit may be readily modified to eliminate lead errors. The resistor is arranged with four leads as shown in Fig. 1(b). The two extra leads which return to the indicating device carry practically no current, hence, there is no great error introduced as their resistance varies. The drop across the temperature indicating element must be read by a very high resistance voltmeter if its lead current is to be kept negligible. Since this potential drop is small, an electronic amplifier-voltmeter is often used as the temperature indicating meter. The meter scale can be calibrated to indicate temperature directly.

A simple bridge circuit proves to be especially adaptable to remote measuring devices and the effects of lead variations can then be compensated for simply and completely. Fig. 2(a) shows the basic bridge circuit. One arm of the bridge consists of the special temperature element, and the other three arms are normally of equal value but wound of some very low temperature coefficient material, usually manganin. The unbalance of the bridge is indicated by M, which may be a galvanometer, or an electronic circuit. The temperature can then be read directly by calibrating the scale of M. The basic circuit of Fig. 2, will of course, be affected by lead temperature variations, thus, introducing lead errors. Several effective circuits may be arranged to eliminate this error.

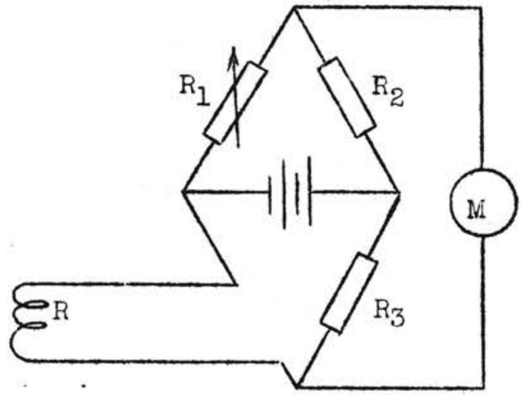


Fig. 2. Basic temperature indicating bridge.

Fig. 3 indicates two methods of modifying the bridge to compensate for lead effects. Additional resistance due to the lengthened leads will vary equally in both arms so that their change is completely cancelled.

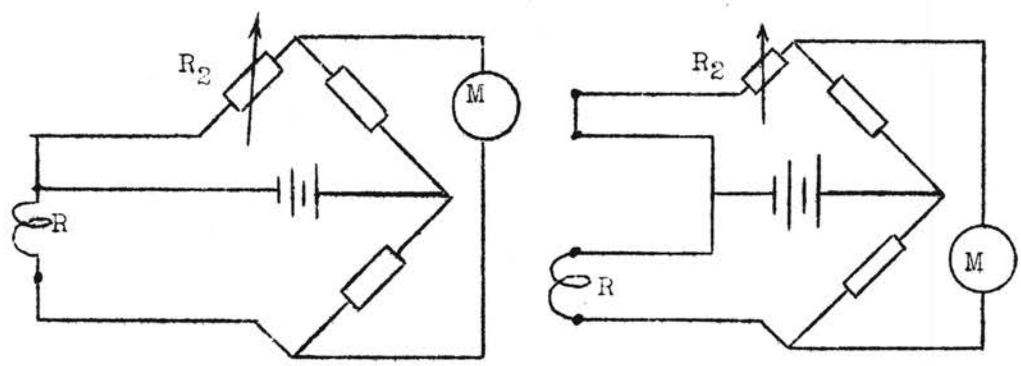


Fig. 3. Bridge Compensation of temperature Converter.

In operation, the bridge is first balanced to the desired reference or ambient temperature by adjusting R_1 so the meter M gives a null indication. As the temperature of R changes, the meter will swing in proportion to the bridge unbalance. The scale of M may be calibrated directly in temperature change or one of the resistors, R_2, may bear a temperature scale and be adjusted to bring the meter M back to the balanced or null point for each reading.

In addition to the direct indicating characteristic of the bridge, it lends itself readily to remote automatic control. The output of the bridge may be applied to the input of electronic circuits designed to automatically control the process. These automatic control systems will later be discussed in detail.

There are many processes where the bridge may serve, but occassionally, it cannot be in a fixed or stationary position. Perhaps it must rotate at high speed with the variable, or possibly, it must move along a track. However, if some sliding contact or slip ring arrangement can be devised, the temperature bridge may still be satisfactory. Now, not only lead resistance variation must be taken into account and compensated for, but also contact resistance variation, sparking, dust effects, etc. If the entire bridge arrangement is mounted in its traveling position, these effects may be minimized to a great extent. Usually two of the arms are arranged to be active with temperature while the other two are neutral and will be chosen to give balances at the desired operating temperature. Fig. 4 shows how this circuit would be connected and arranged. Any contact resistance variation at the slip rings can only affect the battery circuit or the measuring circuit. If these are both high resistance circuits, the variations will be minimized. Additional resistance is shown in series with the battery to achieve this effect, while the indicating device can be electronically controlled by the bridge unbalance voltage so that its loading effect becomes negligible. As the bridge was designed to balance at the operating temperature, only very small currents will be flowing in this type of circuit still further reducing the effects of contact irregularities.

Another type of temperature sensitive resistor is the "thermistor" developed by the Bell Telephone Laboratories. It is a high resistance unit which makes it especially adaptable to the high impedance circuits of electronic devices. The thermistor displays a negative resistance characteristic as its temperature is increased, displaying very large resistance change with variations of the temperature of impressed energy. It not only may be used

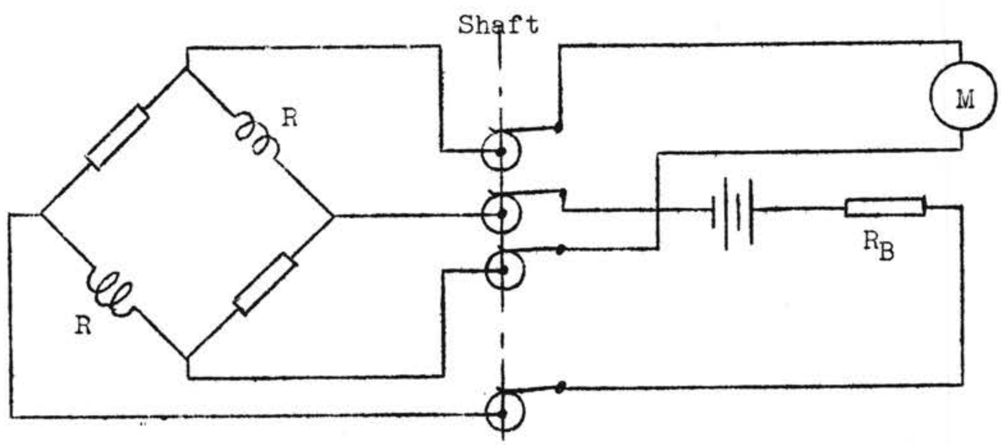


Fig. 4. Slip ring connections to a rotating bridge.

to indicate temperature, either for measurement, control, or comparison, but it is often used to neutralize undesired temperature effects of positive coefficient circuits. The thermistor is also used where power flow must bear a definite relationship to temperature. The mass of the thermistor introduces definite lag or time delay as it is heated or as it cools. It may thus serve in the field of delay relaying.

