DEVELOPMENT OF EXCITATION SYSTEMS OF A.C. GENERATORS

By

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DISSERTATION

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING IN
ELECTRICAL MACHINE DESIGN.

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CERTIFICATE

Certified that the dissertation entitled Development of Excitation Systems of A.C. Generators, which is being submitted by Sri Y.C. Kohli in partial fulfilment for the award of the Degree of Master of Engineering in Electrical Machine Design of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of three and a half months from April 27, 1983 to August 16, 1983 for preparing dissertation for Master of Engineering Degree at the University.

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Dated August,19 1983.

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INTRODUCTION.

i. Earlier systems made use of common excitation bus bars energised by level compounded D.C. generators and a battery to provide for standby opacity for short durations. With the expansion of interconnected systems, the system stability became vital and in the early twenties a commission was engaged to study the matter in detail. This commission recommended an improvement in the design of exciters. As a result, engineers took more interest in designing excitation systems, the principle depending on the size of the main generators and the installations for which it was required.

One method was to use three-winding exciters for working on the linear and stable portions of the magnetisation curve. A second way for low speed machines was to use individual motor-generator sets for each machine. Very soon exciters with high speeds of response and more accurate voltage regulators were added to the industry.

ii. Soon it was felt that direct connection of the exciter to the generator shaft solved many difficulties of separately driven exciters and this became popular. For standby a spare exciter was kept and for any trouble the change-over was done manually.

Designers are always finding ways of improving the performance of excitation systems by different types of D.C.

generators, electronic converters etc. The aim is to reach the greatest accuracy, sensitivity, simplicity, reliability and an ideal rate of response.

The source of field current for the principal electric machine is known as the main exciter, which may be a D.C. Machine of either a Rotating or Non-rotating type. Among the first category we have the D.C. generator, or the Rotating amplifier called Rototrol. The major form used of the non-rotating type is the Electronic Exciter.

iii. In Rotating Amplifiers, there can be several stages of amplification. The Rototrols have been used with one stage of amplification for several years, but in some recent applications the control energy available was found too small for satisfactory regulation.

The development of the 2-stage Rototrol uses only one machine, and the simplest construction is a 6-pole machine. It is a conventional generator except for the field coils and armature connections. The machine may also be considered as three generators superimposed on one another, although the output of only two may be used. Tests on such designs showed high-sensitivity and response and it provided a generating element for such systems requiring a very low control energy.

INTRODUCTION.

The use of Rotating Machines for controlling the excitation made engineers use the name 'Rototrol' for all such arrangements. They give satisfactory performance and are used in all industries where electric machines are employed. To control any system, it is necessary to measure the output and compare it with a predetermined standard. The system should provide necessary action to correct the output when any variation occurs; and also cancel any action when the correct output is obtained. These features are introduced into a Rototrol generator by additional windings on the field magnets. If this comparison between the output and the standard is made inside the machines, separate windings are used for each intelligence and they are called pilot and standard fields.

If comparison is made externally, then only one field called the control field is required. Here when the output does not match the standard, a net excitation will exist, and this is used to initiate the required correction. Again when the output is correct, there is no net excitation resulting from the control energy and so no action is initiated.

We observe that the pilot and standard intelligences give us a means of causing the Rototrol to change its output. At the correct output, these would neutralise each other and the net resulting output would be zero, so some other way is required to maintain the output. This is done by a self energizing field of shunt, or series type, or a combination of shunt and series types, which is so designed that it has a sufficient strength to supply the necessary excitation to generate sufficient voltage to sustain itself. This is possible over the range where the saturation curve is a straight line and hence the operation of these machines is limited to the air gap portion of the saturation curve.

Sometimes we may require a Rototrol output proportional to the control energy. In such a case, either partial or self-excitation may be used. Generally rototrol generators of this type use standard parts except the field coils and special materials or treatments in the poles and frames. Use of this class of rototrols has given satisfactory results and can be used for wide types of applications. For a few applications, additional amplification is necessary. One satisfactory method is to use electronic means to amplify the control energy and provide control input for the rototrol and to have regulating and antihunting features.

Another method is to use two Rototrol units in cascade; and a third method of handling regulating problems involving low control energy is to design a single 2-stage Rototrol which will give results similar to cascaded systems.

INTRODUCTION.

MAIN EXCITER ROTOTROL.

One of the large sizes used is 200 KW 250 Volt, 3600 RPM main exciter Rototrol which can be used to excite a 60,000 KW 13,800 Volt 3600 RPM turbo generator. For normal operation it is a closed machine; but with the cover removed, it has greater ease for brush replacement and inspection than a D.C. machine of similar size. The brush holder is of double type and brushes can be replaced by using standard shunted brushes. So while replacing brushes the machine can remain in operation and no tools are required.

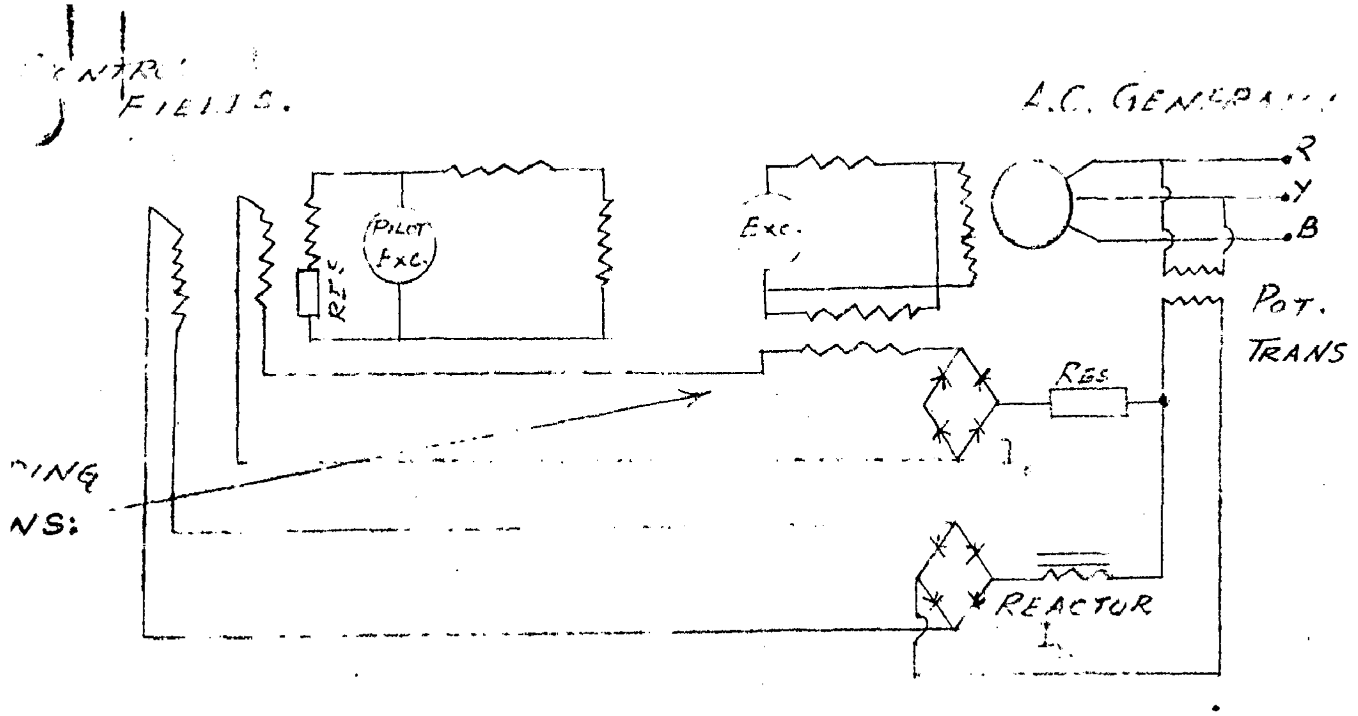
Due to the high speed involved shrink rings are used and the shrink ring commutator is the Westinghouse floating type. The armature winding is of the lap type. The stator is of normal type, with modified brush holder cross connections and additional windings on the fields are required to obtain two amplification stages in one unit. A laminated type frame is used to minimise effects of hysteresis and eddy currents and for a faster speed of response. Commutating pole, series field and shunt field windings are insulated throughout the full length to avoid creepage paths.

iv. Static Voltage Regulators for Exciters:

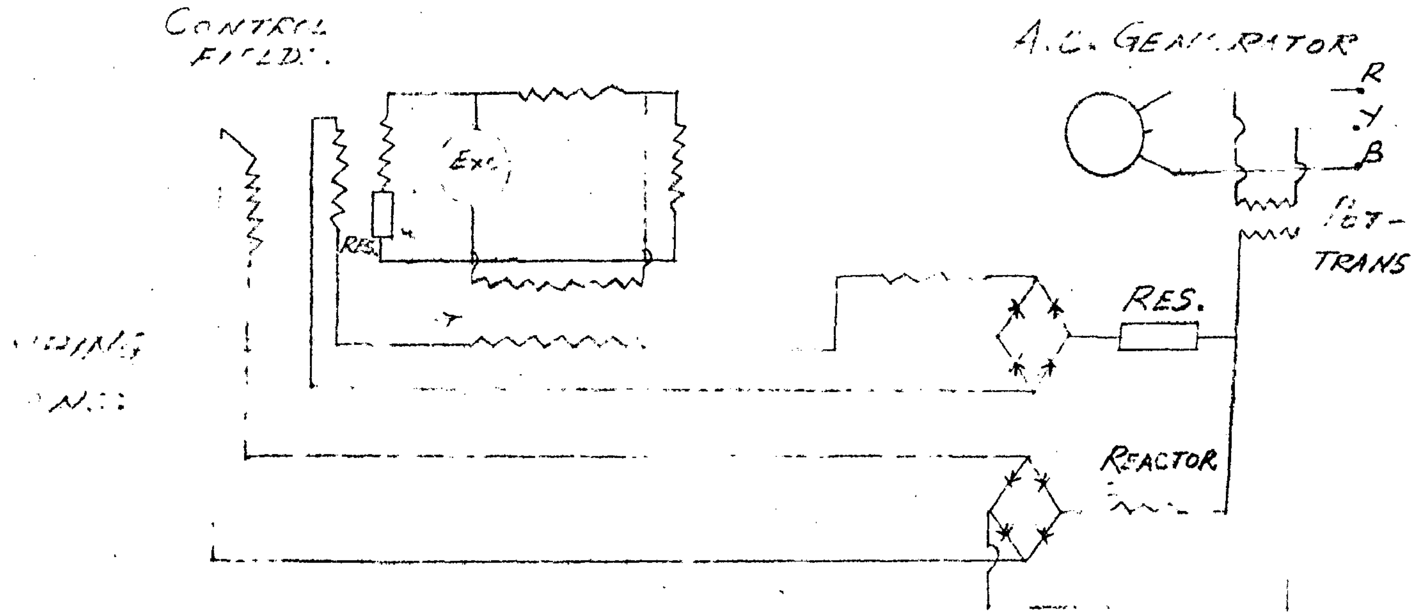
In an ordinary regulator we use an amplifier to produce a large correction in field current for a small change from normal voltage. In the direct acting type, this amplification is obtained both in the regulator and the exciter. However in a rotating amplifier type regulator the amplification is provided mostly in the rotating machines. We may have two or more stages of amplification or use a single machine having high amplification such as a rototrol exciter.

Let us first consider a two-stage excitation, where the regulator works in a pilot exciter field. When high amplification is available, voltage regulation can be obtained by arranging the control field of the exciter or rototrol to raise or lower, in response to any change of generated voltage from the normal value.

Now consider a D.C. generator operating on the linear part of its saturation curve and completely self-excited by shunt and series fields. It will support itself at any voltage from zero upto the point of saturation. It has one or more control fields which increase or decrease its voltage as needed, and keep it operating stably at any desired point. This system is used where battery or vacuum tubes cannot be used and there should be no moving parts other than the rotating machines. These machines would be having air gaps nearly as large as ordinary D.C. generators.



d) Pilot-Exciter Regulating System.