The thermal conductivity cell is used to measure not only temperature but pressure, gas content, displacement, humidity, flow and other effects. A carefully chosen wire having a high ratio of resistance change to temperature change is utilized. The wire is usually mounted in a glass tube and arranged to operate under either constant current or constant voltage excitation. Often a dual arrangement is used for comparison purposes. Two forms of these cells are shown in Fig. 5, The method

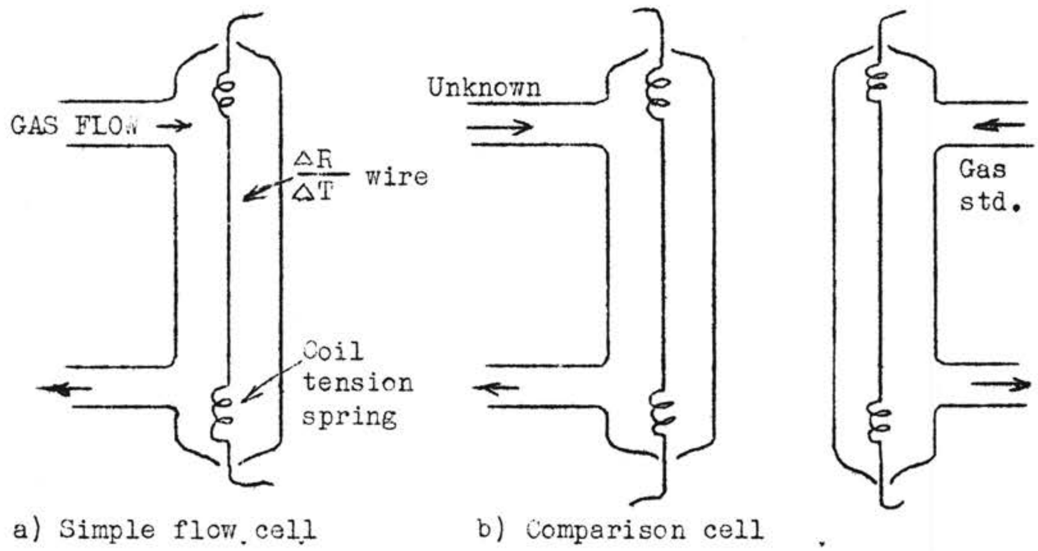


Fig. 5. Thermal conductive Cells.

of coupling these cells to the process variable depends upon the quantity to be measured.

The filament of the cell is energized and develops a certain definite amount of heat. This heat is conducted away from the wire by the material inside the enclosing bulb. As the rate of conduction varies, the temperature of the filament itself varies resulting in a change in the filament temperature. The resulting resistance change will cause a change in the filament current which may be measured by some convenient method. The comparison cell conveniently forms two arms of a bridge circuit for measurement work or comparison measurements as shown in Fig. 5(b).

Resistive converters are conveniently applied to processes to utilize process pressure, motion, or displacement effects. The resistance unit is generally light weight, inexpensive, easy to build in uniformity, simple to apply, and easy to calibrate. So long as the process is of such a nature that some displacement or motion has the desired relation to the final product, it may be utilized. If the motion is of such a nature that the associated energy may be coupled to a shaft, or otherwise coupled to a variable resistor unit, the resulting resistance variation can be utilized to convert the motion to a control voltage for measurement or automatic control purposes.

The rotary type of potentiometer is often readily adaptable to the process motion. These controls are readily available commercially in a variety of windings. It must be kept in mind that as the slider travels over the wire wound resistor, the variation is actually a stepped change. This can be overcome by using carbon plated resistor strips. This type of construction is limited to rather low current applications, and further, their life is somewhat shorter than the wire wound type of control. If extremely high resistance values are involved, the wire wound unit becomes too awkward and resort is made to the carbon strip potentiometers. Some controls are of conventional design, arranged so a slider moves through an arc of about 300° to 330°; others are available which have continuous windings so the slider may revolve over the full 360° arc. Fig. 6 shows the schematic of several of

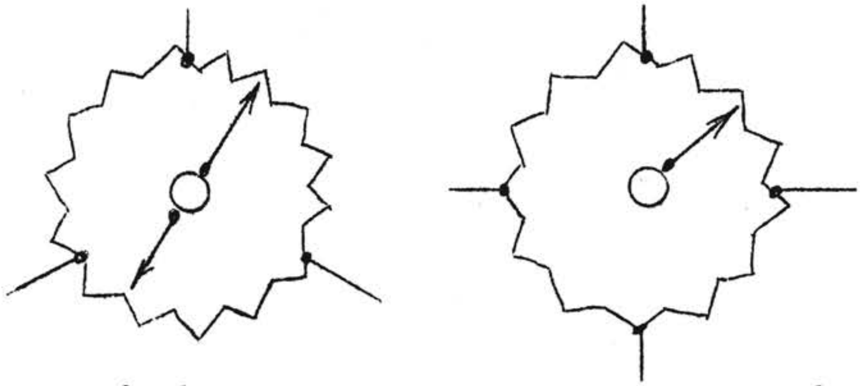


Fig. 6. Special 360° Control Resistors.

these continuous types of windings. The winding at (a) is tapped every 120° around the slider arc. The shaft is coupled to two insulated sliders diametrically opposite each other. This sort of control shaft is easily applied to a rotating process. The tapped winding may then be remotely connected to a special indicating instrument actuated by a small DC selsyn or synchro. The general arrangement of such a system is shown in Fig. 7.

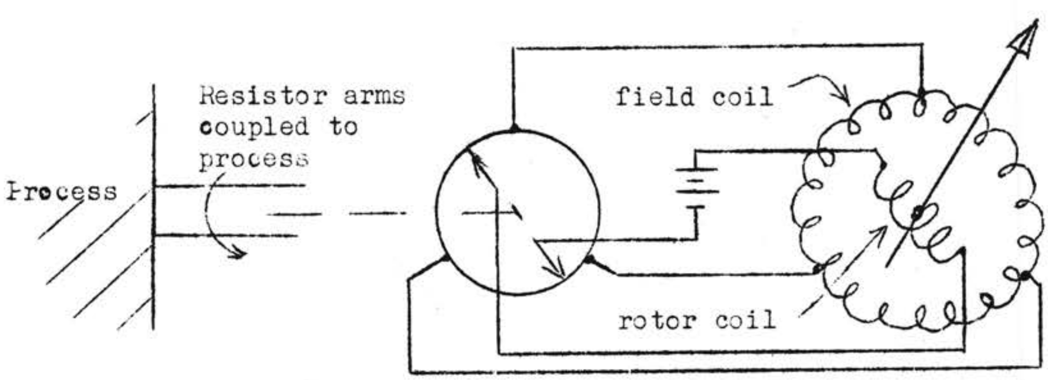


Fig. 7. Remote Indicating Control System.

This form of variable control may be tapped every

90° around the slider path as shown in Fig. 5(b). This sort of control may function as a bridge whose unbalance depends upon the slider position, or if the windings are properly distributed or tapered in terms of the slider rotation, special displacement-voltage characteristics can be obtained from the direct current bridge connection. Special types of resistors are arranged so that as a moving arm is rotated over the surface of a resistance card, the variation is sinusoidal. This sinusoidal resistance variation may then be used to set up a sinusoidal iR change with rotation. Because of the relatively simple construction of these resistance elements specially tapped, or specially tapered, potentiometers can be obtained at moderate cost.

Since these control potentiometers are normally designed to carry relatively small currents, they are limited in their applications. If very large currents must be controlled by the process, either some primary and secondary control arrangement must be devised or perhaps the process may be directly coupled to a carbon-pile. While the carbon-pile rheostat is not the most uniform smooth sort of control, it will carry great amounts of current with reasonable dependancy. The carbon-pile, as the name implies, is made of a stack of carbon washers. As the pressure on this pile is varied the contact resistance changes between carbon slugs, hence, the total resistance depends upon the pressure applied to the pile. While the total variation of the high current pile is limited, it may be arranged to obtain the desired control. However, there is some backlash in these controls as the original condition is not restored when the pressure change is removed. Furthermore, carbon has a negative temperature coefficient so the pile resistance does not depend upon pressure alone. Humidity and internal power dissipation also result in errors; hence, this form of control does not lend itself too well to automatic control systems where reproducibility and regulation are paramount.

An interesting application of the carbon pile principle is found in the common telephone transmitter button. When only qualitative sound or pressure measurements are required, this carbon button may prove satisfactory. It must be born in mind, however, that the button will not respond uniformly if the pressure variation becomes too rapid or too slow (poor frequency response).

There are times when the carbon pile principle may be utilized to measure displacement or deformation. If an insulated surface is coated with a film of finely divided carbon particles in close contact, and then subjected to deforming stresses, the resistance will change. Usually the carbon particles are suspended in some sort of binding or glue base which will adhere and cement the carbon to the insulating surface. If the carbon coating is to be applied to an object of insulating nature, it may be painted directly on the surfaces to be analyzed; or if the object is a conductor, the carbon film may first be spread on insulating paper and the unit then cemented to the objects surface. This form of "resistor" can be conventiently applied "on the job", and can be made to have most any resistance desired by controlling the amount of carbon used. This is convenient for electronic circuit applications. The resistance of the carbon patch varies in proportion to any longitudinal or transverse strain, hence, the unit may prove quite effective for testing structural disturbances. The carbon patch may be utilized in any of the previous circuits to function as a variable resistor although it is commonly applied to the bridge circuit utilizing electronic indication.

Another interesting application of the resistance bridge is the Silverstat. The balance is disturbed as the control shaft rotates, and sections of the tapped resistor are short-circuited as shown in Fig. 8. As the

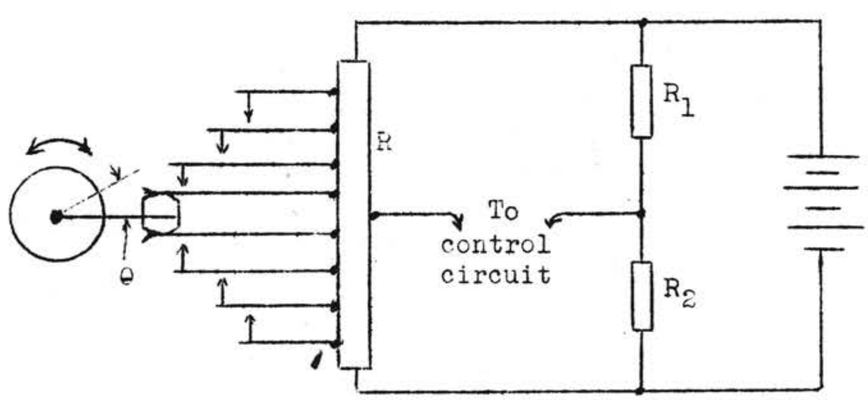
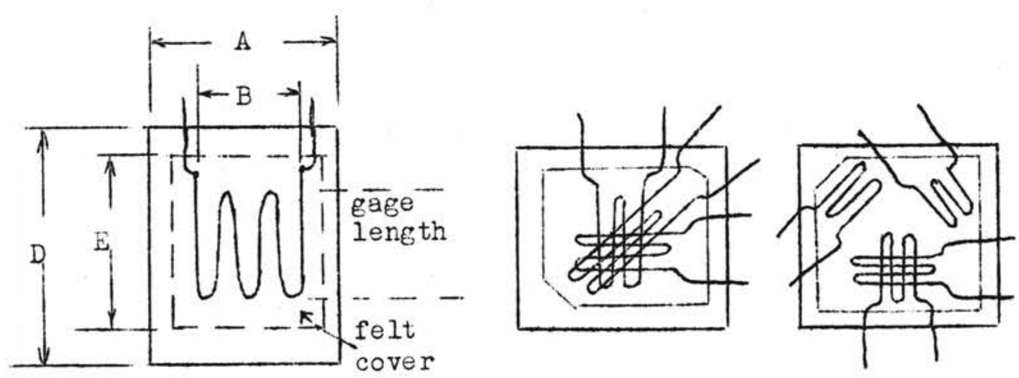


Fig. 8. The Silverstat Bridge.

shaft rotates it moves the arm to successively short the silver contacts at the ends of the spring leaves of the switch. As the springs are shorted, the resistance is successively varied in steps to give the unbalanced control voltage required in the control circuit. The bridge can often be arranged to carry sufficient current to directly operate the control circuit without requiring additional amplification.

It has already been indicated in Chapter II that the resistance of wire can be made to vary with its dimensional changes to give a good strain indicating device. Practice indicates that while changes in resistance due to strain can be approximated by calculation, actual calibration of the wire must be made before great reliability and accuracy result. These resistance converter units are normally made by cementing a grid of selected alloy wire to a paper backing strip.

The construction of several gages are shown in Fig. 9. The single gage is usually applied to give stress



a) Single gage b) Rousette gages

Fig. 9. Typical Strain Gage Construction.

or strain indications in a single direction while the rousette gage is applied when the direction and magnitude of the relative strains in each direction are not known.

TABLE VI. STRAIN GAGE DIMENSIONS[1]

Type	Effective Gage Length	Resistance	Overall Dimensions	Application
A-1	3/16"	120	$\frac{1}{2}$"x1$\frac{1}{4}$"x1/16"	
A-5	1/2"	120	$\frac{1}{2}$"x1$\frac{1}{4}$"x1/16"	Accurate over wide temperature Range
A-7	1/4"	120	$\frac{1}{2}$"x1$\frac{1}{4}$"x1/16"	
A-8	1/8"	120	$\frac{1}{2}$"x1$\frac{1}{4}$"x1/16"	
C-1	1 1/16"	500	$\frac{1}{2}$"x1$\frac{1}{2}$"x1/16"	Dynamic strain measurements.
C-5	1/2"	350	$\frac{1}{2}$"x1$\frac{1}{2}$"x1/16"	
R-1	(3 type A-1 at 45^{0})		1$\frac{1}{2}$"x1$\frac{1}{2}$"x1/16"	Two dimensional stress analysis

(For detailed description of many intermediate gage types, see reference 2 below)

The entire unit is considerably smaller than a postage stamp (see table VI) and can be readily applied to almost any size or shaped object under study or in some cases the gage may be assembled as an integral part of the object. Several types of strain gages are available commercially for various types of tests. One type is designed for static strain measurements over a reasonably wide temperature range; another type for dynamic strain measurements; the rousette type for two dimensional stress analysis; and special types are available to meet unusual requirements.

The strain gage element is usually wound either with a copper-nickel alloy resistance wire or with wire known as Iso-elastic. The latter has a greater sensitivity, but has a much higher temperature-resistance sensitivity also, which at times limits its application.

The strain sensitivity is defined as the ratio of unit resistance change to unit strain change, and its unit is ohms per ohm divided by inches per inch. For the copper-nickel wire - in straight lengths - this figure is about 2.15 while for the iso-elastic wire, it is about 3.6. When formed into grids for commercial service, these numbers become progressively smaller with decrease in gage length. The gage may be connected in either an a-c or d-c bridge arranged to measure its resistance change under strain. By the definition of the sensitivity factor

$$\Delta R = \frac{R \times \Delta L \times F}{L}$$

Suppose a particular gage had a resistance of 119.5 ohms and a sensitivity factor of 2 (see type A-1). The maximum wattage which this gage will handle is one-tenth watt. Under strain, the change in resistance was measured and found to be 0.3 ohms per mil. If a current of 28 milliamps was flowing in the gage during measurement, the voltage change is only 8.4 millivolts per mil displacement. Such a small voltage change calls for electronic amplification. If the strain is static in nature or very slowly changing, the electronic amplifier must be designed to pass and amplify d-c. While, if the strain varies rapidly and continuously, and a-c amplifier may be used.

Gages are seldom used singly. Often many gages will be distributed about the material to be analyzed and arrangement can be made to switch the measuring instrument from one gage to another. One terminal of each gage can be connected to a common ground buss on the instrument. The other connection must be switched as information is desired.