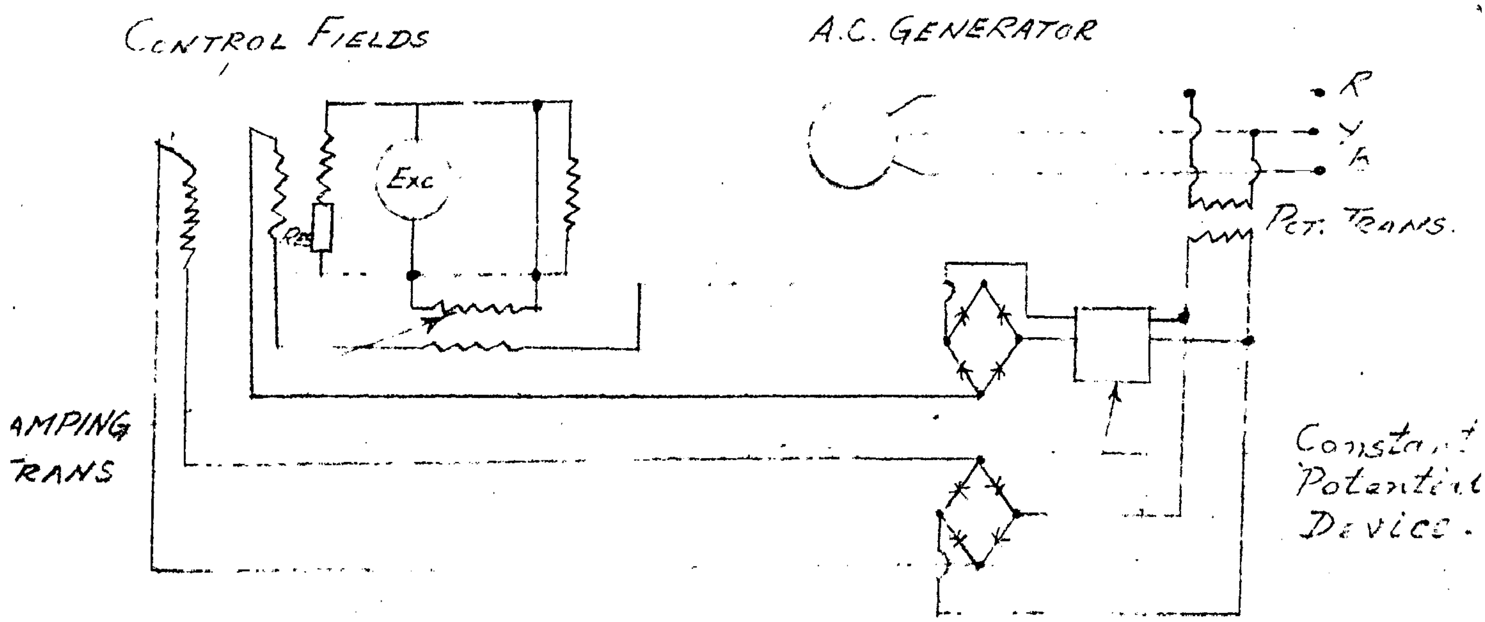
([illegible]) Exciter Regulating System With Opposed Control Fields

Fig-1.

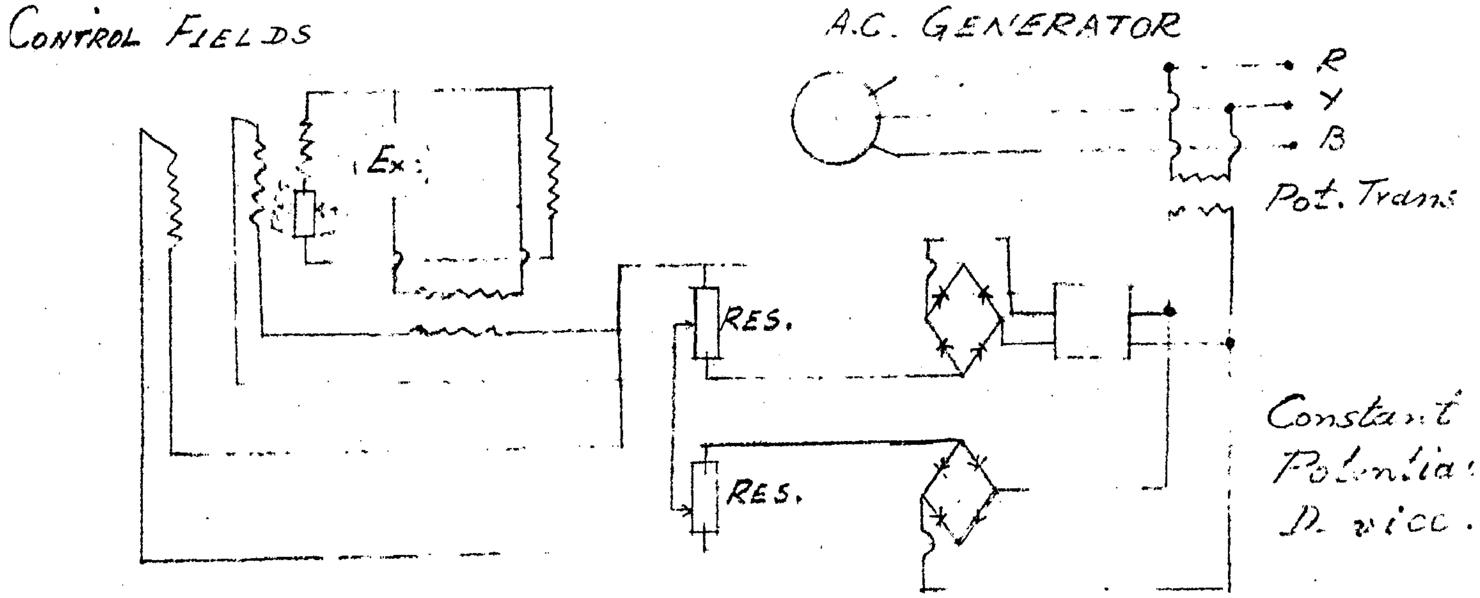
INTRODUCTION.

The voltage reference used has 'intersecting impedance characteristics.' This means circuits that detect and respond to the voltage level as follows. With normal voltage, two impedances are adjusted to draw equal or proportional current, one of which is linear and the other is non-linear. As the voltage increases, one of the impedances draws more current and the difference current is in a direction showing voltage above normal. Again if the voltage falls below normal voltage, the same impedance draws less current than the other and the difference current is reversed showing voltage below normal. The currents are rectified before comparison. In the static type of voltage regulation one of the methods is the use of a three core saturable reactor. We can use similar circuits using Rototrols for amplification.

The circuit shown in Fig.1(a) consists of two branches, a resistance path and saturating reactor path. Currents in each path are rectified and fed into the control fields of the rototrol. Here use is made of rototrol pilot exciter, an ordinary exciter and an A.C. generator. The control fields of the rototrol are connected to be magnetically equal and opposite, when the A.C. generator voltage is normal. For this condition, the rototrol output voltage is maintained at the required value by its self-excited shunt and series fields. Now if the voltage rises or falls, the control fields adjust the rototrol as required to



(a) Opposed Control Fields



(b) Balanced Voltage Network With Single Control Field

FIG-2.

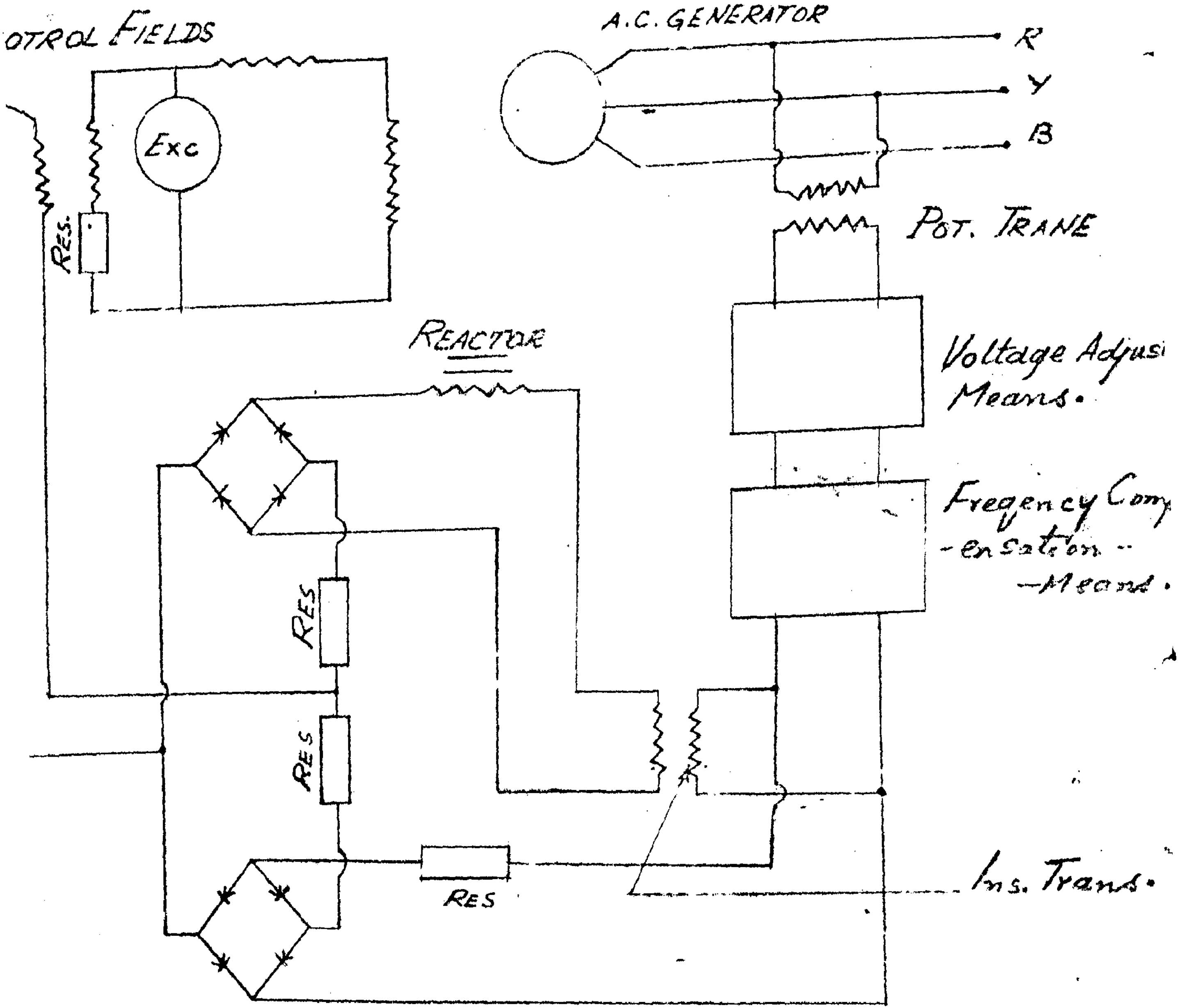
restore normal voltage. For such regulating circuits, there are means of raising or lowering the point of intersection of normal voltage, to permit adjustment of the value the regulator is set to maintain.

The same circuit can be used by eliminating the pilot exciter. The rototrol exciter has a relatively high amplification such that the output of A.C. generator field may be controlled by a small quanity of energy in the control field, as shown in Fig.1(b).

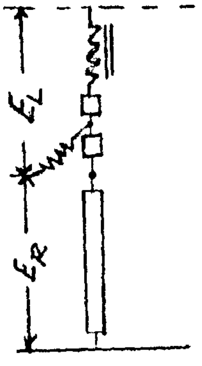
Other circuits are also possible. The normal voltage at the generator terminals is balanced against a reference voltage and the difference voltage whenever there is any alteration in the generator voltage from the normal is fed to rototrol fields. The reference voltage can be obtained from a separate D.C. or A.C. source, but usually a constant potential device is used, energised by voltage of generator with which the regulator is being used. The potential device is designed to provide constant alternating voltage at its output, irrespective of large changes in the input voltage.

In one of the circuit arrangements, the two control fields of rototrol exciter are connected to have equal and opposite magnetic effect when the A.C. generator voltage is at the required normal value as shown in Fig.2(a). Now if load is added to the generator, it will cause a drop of terminal voltage. Under such circumstances the raise field predominates and increases the rototrol armature voltage, thus restoring the alternating voltage to normal. Hence the rototrol control fields again reach a state of balance.

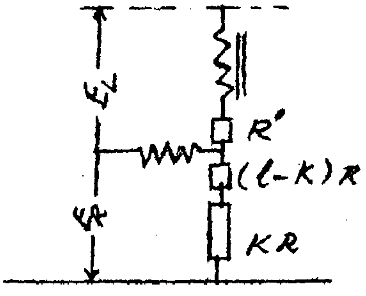
Another circuit has a single control field, which normally has no current flowing through it (refer to Fig.2(b)). Thus as long as the A.C. generator voltage remains at the normal value, there are no losses and no heating in this field. Thus we need a minimum of material in the frame of the rototrol, as losses and space for winding are less than if the two equal and opposite fields are used, which have to be energised continuously. Ordinary static regulators would have an excessive size and losses to be able to have adequate power. Thus we know the control field requirements.



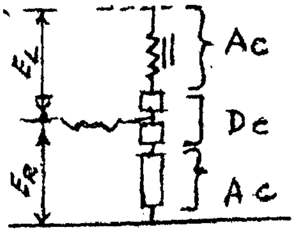
Regulating System, with Circulating Current Net Work



Over Voltage



(c) NORMAL VOLTAGE



(d) UNDER VOLTAGE.

INTRODUCTION.

NEW REGULATING CIRCUIT.

It is necessary to thoroughly analyse the design to get maximum energy output for a given voltage deviation for controlling generators having 1000 KVA or more capacity at 1200 RPM, where exciter air gaps are to be kept as small as for conventional D.C. generators.

We require average three phase or positive sequence voltage response, so the size should be enough to vary the large power of measuring circuit and this increases our energy requirements. In this method, the negative sequence voltage is deducted from the line voltage instead of filtering the positive sequence voltage directly.

Fig.3 shows the new arrangement having two branches; a resistor as the linear branch and a saturating reactor for the non-linear branch. The voltage across the saturating reactor remains nearly constant and fluctuations in voltage affect only the linear branch. This is explained fully in Chapter IV.