The common bridge circuit used with the gage normally uses two gages, one connected as a dummy as indicated in Fig. 10. This dummy is usually a duplicate of the active gage, which is mounted on a piece of similar material to be tested (but not stressed). Thus, temperature effects are effectively cancelled leaving an indication of only strains due to loads.

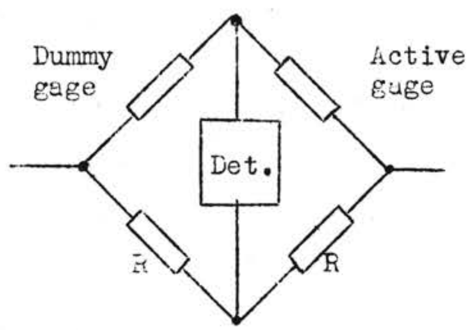


Fig. 10. Simple Strain Gage Bridge.

Capacitive Converters

The capacitive converter is fundamentally a very simple device but proves to be very versatile in application. It may be arranged to convert displacement, or motion, or temperature change into an electrical quantity proportional to the process change. Capacity change can be affected by a change in any of the physical dimensions of the converter, or by a change in the dielectric, since

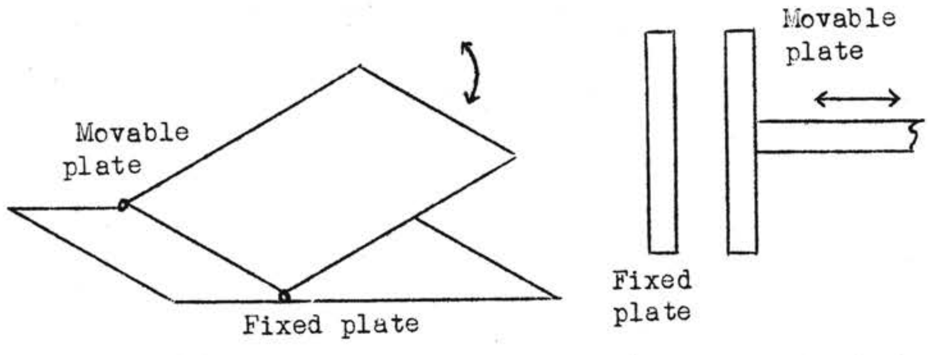
$$C = \frac{kA}{4\pi t}$$

It becomes a matter of ingenuity of design to arrange the condenser so that the process may change the spacing (t), the area (A) or the dielectric (k), or any combination of these three quantities. The capacity variation, of course, must occur in some known way and have the desired proportional change with respect to the process change. Capacity converters can be built so they are independent of temperature (zero temperature coefficient) variations, although the design becomes quite critical. The capacity of any of the usual converters is quite small - often in the order of a few micro - micro farads. There are several circuits available which can utilize this change and evaluate it. Bridge circuits and electronic amplifiers may be used or frequency controlled oscillators may be employed with the lower capacity converters.

Some converters may be set up by simply arranging a mechanical coupling device to a standard variable condenser. These are available commercially which have straight-line capacity characteristics, or so-called straight-line frequency characteristics. It is best to choose a condenser which varies with a desired relationship to the particular changes of the process.

The book type condenser, Fig. 11(a), can be arranged to follow linear, the inverse square law, or other variations as desired. A reciprocal law condenser may be arranged as in Fig. 11(b).

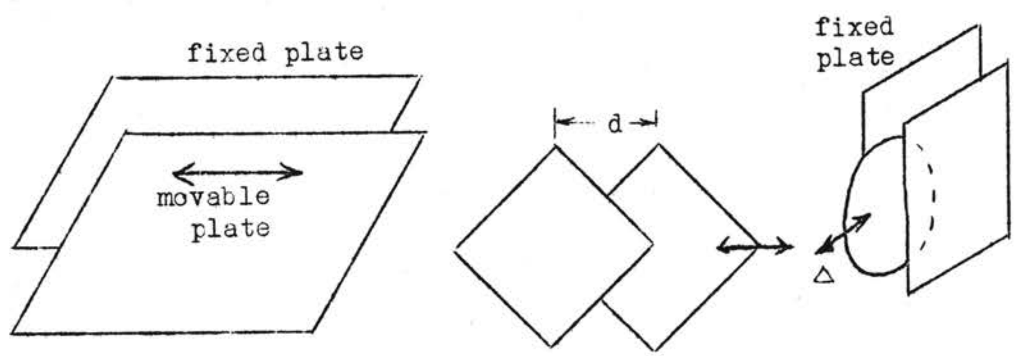
If the plates are arranged to move along their own axis parallel to a fixed plate, the capacity variation may be made linear by Fig. 12(a). The capacity could



a) Book type capacitor b) Modified book type

Fig. 11. Simple types of Condensers.

be varied in the same manner by utilizing a similar movement of a dielectric strip in the field of the fixed plates. (Fig. 12(a). Fig. 12(b) shows an arrangement such that the capacity varies in proportion to the square



a) $\Delta C \propto \Delta d$ b) $\Delta C \propto \Delta d^2$ c) $\Delta C \propto \sin\Delta$

Fig. 12. Several types of Capacitive Converters.

of the displacement, while Fig. 12(c) will produce capacity variation proportional to the sine or cosine of the displacement.

Many other forms of capacitors can be readily devised which may prove entirely satisfactory for the application. In any application design, it should be kept in mind that; first; as much capacity variation as possible is desired;

and second, the capacity of the converter should be as large as possible so that distributed effects and conditions will introduce minimum disturbance in the measuring equipment. These conditions are necessary if reproducable results are to be obtained.

The capacity of most any converter, however, is limited to relatively small values, hence, great care must be exercised to shield the equipment from extraneous effects. Furthermore, a low capacity device presents very high impedance, even at reasonably high frequencies, and calls for careful attention when installing. The leads themselves may have more distributed capacity than the pickup device. If the operating cycle of the device is fairly uniform a series inductor may be connected at the pickup and the combination made resonant at the operating frequency. This arrangement presents a low impedance to the connecting system and thus minimizes external effects. So long as the frequency variation of the operating cycle is limited, linear change can be affected in the pickup device.

Temperature change can be readily measured if the condenser plates are arranged to move as the process temperature varies. The plates should be made of thermostatic metals and arranged so they are free to move as the temperature changes. The condenser may be arranged to have any convenient physical form. In order to accentuate the plate displacement, it is often convenient to use bimetalic plates. Bimetalic material is composed of laminated layers of metals having very different expansion coefficients. When cooled or heated the bimetal sheet will bend or warp due to the unequal expansion of the surfaces. The sheet tends to bend following a spherical surface whose radius of curvature is approximately

$$R = \frac{tk}{T}$$

where t = thickness

k = constant of the metals

T = temperature change

If the bimetal is arranged in the form of a beam (Fig. 13), the approximate deflection per degree F change

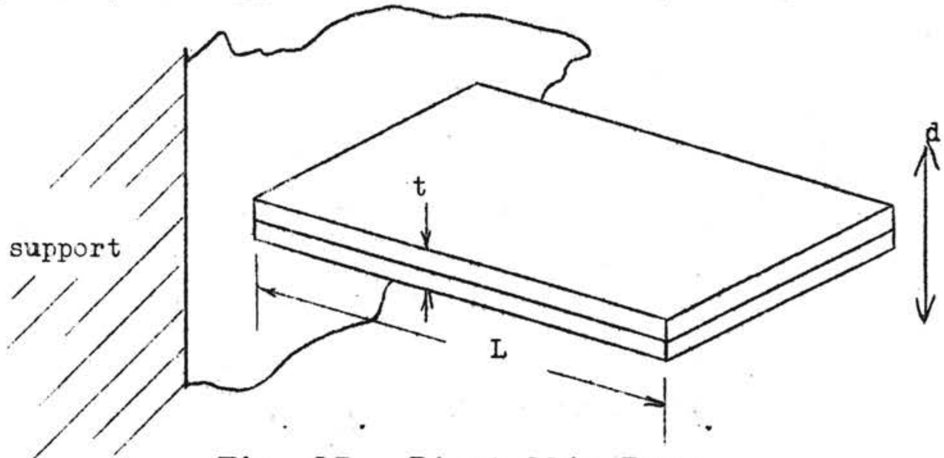


Fig. 13. Bimetallic Beam.

can be calculated

$$\frac{d}{T} = \frac{6.4 \times 10^{-6} L^2}{t} \quad \text{inches/degree F}$$

where the dimensions of Fig. 12 apply.

The change in capacity between two such beams can then be determined as a function of the temperature change. The longer and thinner the beam the greater the change which would result. It may not always be convenient to install a long converter of this type, but the same action could be obtained by coiling the bimetal strip in the form of a spring and allow it to move relative to a fixed plate as shown in Fig. 14.

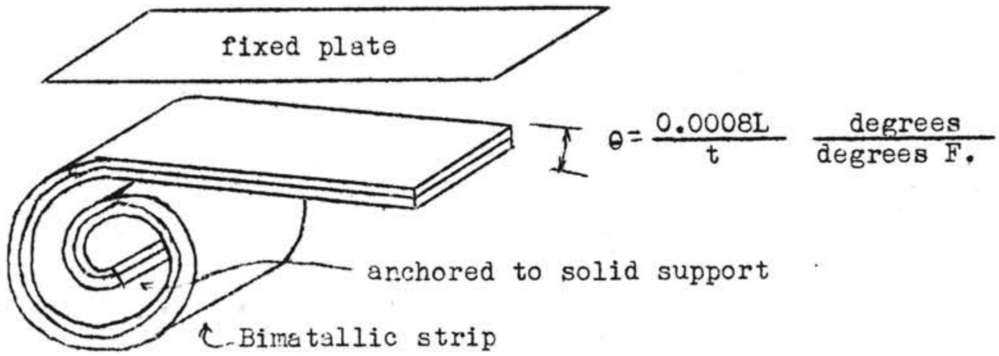


Fig. 14. Modified Beam Capacitor.

Other arrangements will suggest themselves as the application is analyzed.

Occasionally sound effects (pressure effects) have to be measured. This may conveniently be done by utilizing a condenser microphone. A very thin stretched diaphram is arranged to vibrate relative to a fixed back plate as shown in Fig. 15. As the diaphram vibrates the spacing between the back plate and the diaphram changes with a resulting change in capacity which is then applied to some electronic measuring device where frequency, amplitude, or phase variation may be measured. A modified form of condenser microphone is the Electret. Two parallel

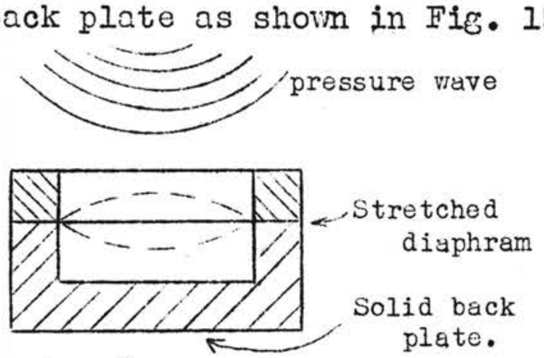


Fig. 15. Cross-section of a simple condenser microphone

plates are arranged to have a thin layer of wax between them. During the construction, a high voltage is applied to the plates while the wax is molten and allowed to remain until the wax has completely cooled. This gives a capacitor which has the characteristics of a condenser charged continuously through a high impedance. As the plates are subjected to some force, a voltage appears at the terminals which is proportional to the bending or distortion.

Flow and level variations may be conveniently measured by the capacitive type of pickup. Two electrode plates immersed in an insulating liquid form a capacitor. As the dielectric of the condenser varies (Fig. 16), the capacity of the pickup will vary. The capacity change can then be utilized to control the electronic device. Many liquids display high dielectric constants at normal temperatures and some have negative temperature characteristics. Often chemical processes can be arranged to produce capacitive changes as required for control. Concentrations are easily read due to dielectric variations and continuous flow measurements may be easily established.

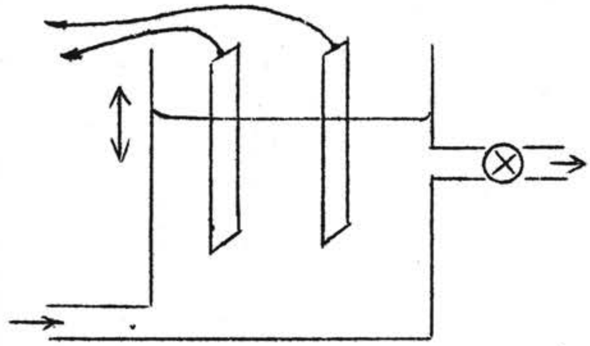


Fig. 16. Capacity variation due to dielectric change.

The dielectric moisture meter is an interesting application. The sample, whose moisture content is to be measured, is inserted between two electrode plates. Since the dielectric constant of water is about 8 times that of most common non-conducting materials, the moisture content of the sample will have a marked effect upon the capacity of the measuring element. This change in capacity, due to the moisture content, may then be utilized in a phase shift or LC oscillator circuit and desired measurements can be made. The measuring plates remain fixed during any measurement, so their capacity alone can be readily measured and corrections allowed.

Inductive Converters

Inductive converters are arranged so that some physical change of the process will produce a known change in the inductive pickup. The pickup changes result from relative change in a magnetic field and can represent either inductive change or voltage change. Certain of these converters generate a voltage due to vibration, etc., and will be considered in a later section.

The principle of the inductive converter depends upon the inductance equation for $L = \frac{0.4\, N^2 A \mu}{10^8 l}$ henries.

It is quite practical to control the inductance by changing the permeance of the magnetic path. Hence, if some part of the process can alter either l or μ, the inductance change will be related to the process change. To make the problem more general, consider that any change in the magnetic field will produce the desired inductance change.

Perhaps the simplest inductive converter is shown in Fig. 17. When the "keeper" is moved, a variation in the air gap will cause a proportional change in the magnetic field which disturbs the normal inductance. This form of variable inductor may be connected in an initially balanced bridge of either the single or double angle type. As the "keeper" is displaced from its normal position, the bridge will be unbalanced.

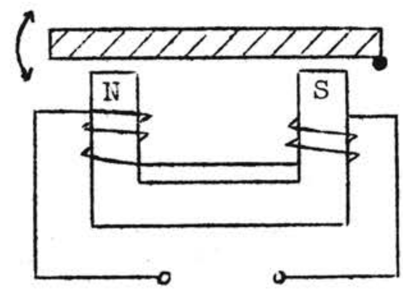
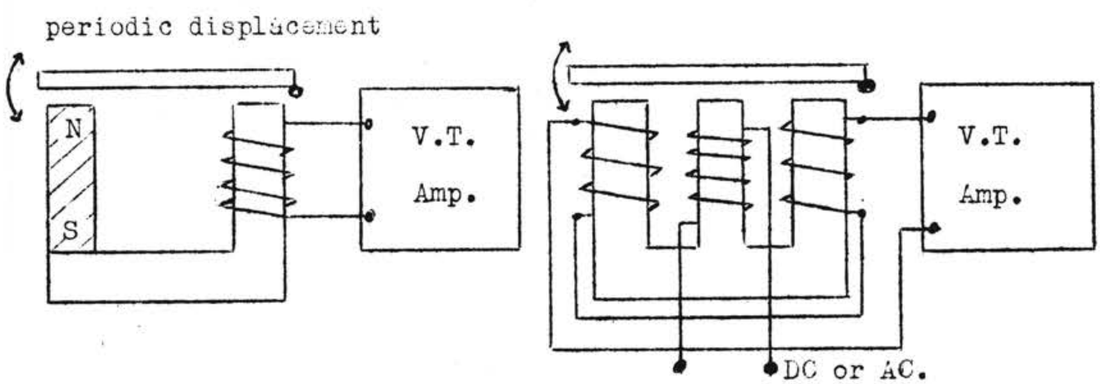


Fig. 17. Simple form of Inductive Converter

The unbalance voltage is quite small and is normally amplified electronically. The movement of the "keeper" may be amplified somewhat by proper lever action.