In order to find the most efficient design for this type of network, it was required to develop a method of calculating the power output from the network as a function of the parameters; resistance, reactance and control field resistance.

This improved regulating circuit for static regulators has long been superseded by Rotating Amplifiers or Rototrols of two or more stages, as these were found more economical and more efficient. A more recent type of arrangement for regulation is by the use of Electronic Exciters. These are more costly than Rototrols and hence have a limited use for A.C. synchronous machines, but they are more reliable.

Essentially they consist of Ignitron type power rectifiers fed from an A.C. Source. The advantages are elimination of moving parts, reduced maintenance, avoidance of failure of excitation as long as the main generator is generating A.C. and lastly by no risk of instability of the exciter system. By providing two ignitron tubes per phase and overload capacity for each tube, we can replace defective tubes without affecting the excitation of the A.C. generator. The details are given in the text.

v. Harmonic Excitation System.

This system uses the harmonic power developed in a generator for self-excitation. Power is collected by a separate stator winding and is controlled and rectified by a magnetic amplifier and silicon rectifiers. Tests show very rapid response to disturbances of the system.

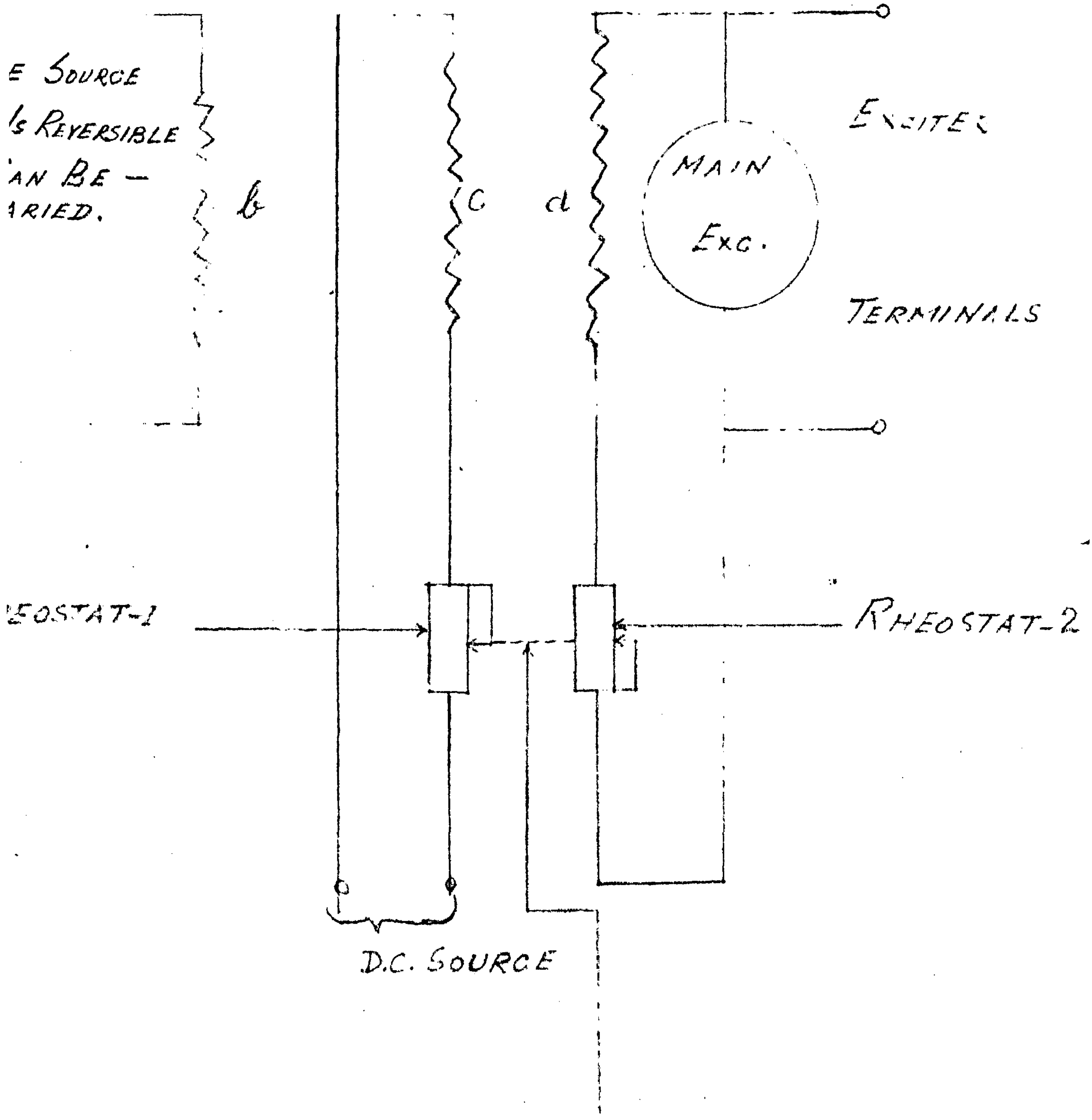
For steam turbine generators there have been several new excitation systems, in place of the conventional rotating exciters to eliminate their commutators which require high maintenance. Energy for such systems is obtained from the main generator terminals or from an alternator directly connected to the shaft of the main generator. The silicon rectifiers used in the new excitation system for converting the alternating to direct voltage are highly efficient.

The system considered offers all advantages of a static excitation system, but eliminates the disadvantages of high voltage insulation levels encountered in a Rotating A.C. exciter. Having proper static control equipment, the power can be controlled to match the generator excitation requirements for different loads and power factors.

vi. Excitation Systems for small Military and Aircraft Generators.

Prior to 1940, excitation for all automatically regulated generators was obtained by rotating exciters controlled mechanically by regulators. However in 1949, the improvement of square-loop core materials and selenium rectifiers made it practicable to use Magnetic Amplifiers in voltage regulators and excitation systems. Naturally the cost of these new systems was higher, so magnetic-amplifier regulators and exciters were used for Military and Aircraft purposes, but were not used for general purposes.

A reduction in cost of magnetic materials and the use of silicon rectifiers and other semiconductor devices have helped



Interlock Between Rheostat Arms

Fig I-1-Three Field Main Exciter.

in great progress in static excitation equipment. Now there is an increased use of these excitation systems for commercial applications on A.C. generators upto a capacity of 2000 KVA.

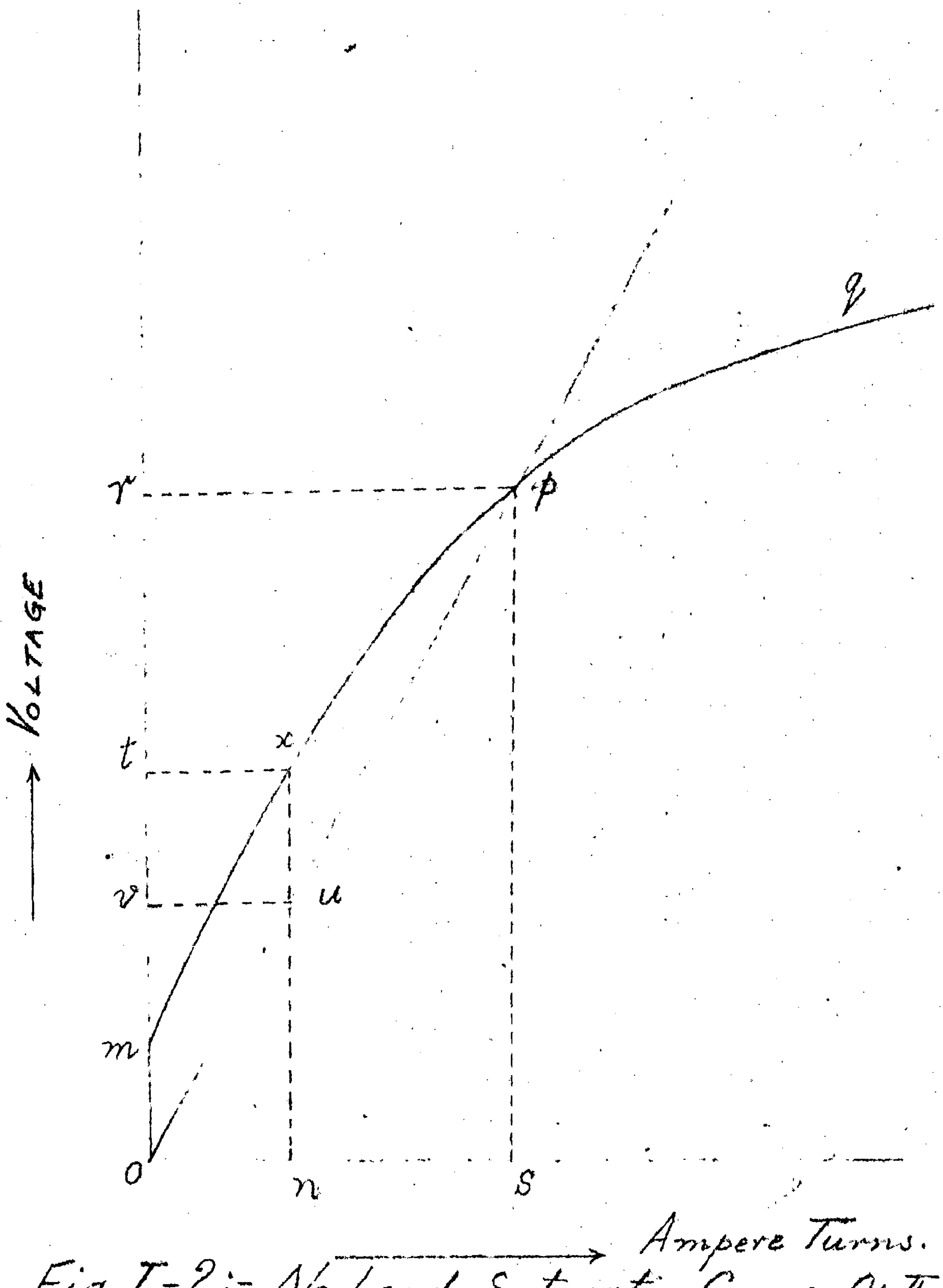


Fig I-2:- No Load Saturation Curve Of Three Winding Main Exciter Showing Effect Of - Stabilizing Field (c) With Field (b) Being Open-

CHAPTER I.

THREE-WINDING EXCITERS AND OTHER IMPROVED METHODS.

A three-winding main exciter is of usual construction as regards armature winding and mechanical details; but it has three shunt fields, which are electrically independent of one another as shown in Fig. I-1. The combination of field (a) and a rheostat in series are connected in parallel with the main terminals of the exciter, and operate in the same way as a self-excited field.

Field (c) is a separately excited shunt field which is supplied by some source of constant D.C. voltage, such as a battery. It can supply about 10 per cent of the excitation of the main exciter, and it is used to have stability at low voltages under hand control. This field is used when voltage range and speed of response make it desirable to do so. Field (b) is the third shunt field, and is excited from a Voltage Source, which is reversible and can be varied. It also gives stability of the exciter when the voltage regulator is controlling the voltage regulation. The rheostats in fields (a) and (c) are motor operated under manual control, the arms being mechanically coupled, so that as resistance is added in one circuit, it is removed in the other. When the self-excited field (a) is carrying a high current, the separately exciter field (c) carries a negligible current.

The combined effect is shown in the curve in Fig. I-2 where it is assumed that the current in field (b) is zero. If the rheostat is adjusted to give a voltage greater than OF, all the excitation is supplied by winding (a), and the total field ampere turns are shown by the curve pq. For this portion the operation is similar to that of a self-excited exciter. Now if the resistance of field (a) is increased to give ampere-turns less than Os, and it was the only field excited, then it would be unstable.

If we have to obtain a terminal voltage Ot which is less than Or, the resistance in the self-excited field would be increased to reduce the ampere-turns produced by that field to On. The ampere-turns On will generate a voltage Ov. Due to the connections, when the current in field (a) is reduced, the current in field (c) increases and the voltage generated due to field (c) is vt. Ampere-turns of the two fields and the generated voltages add up, so that Ot is the total terminal voltage.

As the current in field (c) is regulated by the amount of current in field (a) through the mechanical coupling of the two rheostats, we can plot terminal voltage as a function of the ampere turns of field (a) above and is shown by curve mnpq. On the same curve is plotted the field-resistance curve of the self-excited field, then the intersection point is positive for the resistance line and the saturation curve mnpq. Thus operation is stable for any voltage greater than Om, which is less than 10 per cent of the rated exciter voltage.

CHAPTER X.

THREE-WINDING EXCITERS AND OTHER IMPROVED METHODS.

To obtain smaller terminal voltage, the current is held at zero in the self-excited field (a), and it is reduced in the separately excited field (c). For reversing the polarity, both field circuits are reversed when currents are zero and increasing in the opposite direction. Hence we observe that manual control is possible for the complete range.