If only direct variation in inductance is to be utilized, the core of the magnet must be excited by some externally applied energy. The core may be energized by using either a permanent magnet or by exciting the core with d-c or a-c. Fig. 18(a) indicates a method utilizing



a) Permanent magnet excitation. b) Seperate excitation.

Fig. 18. Forms of Electromagnetic Converters.

the permanent magnet, while Fig. 18(b) utilizes an a-c or a d-c field separately excited.

The magnetic variation caused by the process may be either slowly varying or rapidly varying. Care must be exercised to insure that the mass of the "keepers" is not set in motion so mechanical resonance develops in the moving system.

The application of these converters depends upon the ingenuity of the designer. The "keeper" may be acuated either through some connection to the process or it may be an actual part of the process itself.

Temperature variations can be readily converted by the device. Suppose the "keeper" was made of a bi-metalic magnetic strip. As the surrounding temperature changes, the "keeper" deforms and produces a change in the flux path. Care must be exercised, however, as not only the "keeper" will be deformed but as the core and winding are heated, they also change. The resistance of the copper coil depends upon its temperature. Furthermore, the coil will tend to expand as its temperature increases. Likewise, the magnetic core has a fairly high expansion coefficient, hence, the reluctance of the path changes as the temperature. Those difficulties can be offset by using a balance coil of the same dimensions and operated at the same temperature as a second arm of a bridge. The dummy would have a fixed "keeper" however, and the circuit can then be balanced for any initial reference.

The magnetic variation caused by a diaphram movement is easily adaptable to inductive converters. If the "keeper" is replaced by a magnetic diaphram, pressure or sound variations will cause the diaphram to move. This movement in turn produces some change in the measuring circuit. This sort of converter has been extensively applied to the analysis and study of combustion engine operation, and to pressure distribution analysis. One type of device used for combustion pressure measurements is shown in Fig. 19. As the pressure wave hits the diaphram, it is moved. This alters the air gap with a resulting change in the reluctance of the flux path. Other types of pressure converters are arranged so they form arms of a bridge circuit. However, the particular application will finally determine the type of converter most adaptable to the process.

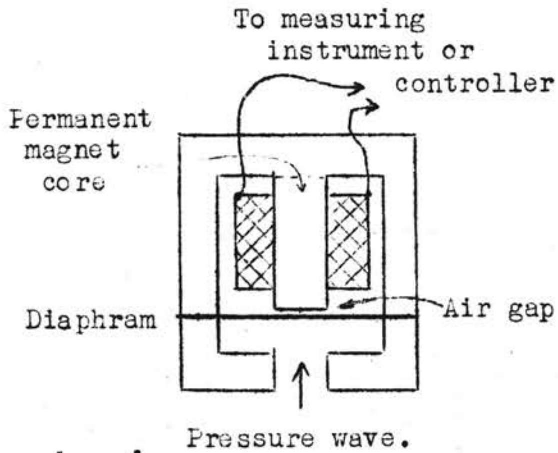


Fig. 19. Inductive converter for pressure analysis.

An advantage of the inductive converter is that it normally has a rather low impedance. This results in simplified installations as long as connecting leads do not disturb the converter response characteristics. On the other hand, the inductive pickup is very susceptible to extraneous magnetic field errors and care must be exercised in placing the converter in a magnetically neutral position, or it must be adequately shielded against external fields.

Certain pickups may be arranged so the magnetic core moves with the process rather than the "keeper". An inertia pickup of this type is shown in Fig. 20.

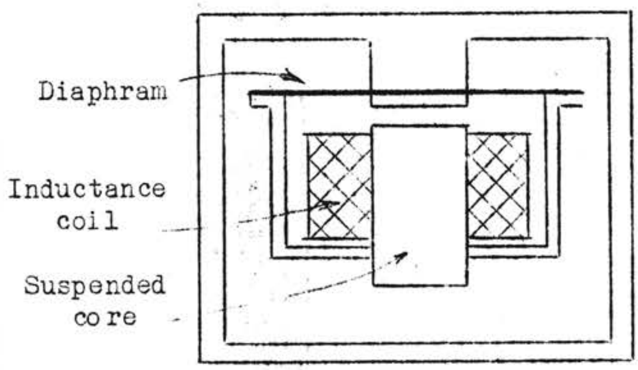


Fig. 20. An inertia pickup.

The outer magnetic housing is bolted to the moving process. As it moves about, inertia effects tend to move the coil and core arrangement which is suspended by the diaphram. Movement of the inner construction alters the magnetic flux path and results in an inductance change. This system has rather high inertia effects due to its large mass and care must be exercised in its application so that it does not vibrate at its natural resonant frequency. This type of pickup gives a variation which is proportional to acceleration, so if velocity or displacement studies are to be made, it must be followed by integrating circuits.

Any of the pickup elements described may be readily converted from acceleration to velocity response if the moving element is rigidly coupled to the process so the change depends only upon the rate of change of the process. In practice, the acceleration pickup is arranged so the driving energy acts directly on the housing, while the velocity pickup applies the driving energy so motion is independent of the housing. Any velocity pickup may be converted to a displacement unit by integrating its output voltage. However, the inductive pickup can be made to have a linear displacement characteristic if the magnetic field is excited from an a-c source. The device shown in Fig. 18(b) will give a response proportional to the velocity of the keeper if the field is excited from a d-c source, or its response can be altered to yield a displacement voltage if the excitation is changed to a-c. The action under a-c excitation is equivalent to a variable ratio transformer arranged so the ratio changes in a pre-arranged manner.

It must be kept in mind that the displacement controls the output response. As long as the displacement is very small, the output tends toward linearity with respect to the displacement, but as soon as the displacement becomes large, some different law will apply. If the arrangement simply varies the inductance, large displacement of the keeper tends to produce a reciprocal relation between displacement and the process.

Another form of this type of pickup may be arranged to respond to variations in non-magnetic conditions. The magnetic conditions of an a-c field may be appreciably altered if some non-magnetic metal is introduced due to the eddy current losses. An interesting application of this principle is used in the thickness gage. The pickup device is arranged as in Fig. 21. Two equal coils are wound on the outside core pieces and connected in opposition. The core is excited from an a-c supply whose frequency is considerably higher than the variations of the process. If the process to be measured is non-magnetic, the higher frequency produces a greater eddy current loss (remember the loss is proportional to the square of the frequency). The balance gap is initially adjusted so that Δe is zero with the desired sample in place. As some deviation is now encountered in the measuring gap, due to process variation, the eddy current loss unbalances the two magnetic paths and a difference in voltage Δe results. This can then be fed to some indicator or an electronic controller.

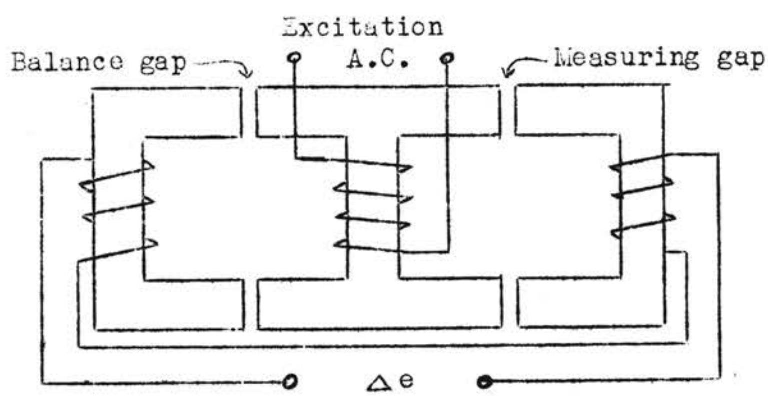


Fig. 21. Magnetic circuit of a thickness Gage.

Voltage Converters

This type of converter is coupled to the process in such a manner that the process variation will genetrate a corresponding voltage. This voltage is normally quite small and requires amplification before measuring or control can be achieved. Continuously changing conditions are required by this type of converter so it would only be applied to dynamic or motional processes.

Lenz's law is applied successfully to several types of converter units. If a coil is arranged in a magnetic field, relative motion will generate a voltage proportional to $-N\frac{d\phi}{dt}$. The moving coil converter is one of the simplest applications of this principle. The coil can be inertia operated, or it may be directly coupled to the process. The unit consists of a light weight coil suspended in a strong unidirectional field. Some sort of returning spring mechanism or spider is arranged to allow freedom to the coil motion, as shown in Fig. 22. This type of converter is especially adaptable to vibration studies. The moving coil under these conditions would vibrate violently and give false readings. However, if this coil is wound on some lightweight non-magnetic metalic form, such as aluminum, the eddy currents induced in the coil form will damp the movement and the response voltage will be generated. The pickup is rigidly mounted on the moving object and any sudden motion or vibration will then move the coil relative to its field due to the inertia effect of the coil mass. Hence, the generated voltage will be proportional to the acceleration of the vibration which in turn is proportional to the displacement times the square of the frequency of the generated voltage.

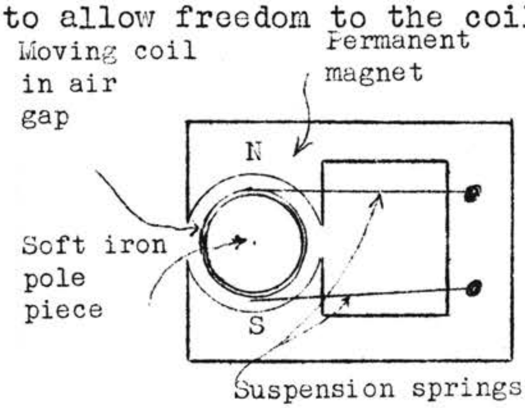


Fig. 22. A moving coil Converter

Another form of voltage generating converter depends upon the piezoelectric effect. When a natural quartz or a Rochell salts crystal is strained, a dielectric polarization occurs, with the result that changes appear at the surfaces. If some electrode is in contact with two opposite crystal surfaces, the charge appearing at the electrodes gives a potential difference which is related to the distorting force on the crystal. The generated potential must be amplified and converted to a corresponding power pulse before it can be utilized for measuring or control purposes. Fig. 23 shows a piece of cut crystal mounted between two electrodes. When pressure is applied as indicated, the direct piezoelectric effect produces polarization in the crystal structure inducing equal and opposite charges on the crystal faces at the electrodes. As the pressure varies, the difference in charge varies directly. The Rochelle salt crystal also displays large variations in its dielectric constants as its temperature is changed. A special form of capacitor may be built up using the crystal as the condenser dielectric. This special crystal condenser may then best be utilized to control the oscillating frequency of an electronic generator. Care must be used to see that the Rochelle crystal is not subjected to temperatures exceeding 125°F.

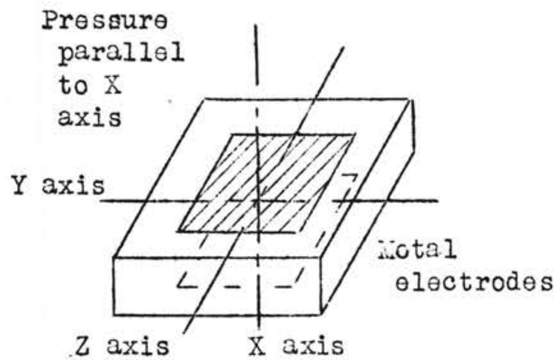


Fig. 23. A piezoelectric generator

The crystal generator is an extremely high impedance device and the same installation precautions must be observed as with the capacitive pickups. The voltage output is quite low under normal conditions but the smaller the area and the greater the thickness of the crystal, the higher the voltage output. The natural resonant frequency of these units is quite high and, for normal applications, the crystal is forced at a relatively low frequency.

The common crystal microphone unit operates on this principle, and may have a frequency response of from about one cycle per second to well above ten thousand cycles per second. However, the output is normally several DB higher at the higher frequencies and, hence, care must be exercised in the application that false readings are not obtained. The crystal is cut from a Rochelle salt formation which displays the greatest piezoelectric effect known. However, these crystal units can be permanently damaged by temperatures above 125°F. The method of mounting the crystal will determine its voltage relation to the process. It may be arranged as an inertia pickup by proper mounting (geophone) or the crystal may be directly propelled by the process giving velocity characteristics.

An interesting application of the piezoelectric effect is the smoothness gage.[1] A lever arm is arranged to move over the test surface. The arm in turn is arranged to activate a crystal converter. As the arm is moved over the surface, any irregularity or roughness is

[1] An instrument for measuring surface roughness. Electronics, November 1942, pg 70.

transferred through the arm to apply pressure on the crystal. It in turn induces a charge voltage between its electrodes which is fed to a high gain amplifier to record the variations in the surface.

Chemical processes may sometimes be arranged so that if electrodes are immersed at several points in the process, potential differences will exist between them. By proper choice of the electrode materials, the induced voltage may be utilized to indicate variations in concentrations, impurities, and other undesirable conditions in the process.

Liquid flow through a pipe may also be arranged to induce a voltage. If an insulated section of metal pipe is mounted in a strong magnetic field, liquid flowing in the pipe will generate a potential normal to the field and the direction of flow. Care must be exercised that the liquid does not react with the electrode surface if dependable results are to be obtained.

Heat can be readily converted to a proportional electrical voltage by employing the thermocouple as a converter unit. Its output can then be readily amplified for instrumentation or control purposes.

The thermocouple is made of two dissimilar metal wires bonded together at a common junction. The greater the separation of the wire material in the electrochemical series the greater the voltage produced per degree temperature. The wire filament should be very small if small thermal lags and high sensitivity are obtained.

It is necessary that the thermocouple material be unaffected by its surrounding atmosphere if reliable readings are to be obtained. This results in several alloys being used, the choice depending upon whether the surrounding atmosphere is acidic or alkaline. In some instances, it is necessary to enclose the thermocouple in a glass bulb if oxidation is to be prevented . When high temperatures are to be measured, the wire must be quite heavy even though the sensitivity is reduced somewhat. The lower the temperature to be measured, the smaller the wire must be. The thermocouple always displays some lag but will be reduced as the wire size is reduced. Since the thermocouple is sensitive to heat radiations, it has been applied in spectral analysis equipment, celestial observations and other light radiation measurements. The radiation thermocouple junction is formed of extremely thin ribbons and the junction temperature is effective in producing corresponding circuit changes. The construction yields a low impedance device and, hence, it may be directly connected to a galvanometer of matching impedance when instrumentation is desired, or it may directly trigger thyratrons at predetermined temperatures. The thyratrons may then operate corrective or control devices

Another device for measuring radiant energy is the bolometer, and the thermal conductivity cell, previously mentioned. The bolometer tube is arranged so the sensitive wire is made of two different pieces of material joined at their center. This, in effect, forms a thermocouple junction. A constant current flows to heat the junction and any radiant energy or any change in the conducting medium causes a superimposed voltage to appear in the bridge circuit. The bolometer tube, shown in Fig. 24, may respond to pressure or vacuum changes in the system to which it is connected, or it may respond to radiant energy focused upon one arm of its resistive bridge by noting the current required to re-establish balance.