If a voltage regulator controls the voltage of the main exciter and varies the magnitude and polarity of applied voltage to the separately excited field (b), the mechanically operated field rheostat of field (a) circuit is set to give some base excitation. This setting is high enough to supply enough field current to the generator field to keep up steady-state stability. With such a setting of the rheostat when the generator is carrying load, the current in field (c) is negligible. Polarity and magnitude of applied voltage to field (b) are then regulated, such that the flux produced by field (b) either helps or opposes the flux produced by the base excitation of field (a). This will either increase or decrease the terminal voltage. As the effect of field (a) is that of an ordinary self-excited machine, a little input of energy to field (b) can control the output voltage over a wide range.

The three-winding main exciter has stable operation by separate means for the two operating conditions; namely, by a separately-excited stabilising field controlled manually and by the voltage regulator varying the input to field (b) under regulator control. Thus an advantage over the ordinary single-field separately excited main exciter this system has is that control of exciter terminal voltage is only partially lost if trouble should occur in the field circuit.

If there is a defect in the variable voltage source of field (b) or the regulator that controls it, the exciter will go on operating at a voltage depending upon the rheostat setting in the self-excited field circuit (c). The minor effect on the A.C. Generator would be a change in the internal voltage, thus causing a change in reactive loading of the machine. On the other hand such a failure in the single-field exciter would mean loss of excitation source for the A.C. generator field, and it would become necessary to shut-down the unit.

CHAPTER II.

SYSTEMS USING CROSS FIELD MACHINES.

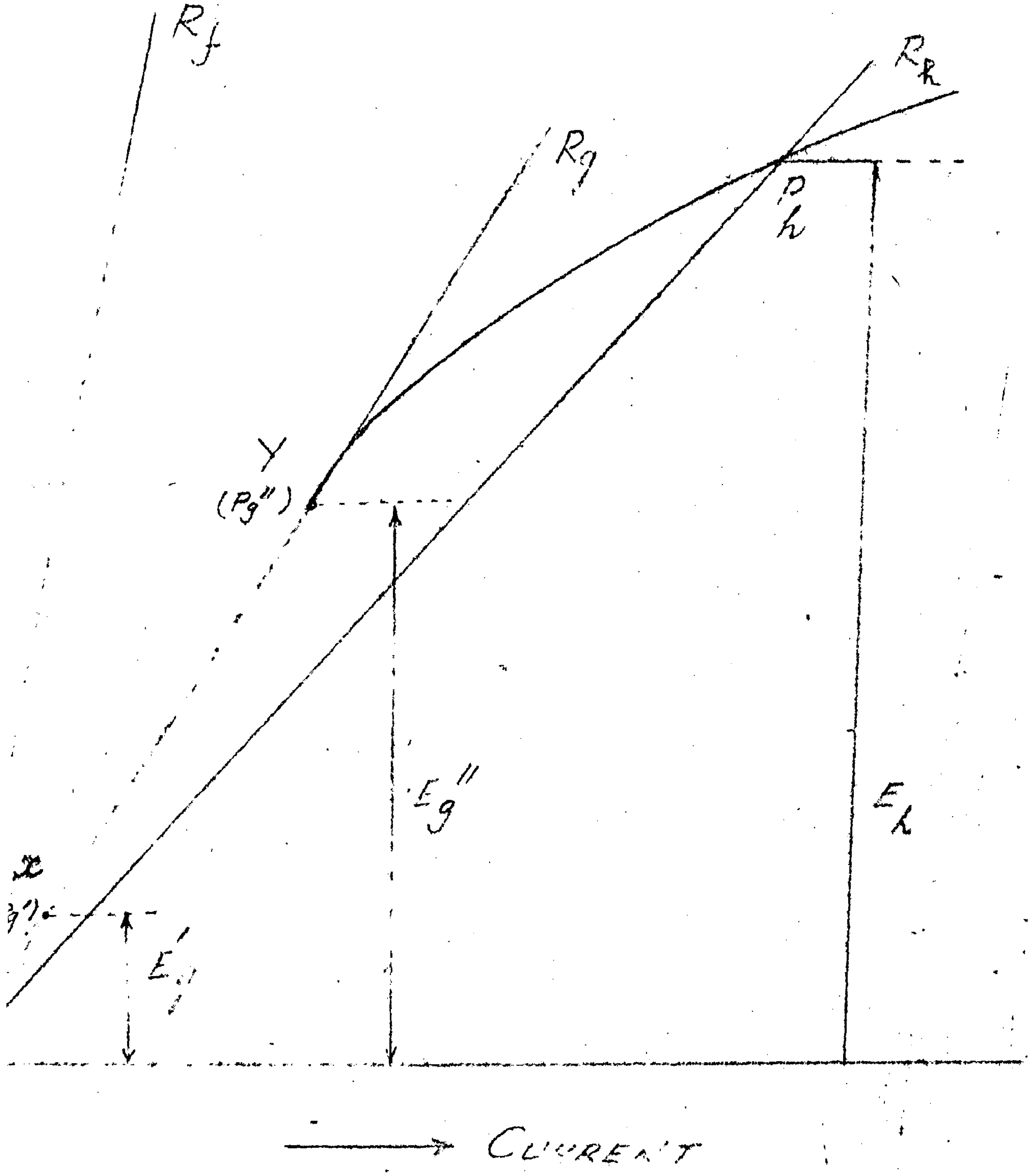
GENERAL.

Storage batteries are usually not used as exciters for large generators due to difficulties in finding space for the battery, for maintaining the charge and to keep the battery in good operating condition. D.C. Machines of conventional and special design are used as Main Exciters. These can be grouped into Rotating and Non-rotating D.C. Machines. A common form of rotating main exciter is the conventional D.C. generator.

The different earlier systems mainly depended on whether the D.C. generators were small or large and whether the power-station was hydro-electric or steam, and the two classes were either those with a common excitation bus-bar or having an individual exciter for each main generator. It was usual to energise the common bus-bars by D.C. generators driven by motors, turbines, steam engines or waterwheels. A battery was used as standby and had enough capacity to supply the full excitation requirements for one hour.

In any A.C. generator if there is loss of excitation it has to be removed from service; thus it is essential to have a reliable excitation source, and a lot of expense for this purpose can be justified. Main exciters of rotating type can be direct-connected or separately driven. The direct-connected type runs at the same speed as the main generator, being coupled to the main shaft. With a drive through a gear, one can run the two machines at different speeds for better performance. A separately driven main exciter is driven by a motor, and the combination is called an exciter m-g set. Alternatively it can be driven by a steam turbine or hydraulic turbine.

The prime mover which drives the A.C. machine being excited is the best prime mover for the main exciter. This arrangement is most reliable and being used since several years; although in the beginning for high-speed turbine generators, there was trouble in operation of the exciters of high speeds. At present direct connection of the main exciter is widely used, as special designs have been developed for operation at 3600 R.P.M.



II 1:- Building Up Voltage at Constant Speed.

CHAPTER II.

STEADY AND TRANSIENT STATE PERFORMANCE OF CONVENTIONAL D.C. MACHINES.

If R is any resistance in series with the armature and field winding in a series generator or the regulating resistance in the field circuit of a shunt generator, then

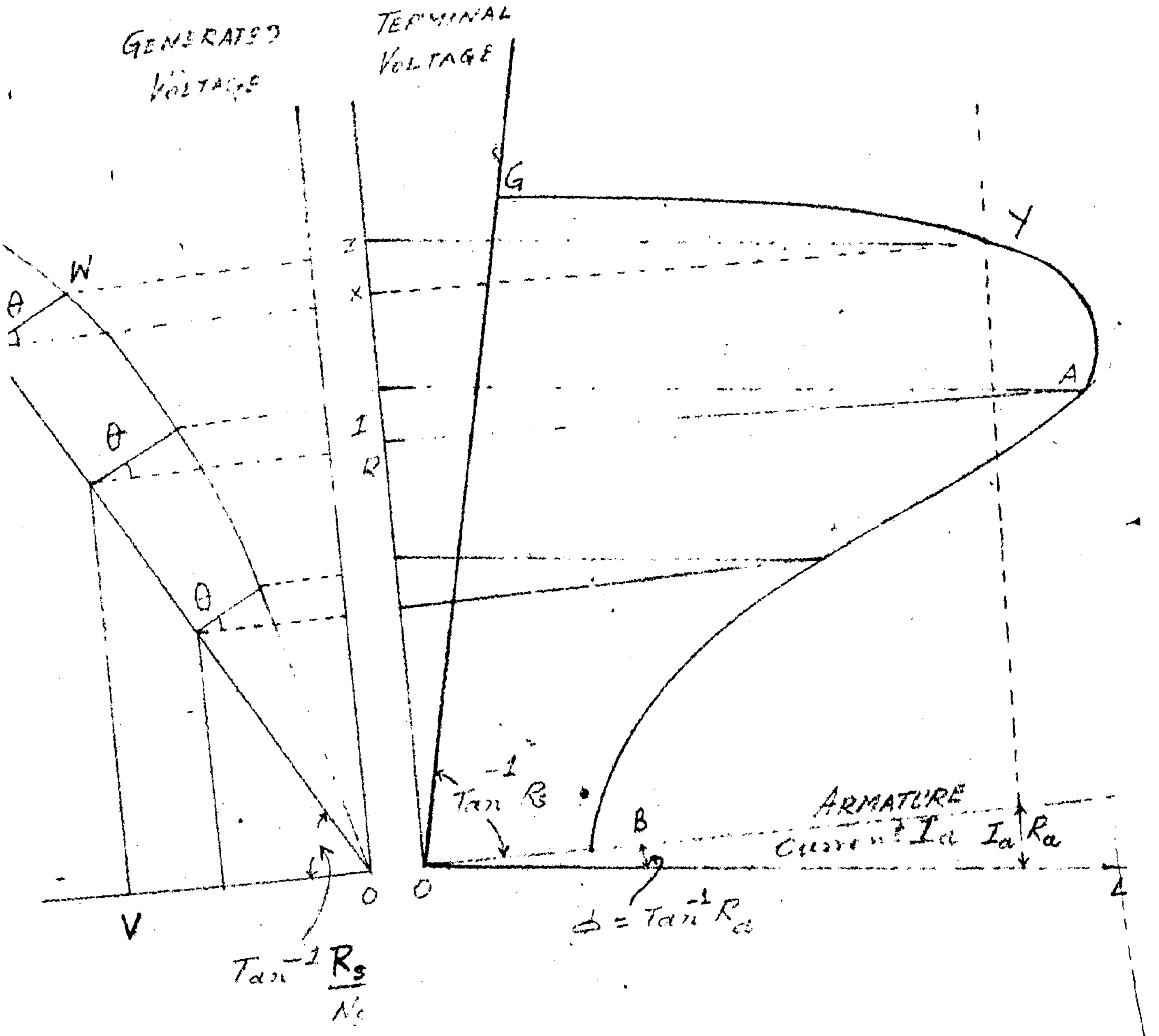
$$E = I\ R, \qquad (1)$$

where E is the generated E.M.F. and I the armature current, and this is the equation of a straight line through the origin as shown in Fig. II-1. Also

$$E = K\ (I) \qquad (2)$$

as the generator voltage varies directly with the armature current. This represents the saturation curve of the machine.

When the machine is operating, it should satisfy both the above equations, and these will be the values of E and I at the point of intersection of the curve and the straight line. The figure shows straight line R_g, R_β and R_h, the points of intersection being P_g, P_β and P_h. If R_g is high, the values of E and I at P_g are small and cannot be increased. The value R_β is called critical resistance and at this value of resistance for the straight line representing $E = IR$ will coincide with the straight portion of the saturation curve x and y. Here the resultant value



II-2:- Characteristics Of a Shunt Generator At Constant Speed.

of voltage and of current can be anything between x and y, or that the solution of equations (1) and (2) is indeterminate and operating conditions are unstable.