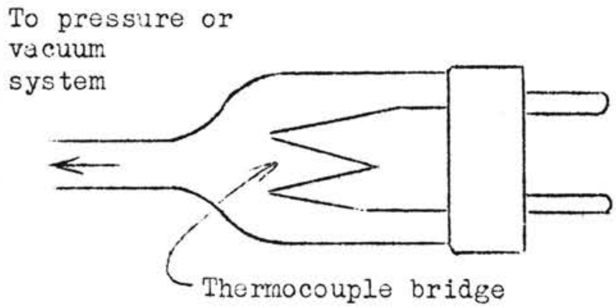


Fig. 24. Typical Bolometer Construction.

Occasionally quartz crystals may be used as temperature converter units. The quartz crystal will control the oscillation frequency of an electron tube oscillator. Certain cuts of the crystal will accentuate the frequency-temperature characteristic and if some method of measuring the frequency drift is arranged, small temperature changes may be accurately measured for control purposes.

The photoelectric cell has received wide application as a voltage conversion unit. They are selective detectors of radiant energy and may be of two types, the photo-emissive cell and the photo voltaic, or self-generating type. The photoemission tube is a high impedance device while the self-generating cell has rather low impedance but still much higher than the thermocouple. The photoelectric converter is one of the most versatile and useful converters. It is usually rather a simple matter of coupling the cell to the process by using a light beam. Photo tubes are made in single and double anode types and are also combined with the electron multiplier tube to give extremely high output with very small change in the impinging light. It is often possible to employ an optical lever system to give highly amplified light changes to the cell. This may prove more convenient than adding equivalent amplification after the photo cell. This is particularly true when very slow changes occur in the system as it often proves simpler and more reliable to employ an optical amplifier rather than a high gain d-c amplifier following the photo cell. An interesting light lever has been developed by General Electric Co.[1] Fig. 25 shows the general operation of this metering system. The systems may be applied to a bridge circuit

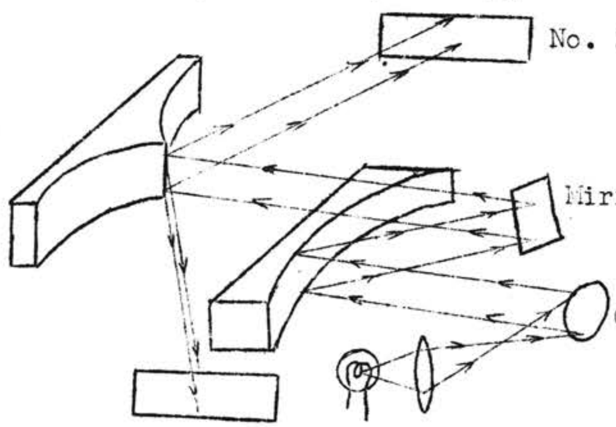


Fig. 25. Photo Cell light beam lever balancing arrangement.

(either a-c or d-c). The galvanometer mirror is caused

1. General Electric Review, 38:189, April 1936; 40:228, May 1937; 46:623, November 1943; 36:271, June 1933.

   Transactions AIEE March 1932, p. 226.

to move by the "detector" current in the bridge circuit. As the bridge is brought into balance, the light beam will divide equally and influence both photocells equally. The cell output works an electronic amplifier which drives a recording meter.

Simpler applications of the photo cell include all on-off control systems. Whenever the light beam is interrupted, the photocell is arranged to operate a vacuum tube relay system. This class of equipment would include such devices as automatic door openers, burglar alarms, counting, inspection, sorting operations, and safety devices for industrial machines. Either visible, ultraviolet, or infrared light may be utilized in the application.

Time delays may be simply incorporated in photo electric control devices, Fig. 26. The choice of R and C will determine the amount of delay introduced in the relaying system. The photocell, being of a high impedance nature, cannot operate the relay directly. The direct coupled amplifier tube is therefore connected so the photo tube faces the very high impedance of the grid circuit. The tube then functions as a converter, giving a correspondingly large current

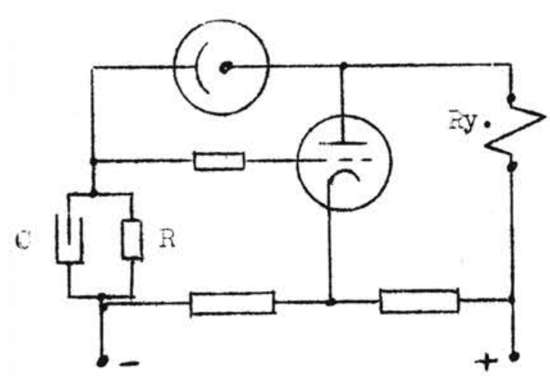


Fig. 26. A Photo-electric Relay with Time Delay.

change in the plate circuit as the light intensity is varied on the cell plate.

Many applications of the photo electric converter are of such a nature that the tube cannot be conveniently located in a darkened room and random illumination could completely impair consistent operation. This may sometimes be prevented by using selective light filters and an ultra-violet or an infra-red light source. If visible illumination is employed, a sharply focused lens system will prevent random illumination from affecting the system. This system may be still further improved by using "in line" pin-hold irises to prevent any randon light from reaching the lens system.

The double anode tube or two individual tubes may be employed at times in a balanced bridge arrangement to correct for random illumination. One plate is subjected to only the random room illumination while the second plate will receive not only random light but also the process illumination. After initial balancing under room illumination only, any change in the process illumination will cause a corresponding unbalance in the bridge which is then amplified by the system.

Photocells respond as well to heat and color radiations as to light radiations and are utilized in many processes where these quantities are to be measured. Usually special filters and comparison or bridge circuits are utilized in these applicatiohs.

Special Converters

There are many process variables which may not be conveniently coupled to the previously described converter devices. Occasionally the process variation must be passed through several stages before the final electrical conversion can be achieved. It would become almost impossible to consider individually the great variety of special converters, some finding wide application, others only an occasional use.

Occasionally converters or even complete control systems may have wide enough application to processes to warrant mass production of the device for industrial consumption. More often, however, control systems are so highly specialized that only one or at best a limited number of the devices will be built and applied to processes. This type of application of process control is quite costly to the consumer and its worth must be justified in extended savings in the complete process.

Industry is however finding that the various applications of control are economically justified to the extent that many companies retain research departments in this field. The men employed in this type of development work are continuously faced with new problems which tax their ingenuity to the fullest extent. An unusual amount of ability is required if satisfactory equipment is to be designed to adequately meet the demands of increased production rates and improved accuracy.

A search of the literature will reveal many interesting applications of the principles outlined in the preceding paragraphs. However, space will not permit detailed discussions of the varied applications. A representative bibliography is included and further reference may be made to such indexes as:

(a) The Engineering Index

(b) Electronic Engineering Master Index

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Abbreviations used for Magazine References

E - Electronics

GER - General Electric Review

EI - Electronic Industries

C - Communications

QST - QST

Rad - Radio

Typing done by Eddie Presgrove