For a lower value R_h the generated voltage increased to E_h and at point P_h the operation of the generator will be stable. The condition for stability is that at the intersecting point, the slope of the saturation curve should be less than the slope of straight line representing the resistance of the circuit. Most often used are D.C. shunt generators and Fig. II-2 shows the curve P obtained from the magnetisation curve, and represents the relation between Ampere-turns and the terminal voltage V.

$$V = IR = \frac{R}{N_a} x (N_a I) \qquad (3)$$

Q is the point of intersection of curve P and straight line OR, and SQ represents the terminal voltage of the machine at no-load. When the machine is loaded.

$$I_a = I + I_{sh} \qquad (4)$$

(or Armature current = sum of load current and shunt field current).

and $$V = E - I_a R_a \qquad (5)$$

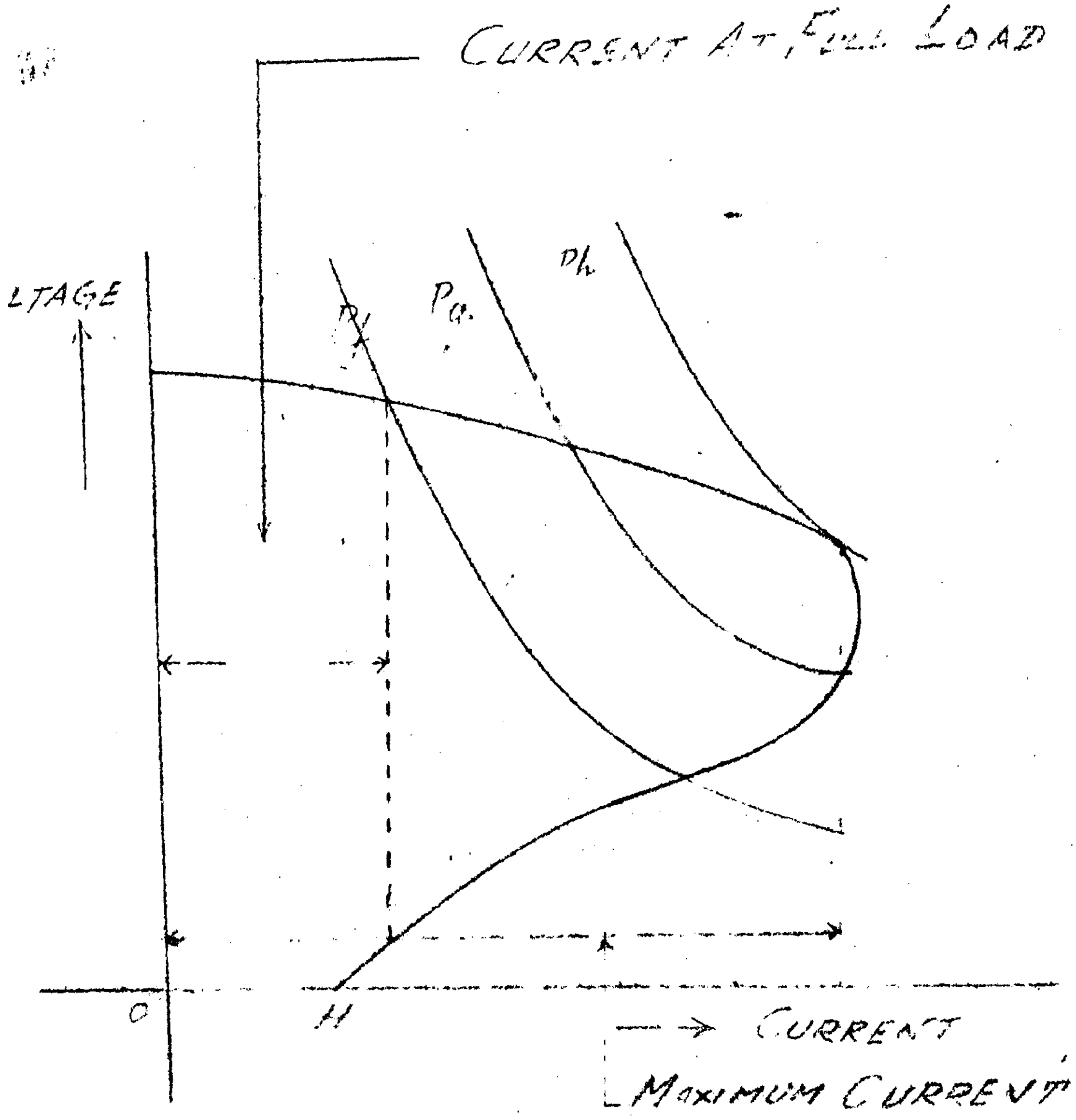
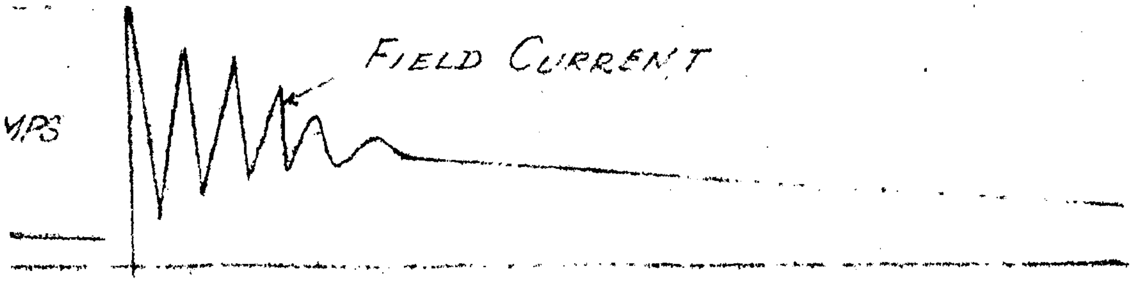


FIG I-3:- RELATIONSHIP OF POWER OUTPUT



GII-4:- Effect Of Three Phase Short Circuit At No Load On The Field Current.

Also, $$E_a I_a = V \times \frac{E_a}{R_a} . \qquad (6)$$

Now if the terminal voltage becomes TU, the field excitation is reduced to OT, and the net excitation to OV, the value TV is demagnetising ampere-turns per pole. The generated EMF corresponding to OV is VW = $I_a R_a$ drop. The armature current I_a is equal to XY. Draw ZY parallel to OL.

$$R = \frac{V}{I} = \frac{V}{(I_a - I_{sh})} . \qquad (7)$$

The curve GYAB on right hand side shows the characteristic between the terminal voltage and armature current, if speed remains constant. As I_a is sum of load current and field current, so to get value of load current the field current should be subtracted from the armature current.

The construction shown in Fig. II-2 has a shape altered by the shape of the saturation curve F. The machine operation will be stable, as long as the increase of armature current is more than the relative decrease in terminal voltage. Fig. II-3 shows a curve between the power output and current. As the output goes on increasing beyond P_h, a further fall of load resistance reduced the

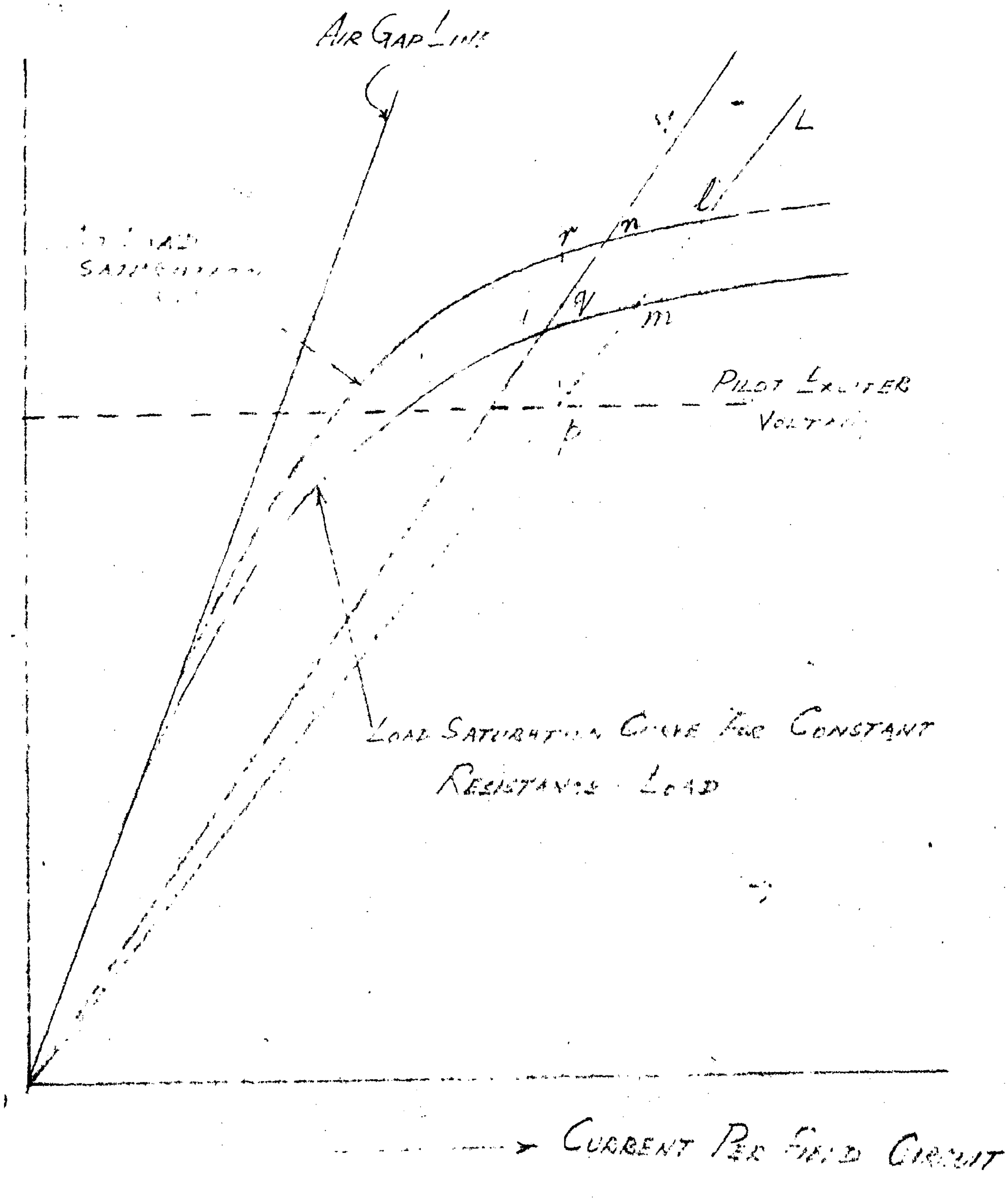


FIG II-5:- STEADY-STATE OPERATING POINTS FOR UNLOADED AND LOADED D.C. MACHINES.

output and operation will be unstable. The reason of instability from A to B is that for terminal voltage less than OR, the machine operates on the unstable portion of the magnetization curve. In a shunt generator, the rated full load current is less than the maximum current which the machine can deliver.

From the above discussion one can conclude that a sudden short circuit would have no consequences, as the current falls to a safe value soon after the maximum value. However a short-circuit would have heating effects and mechanical shock for the generator and the prime mover, for which circuit breakers and other protection are very necessary. The effect of short-circuit is depicted in Fig. II-4.

Main exciters can be either self-excited or separately excited. Referring to Fig. II-5, the curve only shows the no-load saturation curve of a D.C. generator that is being used as main exciter. For voltages less than nearly 75 per cent of rated generator voltage, all of the field current is used in forcing magnetic flux across the machine's air gap. A line drawn coinciding with the straight portion of the curve is called air gap line, and here the voltage varies directly with the field current.

Beyond the straight-line portion of the curve; with a given percentage increase in the voltage a greater increase in field current is required, and the voltage output is not directly proportional to the field current. The machine is saturated, and a greater portion of the field ampere turns are used in forcing flux through the magnetic circuit. Very often the field windings of the main exciter are divided into several parallel paths, and in this discussion the field current means that of one of the parallel paths.

For both self and separately excited exciters, the voltage is varied by changing the resistance of the field circuit. Line OL represents the field resistance line and is drawn so that its slope is equal to the resistance of the field, i.e. the ordinate at any point divided by the field current gives the field resistance.

At no-load, the intersection of the no-load saturation curve with the line OL gives the operating point l. Again for a certain constant resistance load for which line otm indicates the saturation characteristic, the operating point m is that where it intersects the line OL.

Now by inserting some resistance, if the resistance line is changed to OM, then the operating points are n for the no-load condition, and t for the constant-resistance load condition. Thus within limits, by changing the exciter field resistance, one can obtain any exciter voltage. If the field resistance is increased so that the resistance line coincides with the air-gap line, then the output voltage can be established at any value from zero to the point where the no-load saturation curve begins to bend away from the air-gap line. In this region the operation is unstable unless additional means are used for stabilizing it.

However if the machine is separately excited by the pilot exciter, the field current of the exciter is found by the intersection of the resistance line with the pilot-exciter voltage line. Looking at Fig. II-1, it is noted that this point is p. The terminal voltage for no-load is at point r and for constant-resistance load at point q.

CHAPTER II.

PERFORMANCE OF SYSTEMS WITH CROSS FIELD MACHINES.

Let us briefly compare the above discussion with the performance of a cross-field machine, the details of the different arrangements and the improvements being given in Chapter III. The equation for a cross-field machine is

$$V_1 = \frac{k_a k_f}{R_q R_f} V - \left[\frac{k_a k_l}{R_q} (1 - C) + R_1 \right] I_1 \qquad (8)$$

or

$$V_1 = KV - \left[k_c (1 - C) + R_1 \right] I_1 \qquad (9)$$

where V_1 is the output voltage, V is the input voltage, K terms are constants and R terms are resistances for field, load and quadrature arms, C is the percentage of compensation, I_1 is the load current, and we have substituted

$$K = \frac{k_a k_f}{R_q R_f} \qquad \text{and} \quad k_c = \frac{k_a k_l}{R_q}$$

From equation 9, the load curve with no saturation is a straight line of which KV is the no-load voltage and the change of voltage varies with the load current. When 100 per cent compensated or C = 1, the curve is similar to that for a conventional

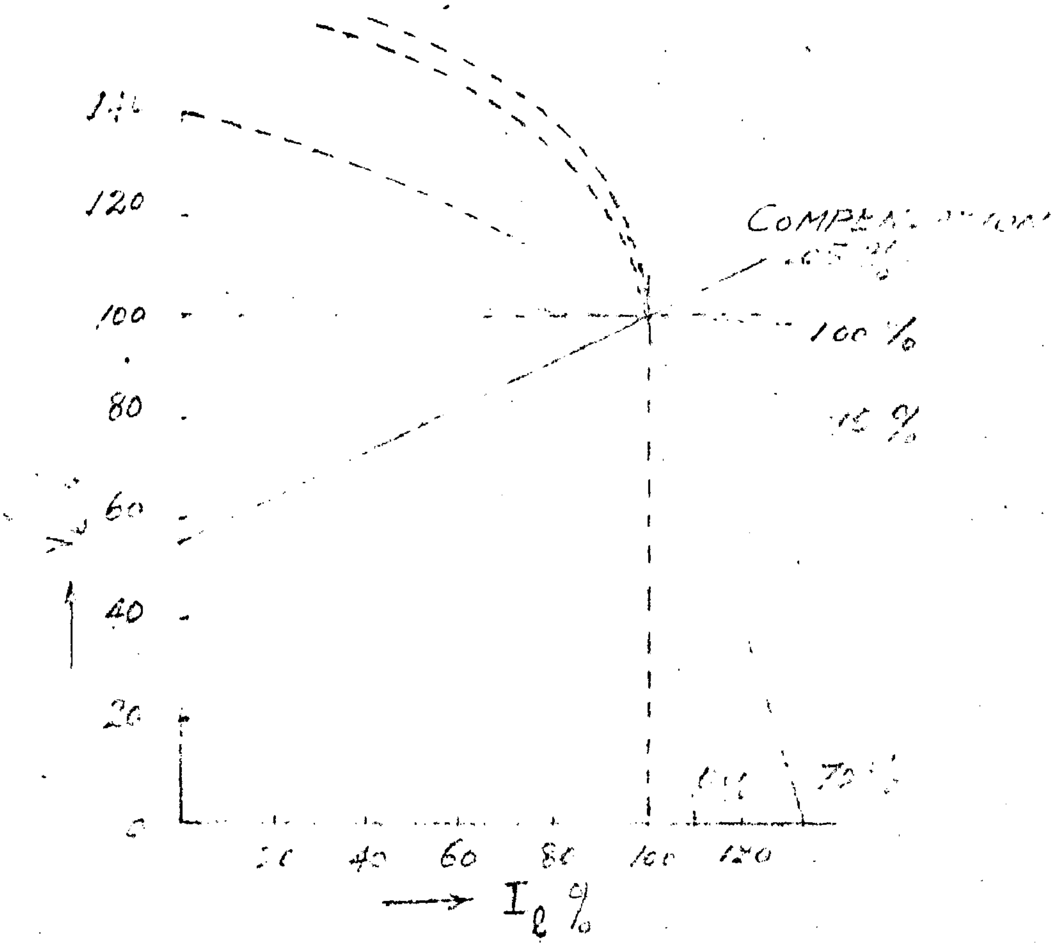


FIG II-6 :- Effect Of Degree Of Compensation On Load Of A Cross Field Generator separately excited D.C. generator, the voltage being nearly constant as shown in Fig. II-6. Such a generator has a constant Voltage characteristic. This acts as an amplifier. The ratio of output voltage to input voltage to field circuit being K, and is known as Voltage Gain.

The output can be controlled by varying the field voltage, but for a given field voltage the output voltage is nearly constant at all loads. Due to compensation there is no interference of load current with the flux set up by the field current, and the amplidyne is a combination of two generators, even on load. The ratio of power output V_1I_1 to the power input VI_f is called power Amplification Ratio, and can be as large as 20,000 for a fully compensated machine.

However it is necessary to know the behaviour of any control system under transient conditions, when the voltages and currents vary with time in any way. So we shall consider instantaneous values and rewrite the equations. For a fully compensated machine we have,

$$v = (R_f + L_f\, p)\, i_f \,, \qquad (10)$$

where $p = \frac{d}{dt}$, similarly

$$v_q = k_f\, i_f = (R_q + L_q\, p)\, i_q \tag{11}$$

$$v_l = k_q\, i_q = (R_l + L_l\, p)\, i_l\,. \tag{12}$$

If we eliminate i_f + i_q from the above equations, we get

$$v_l = \frac{k_f\, k_q}{(R_f + L_f\, p)\,(R_q + L_q\, p)}\, v - (R_l + L_l\, p)\, i_l. \tag{13}$$

To combine the above equations of an amplifying generator with other components of a control system, the resistance and inductance of load circuit are included in those of circuit to which connected and the internal voltage v_o is treated as the output voltage.

$$v_o = v_l + (R_l + L_l\, p)\, i_l\,. \tag{14}$$

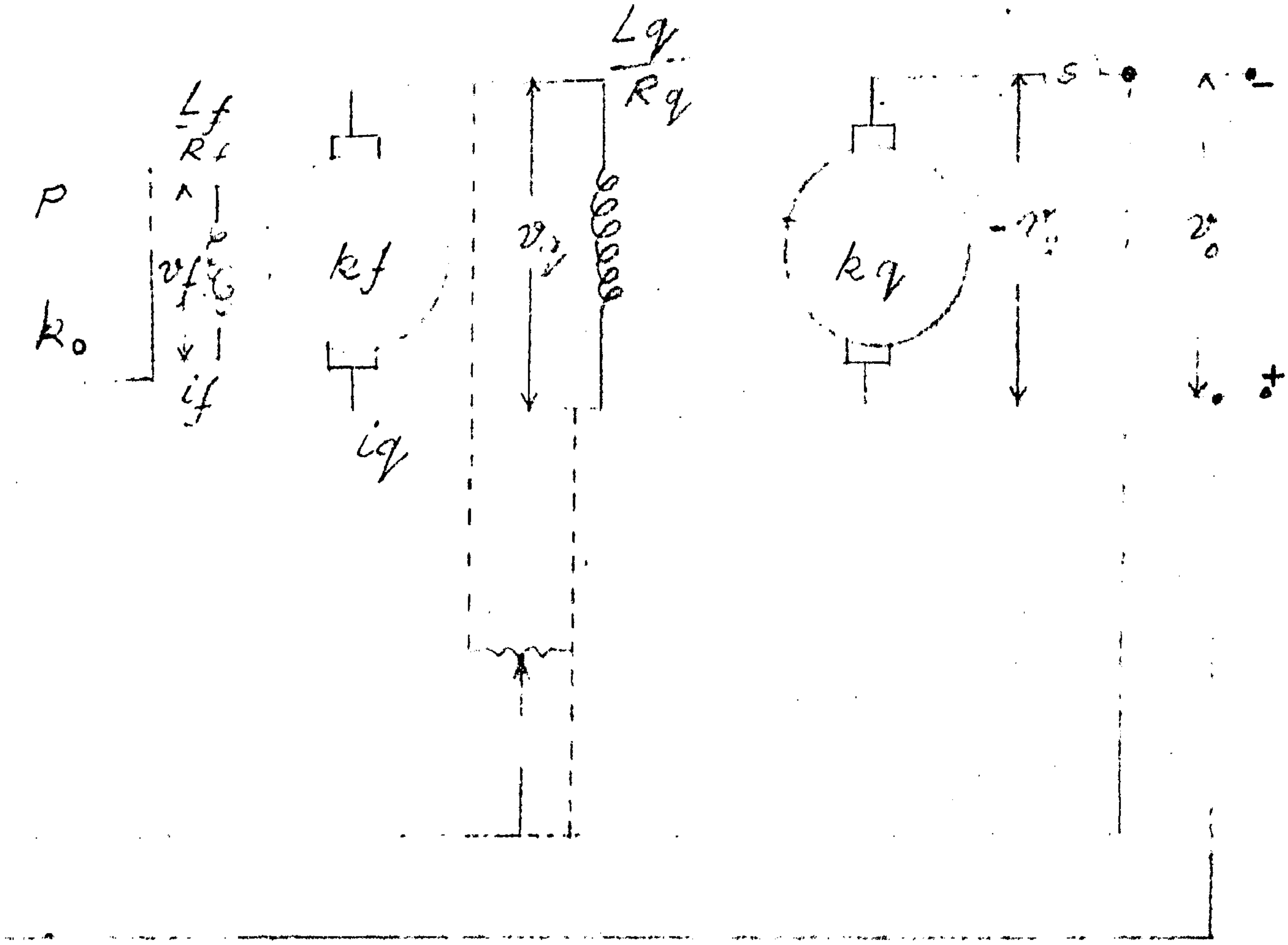
The transient equation of a fully-compensated amplidyne can be written as

$$v_o = \frac{K}{(1 + T_1\, p)\,(1 + T_2\, p)}\, v \tag{15}$$

where K is the voltage gain or voltage amplification ratio

$T_1 = \frac{L_f}{R_f}$ is time constant for field circuit

$T_2 = \frac{L_q}{R_q}$ is time constant for quadrature circuit.



II-7:- Automatic Voltage Regulator Using a Rotating Amplifier And Preamplifier.

CHAPTER II.

THEORY OF THE CLOSED LOOP SYSTEM.

The circuit is shown in Fig. II-7 where P is an amplifier having a voltage amplification of k_o, and a voltage S is supposed to appear in the circuit in series with the output v_2. If we ignore the effect of dotted portion, the equations are -

$$e = v_1 - v_o \, , \tag{16}$$

e being the error voltage and v_1 the desired voltage.

$$v_g = k_o e \, . \tag{17}$$

Also $$v_g = i_g R_g + L_g \frac{di_g}{dt} \, , \tag{18}$$

and putting $p = \frac{d}{dt}$,

$$v_g = (R_g + L_g p) \, i_g \, . \tag{19}$$

The generated E.M.F. of the quadrature circuit is given by

$$v_q = k_g i_g = (R_q + L_q p) \, i_q \, . \tag{20}$$

CHAPTER II.

THEORY OF THE CLOSED LOOP SYSTEM.

Generated E.M.F. on the main axis is given by

$$v_2 = k_q \, i_q \, . \tag{21}$$

From the equations 18 to 21, we get

$$v_2 = \frac{k_f \, k_q}{(R_q + L_q p)\,(R_f + L_f p)} \, v_f \, . \tag{22}$$

This can be expressed in the form of time constants as before.

$$\therefore \quad v_2 = \frac{K}{(1 + p\,T_1)\,(1 + p\,T_2)} \, v_f \tag{23}$$

where $K = \frac{k_f \, k_q}{R_f \, R_q}$ being the voltage gain factor

and $T_1 = \frac{L_f}{R_f}$ and $T_2 = \frac{L_q}{R_q}$.

Again $v_o = v_2 + S$ (24)

CHAPTER II.

THEORY OF THE CLOSED LOOP SYSTEM.

From equations 16, 17, 23 and 24 we get

$$V_o = \frac{K k_o V_1 + S (1 + pT_1)(1 + pT_2)}{(1 + pT_1)(1 + pT_2) + K k_o} . \qquad (25)$$

In the case of steady-state = o, and if V_1, V_o and S are steady-state values

$$V_o = \frac{K k_o V_1}{1 + K k_o} + \frac{S}{1 + K k_o} \qquad (26)$$

But the gain factor $K k_o$ is much greater than unity, and hence

$$\therefore \quad V_o = V_1 + \frac{S}{K k_o} . \qquad (27)$$

The feedback in the Amplidyne is also used for improving the transient response. From equation (25) we see that the effect of an unwanted E.M.F. like S can be made negligible. To simplify further, we will put $S = 0$. Thus as a function of time, the equation becomes

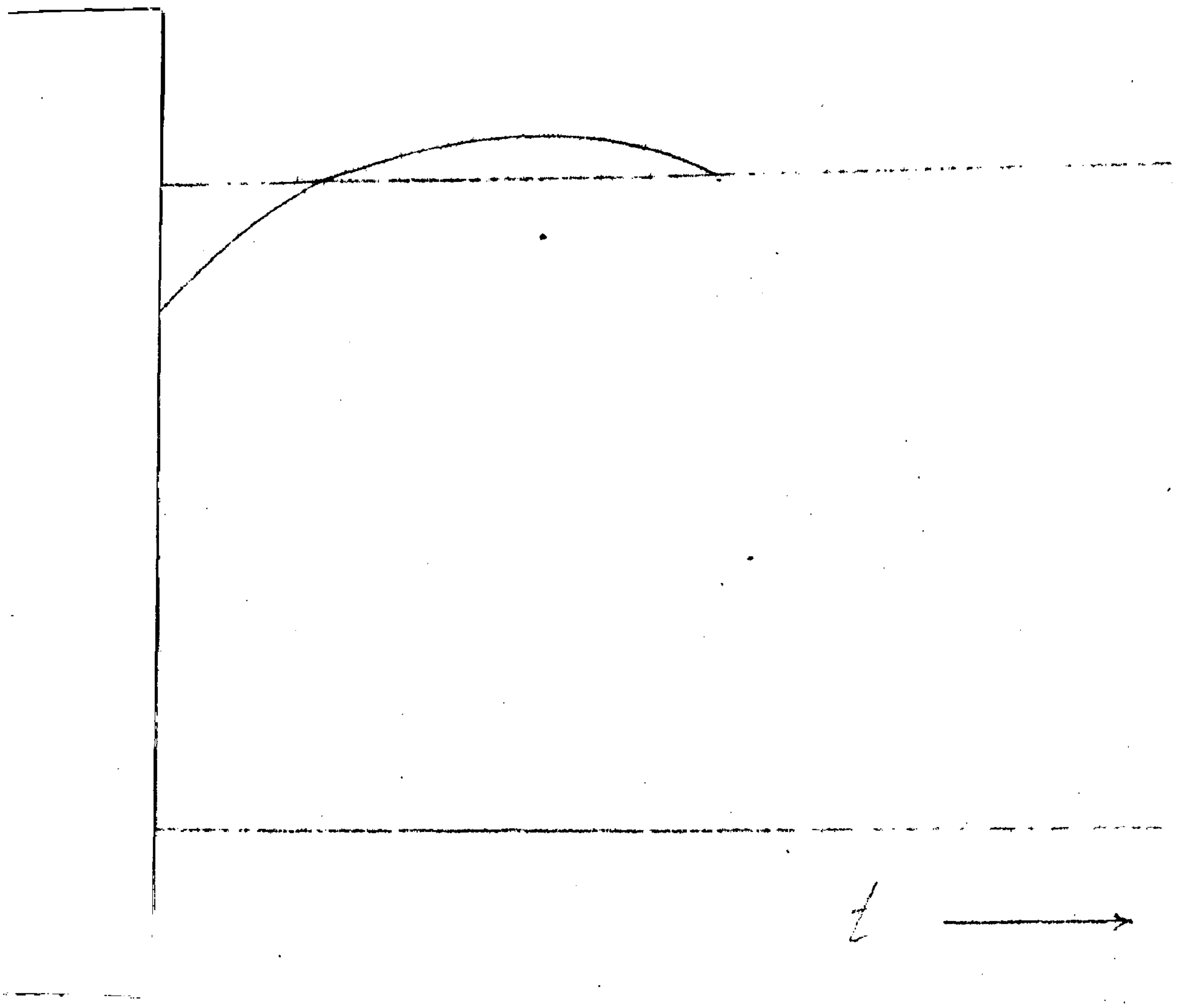


FIG II-8 :- Step Function Input Disturbance And Damped Response Of Output Voltage

$$v_0 = \frac{\frac{K\,k_0}{r_1 r_2}}{2 + \left(\frac{1}{r_1} + \frac{1}{r_2}\right) + \frac{1}{r_1 r_2}\left(1 + K\,k_0\right)}\; v_1 \qquad (28)$$

Suppose that we make a sudden change in the voltage v_1, and make a unit function change in v_1. The arbitrary value of v_1 becomes v_1 1.

Fig. II-6 shows the step function. The system is supposed to be in equilibrium at $t = 0$, and v_1 is the change in voltage level and not the actual voltage of the rheostat at time zero.

Let Z (p) be the denominator of R.H.S. of equation No.28, then the roots of Z (p) = 0 will show the nature of the response. The value of v_0 as a function of time can be found by using expansion theorem.

If $$\left(\frac{1}{r_1} + \frac{1}{r_2}\right) = 2\beta\,,$$

$$K\,k_0 = M$$

$$\omega_o^2 = \frac{1}{T_1 T_2}(1 + M),$$

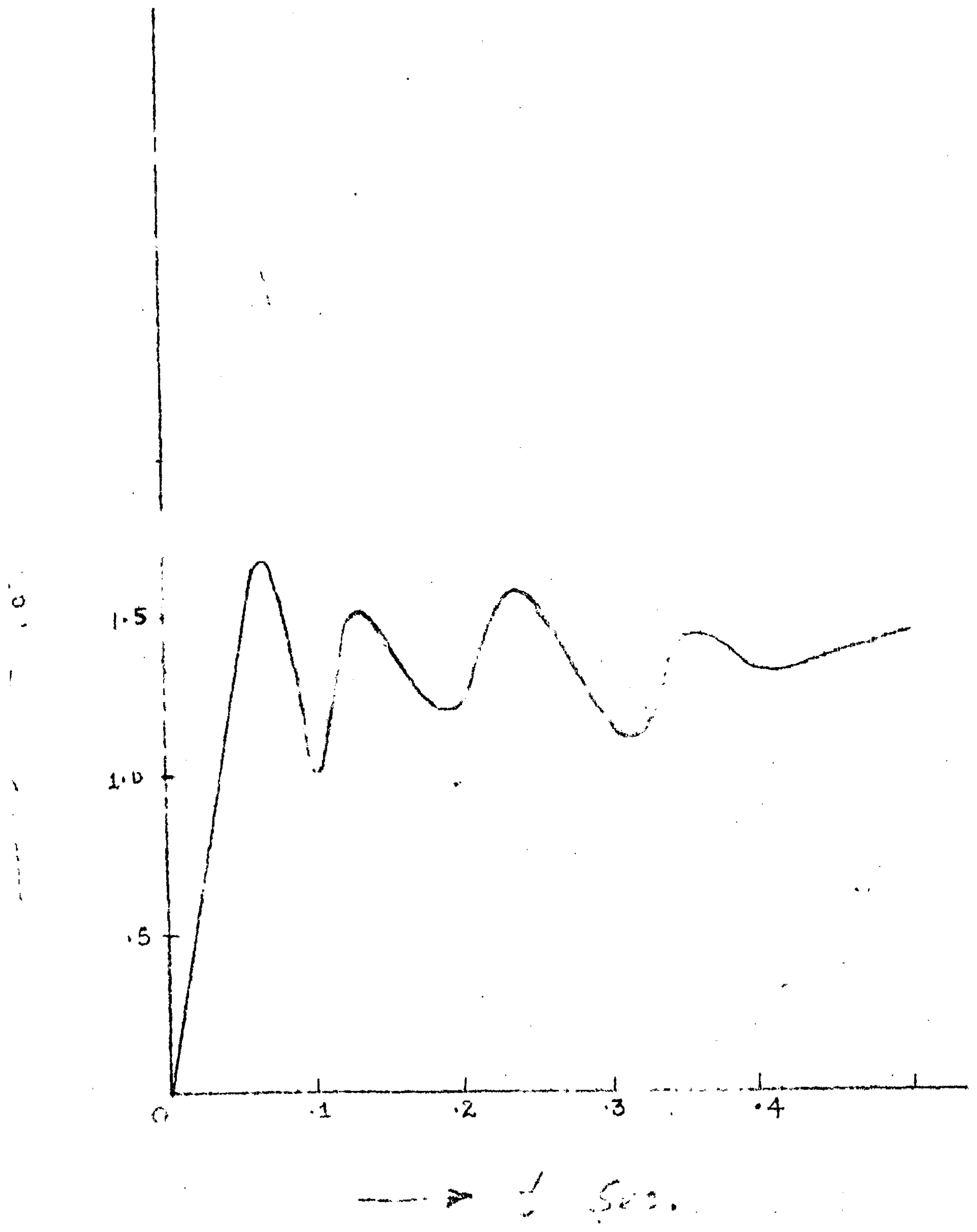
$$\omega^2 = \omega_o^2 - \beta^2 ,$$

and $\tan N = \frac{\omega}{\beta}$.

Then $$v_o(t) = \frac{M}{1 + M}\left[1 - \frac{\omega_o}{\omega} e^{-\beta t} \sin(\omega t + N)\right] v_1 . \qquad (29)$$

Taking an example of an amplidyne generator 10 KW 1500 R.P.M. the time constants are $T_1 = 0.25$ sec., $T_2 = 0.1$ sec. The value of the total gain M would be selected to meet the steady-state accuracy if the arrangement of Fig. II-7 is to function as a source of controlled voltage. For an accuracy of one per cent, a value of M = 100 should serve our purpose.

$$\therefore v_o(t) = \frac{100}{100 + 1}(1 - e^{-7t} \cos 63t) \text{ Nearly} . \qquad (30)$$



ig. II-9 Typical Voltage Response Of A System.

CHAPTER II.

THEORY OF THE CLOSED LOOP SYSTEM.

Fig. II-8 shows the recovery curve for this system, and it is found to be oscillatory. In due course the oscillations will die out, but there is no reasonable degree of damping. The first oscillation is much beyond the desired voltage, but the recovery is observed to be more rapid than from a generator without feed-back. It is noted that the equivalent time constant of the machine is the sum of T_1 and $T_2 = 0.25 + 0.10 = 0.35$ sec., while the rate of recovery from equation (30) is $\frac{1}{7}$th second. It is our aim to add stabilising networks such as shown in the above example, but several such trial and error methods would be lengthy and should be avoided.

Recovery shown by equation (30) is unsatisfactory because the oscillatory component is observed to have a frequency of 10 cycles per second being high compared with β, the logarithmic decrement factor of $\frac{1}{7}$th second. Oscillations would not exist, if the roots were real, or which means that the oscillatory term is absent. In any equation $Z(p) = a^2 + b + C = 0$, the limit for real roots is found by putting $b^2 = 4ac$.

Hence recovery will be just aperiodic if in equation (26) we put

$$\left(\frac{1}{T_1} + \frac{1}{T_2}\right)^2 = \frac{4}{T_1 T_2}(1 + K\mu_0) , \qquad (31)$$

then ratio of time constants is $r = \frac{T_1}{T_2}$ and $r > 1$, it can be shown that

$$r + \frac{1}{r} + 2 = 4\,K\,k_0 \,, \tag{32}$$

or very nearly

$$K\,k_0 = \frac{r}{4} \,. \tag{33}$$

So with a simple feedback loop the allowable total gain is limited by the ratio of time-constants r, and in practice a value greater than r should be selected.

Very often a negative feedback is connected with an amplidyne to give a more linear output and to lessen saturation and hysteresis effects. However these benefits are a limit to the total gain round the loop, to reduce oscillations. Thus we see that accuracy of control of output needs a higher gain in the system than provided by a simple feedback loop, because of its tendency of self-oscillation. In a case where the arrangement shown in Fig. II-7 has three exponential time-lags, oscillations of higher amplitude would be probable. These exponential time-delays are one cause of instability in a closed-loop system.

CHAPTER II.

STEADY-STATE ERRORS.

Referring to Fig. II-7 we will discuss the error e. Assuming linearity it is observed that in the steady-state the error e varies according to the output voltage v_o. From equations (17) and (22), after ignoring the voltage S we have

$$v_o = \frac{k_a k_f k_g}{R_f R_q} e \qquad (34)$$

Here e is steady-state error which changes according to the magnitude of the output quantity . This is allowed in industrial type regulator such as automatic voltage regulators and speed regulators, but is not tolerated for a remote angular positioning system.

The output can be made to vary according to the time-integral of the error,

$$\theta = \theta_i - \theta_o , \qquad (35)$$

where θ_i is the input and θ_o the output. Now ignoring exponential time lags,

$$\theta_o = C \theta . \qquad (36)$$

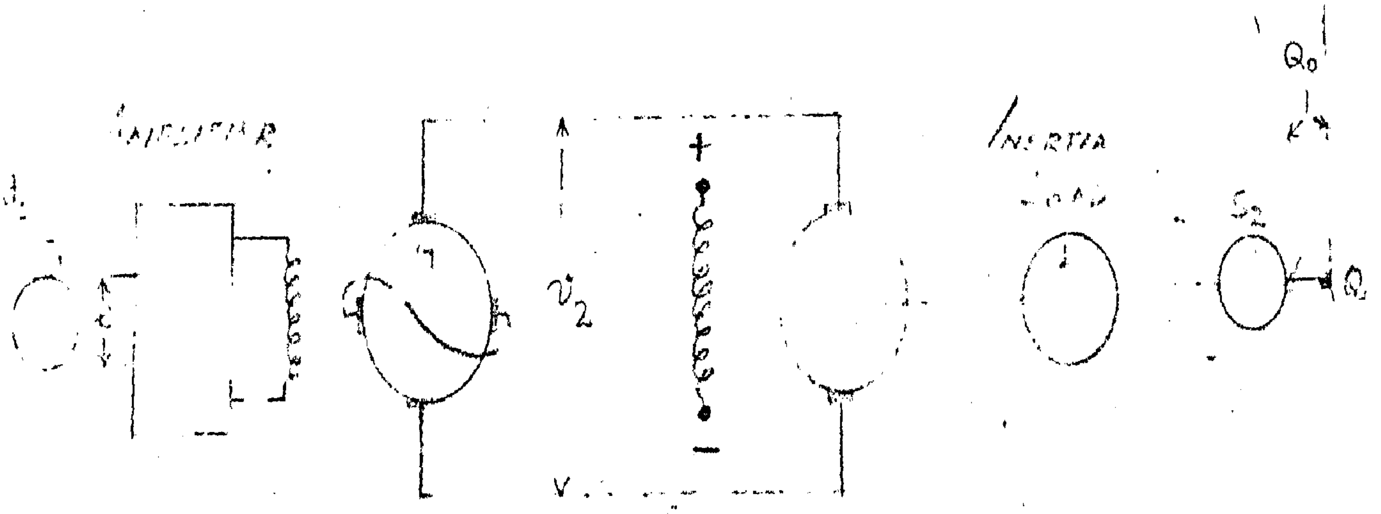


Fig II-10:- Remote Control Servomechanism Circuit

Assuming the output to be dependent on the integral of error,

$$\theta_o = C\int_0^t \theta \, dt \, . \qquad (37)$$

In order to equate θ_i and θ_o, there will be some t_1 at which this may occur. At such a moment θ will be zero.

In Fig. II-10 an elementary form of a remote controlled servomechanism is shown. S_1 and S_2 are position measuring devices such as selsyns, so connected that the signal voltage e varies according to the difference in alignment between the shafts P and Q. Hence e is proportional to θ .

The signal e is amplified by an amplifier which excites the cross-field generator CF. CF supplies armature power to the D.C. Motor M, which drives the output shaft Q. As a simplification we are ignoring time lag effects in the amplifier and cross-field generator. The terminal voltage v_2 of the generator is proportional to the error signal e, and hence also to θ .

In this figure v_2 is not the output, and we should consider the equation for the motor. A D.C. servo-motor has constant field excitation and if inertia is neglected, one can assume the output speed S_o to be proportional to v_2.

$$\therefore S_o = F v_2 \qquad \text{and} \qquad v_2 = G\theta.$$

Also $$S_o = \frac{d\theta_o}{dt} = p\theta_o . \tag{38}$$

Comparing equations (36) and (38),

$$p\theta_o = C\theta ,$$

where the constant C combines the different system constants. From the above and equation No.(35),

$$\theta_o = \frac{C\theta_i}{p+C} . \tag{39}$$

The transform of this equation is known to be as follows, after a step change of θ_i:-

$$\theta_o\ (t) = (1 - e^{-Ct})\ \theta_i. \tag{40}$$

CHAPTER II.

STEADY-STATE ERRORS.

Owing to the assumptions made, the output shaft changes according to changes of input shaft, and in the end the error becomes zero. An input shaft velocity gives the same velocity in the output shaft, which lags the shaft P at an angle proportional to velocity. With one exponential time lag one gets a quadratic equation in denominator of equation (39), and similar to the case of equation (25) the recovery would have oscillations.

For a Remote Controlled system with high accuracy, such as the one shown in Fig. II-10, we want the system to have negligible velocity errors by providing an acceleration of output for an error in alignment. Approximately the generator armature current is proportional to error.

Motor torque $T = C'\theta$

and $$T = C'' I \frac{d\omega_o}{dt} = C'' I p^2 \theta_o \,.$$

when the torque is assumed mainly to accelerate the output shaft.

Putting C instead of C', C'' and moment of inertia I,

$$C\theta = p^2 \theta_o \tag{41}$$

$$\therefore \ \theta_o = \frac{C}{p^2 + C}\theta_i \,. \tag{42}$$

which after a step change θ_i gives us

$$\theta_o(t) = (1 - \cos\sqrt{C}\,t)\,\theta_i. \qquad (43)$$

From physical considerations the expected continuous oscillations exist at the new output shaft position.

Considering design aspect, the assumptions made in the above discussion are not permissible, but they have shown certain indications as follows:-

i. The system depicted in Fig. II-7 has an error varying according to changes of the output from a given datum, and at least two exponential time-lags are required to result in oscillations after any disturbance.

ii. The velocity-error system shown in Fig. II-10 has error varying according to the input velocity, and requires only one exponential time-lag effect to result in oscillations.

iii. The acceleration-error system shown in Fig. II-10, has error varying according to steady input acceleration, and does not require any time-lag effect to result in oscillations.

It can be concluded that the error can be reduced or even eliminated, but this is possible at the expense of more tendency to instability. Also ways are to be found to obtain error time-integrals for different systems, for which a practical method is the use of a cross-field generator.

CHAPTER III.

ROTATING AMPLIFIERS OR ROTOTROLS.

GENERAL.

The first system using rotating machines for regulating or controlling purposes was made by Westinghouse in 1932, and later generators of this type and the allied circuits were called Rototrols. The Rototrols have been used with one stage of amplification for several years, but in some recent applications the control energy available was found too small for satisfactory regulation.

The development of the 2-stage Rototrol uses only one machine, and the simplest construction is a 4-pole machine. It is a conventional generator except for the field coils and armature connections. The machine may also be considered as three generators superimposed on one another, although the output of only two may be used. Tests on such designs showed high-sensitivity and response, and it provided a generating element for such systems requiring a very low control energy.

The use of Rotating Machines for controlling the excitation made engineers use the name 'Rototrol' for all such arrangements. They give satisfactory performance and are used in all industries where electric machines are employed. To control any system, it is necessary to measure the output and compare it with a predetermined standard.

CHAPTER XXI.

GENERAL.

The system should provide necessary action to correct the output when any variation occurs; and also cancel any action when the correct output is obtained. These features are introduced into a Rototrol generator by additional windings on the field magnets. If this comparison between the output and the standard is made inside the machines, separate windings are used for each intelligence, and they are called pilot and standard fields.

If comparison is made externally, then only one field called the control field is required. Here when the output does not match the standard, a net excitation will exist, and this is used to initiate the required correction. Again when the output is correct, there is no net excitation resulting from the control energy, and so no action is initiated.

We observe that the pilot and standard intelligences give us a means of causing the Rototrol to change its output. At the correct output, these would neutralise each other, and the net resulting output would be zero, so some other way is required to maintain the output. This is done by a self energising field of shunt, or series type, or a combination of shunt and series types, which is so designed that it has a sufficient strength to supply the necessary excitation to generate sufficient voltage to sustain itself. This is possible over the range where the saturation curve is a straight line, and hence the operation of these machines is limited to the air gap portion of the saturation curve.

The above details show the general principles for design of Rototrols. For some applications one requires an output of Rototrol which is proportional to the control energy. In such cases, self-excitation is used. The generators use conventional parts except for field coils, and use of special treatment of materials in the poles and frames. For a few applications, additional amplification is required. One way is the use of electronic equipment to amplify the control energy to provide control input for the Rototrol, and also have regulating and anti-hunting devices.

For other applications, two Rototrol units are used in cascade, or the best method of handling regulating problems is to design a single 2-stage Rototrol, which gives similar results.

Consider a 4-pole generator having a multiple armature winding without equalizer connections. Stator is similar to a conventional 4-pole generator except that no brush arm-cross connections are used, and the field windings are connected in a different manner. If the main poles of a generator with multiple windings have unequal field strengths a potential difference is set up, due to which currents flow in the winding and balance the flux from all poles. When equalizers are not being used,

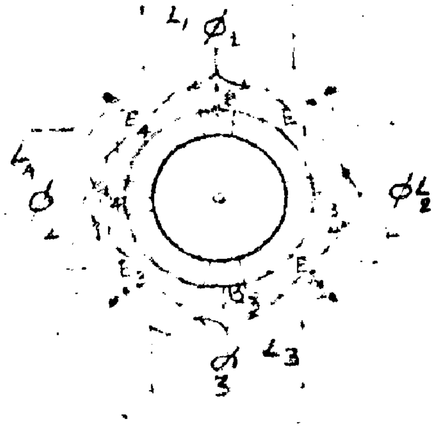


Fig. III-1 [illegible] and

[illegible]

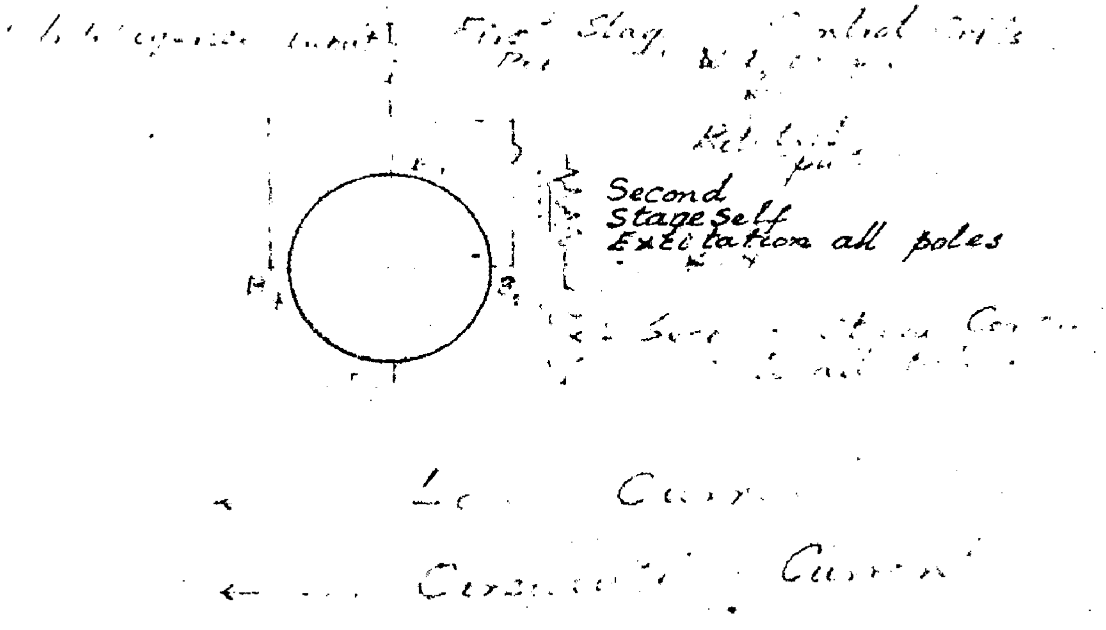


Fig. III-2 [illegible] Circuit Diagram

[illegible] Stage [illegible]

these correcting currents flow through the brushes and brush holder cross connections. This condition is intentionally set up in the 2-stage Rototrol.

The two north poles L_1 and L_3 in Fig. III-1 are unbalanced by current flow in the control coils which are only on these poles, and connected in such a manner that one is strengthened and the other weakened. If brushes B_1 and B_3 are connected, a heavy current will flow, this being a connection between points of equal potential and not a short circuit. This cross-connection between B_1 and B_3 is opened and the circulating current forced to flow through the exciting windings of all main poles. The coils are so used that generator voltage is built up and they form the excitation circuit of the second stage.

This circulating current through the armature and forcing coils produces a M.M.F. to balance the excitation from the control coils, and is not required. So compensating and opposing windings are added to the machine, which are simply corrective. The compensating coils are placed on the same axis as the armature M.M.F. and carry the same current which sets it up. Opposition coils are also placed on the axis of M.M.F., but they have the current produced by it and the resulting flux. Thus they try to suppress the M.M.F. but not completely, as their excitation depends on its existence and the resulting flux.

The mid-points of set B_1B_3 and B_2B_4 are used as output of the armature of second stage. Main fields are connected in the normal way, and the machine terminals to the field of the machine which it is used to excite, and acts as the load.

CHAPTER III.

PRINCIPLE OF THE STAGE ROTOTROL.

As mentioned earlier, if the poles of a multiple winding armature have unequal field strength, potential differences are set up in the armature. Equations can be written for the voltage generated. Fig. III-1 shows a machine of this type. Conductors shown outside the armature circle indicate top conductors in slots, and those shown inside the circle are bottom conductors.

While writing the voltage equations, polarity of the flux should be considered. It should also be kept in view, whether the conductors cutting the flux are top coil sides or bottom coil sides, as like voltages in one coil would oppose and result in zero net voltage e.g. when two adjacent poles are both north poles of equal strength, the net voltage generated on an armature coil (whose coil sides lie under these poles) would be zero, although a voltage exists in each coil side.

Let ϕ be north pole flux in lines.

and $$C = \frac{\text{RPM x Total armature conductors x Number of poles}}{\text{Armature Circuits x } 10^8 \text{ x } 60}$$

$$= \frac{p\,NZ}{60 \cdot a \cdot 10^8}$$

Also assume C and ϕ to be positive when considering north pole flux and conductors of top coil side.

The equations can be written as

$$E_1 = (+ C)(+ \phi_1) + (- C)(- \phi_2)$$

$$= + C\,(\phi_1 + \phi_2) \qquad (1)$$

$$E_2 = (+ C)(- \phi_2) + (- C)(+ \phi_3)$$

$$= - C\,(\phi_2 + \phi_3) \qquad (2)$$

$$E_3 = (+ C)(+ \phi_3) + (- C)(- \phi_4)$$

$$= + C\,(\phi_3 + \phi_4) \qquad (3)$$

$$E_4 = (+ C)(- \phi_4) + (- C)(+ \phi_1)$$

$$= - C\,(\phi_4 + \phi_1) \qquad (4)$$

Hence the voltage between B_1 and B_3 becomes

$$(E_1 + E_2) = C\,(\phi_1 + \phi_2 - \phi_2 - \phi_3) = C\,(\phi_1 - \phi_3)\ , \qquad (5)$$

and voltage between B_2 and B_4 becomes

$$(E_2 + E_3) = C\,(-\phi_2 - \phi_3 + \phi_3 + \phi_4) = C\,(\phi_4 - \phi_2) \qquad (6)$$

So one notices that the voltage between brushes B_1 and B_3 depends on strength of poles L_1 and L_3 only and is not affected by poles L_2 and L_4. Similarly the voltage between brushes B_2 and B_4 depends on strength of poles L_2 and L_4 and is not affected by poles L_1 and L_3. This property provides a method of superimposed two independent generators on the original one, the three generators being as follows:-

a. Poles L_1 and L_3 and brush arms B_1 and B_3.

b. Poles L_2 and L_4 and brush arms B_2 and B_4.

c. Poles L_1, L_2, L_3 and L_4 with brush arms B_1, B_2, B_3 B_4.

It is, therefore, possible to obtain three amplification stages from one machine by properly exciting the first generator, using its output for exciting the second generator and the second output to excite the third generator.

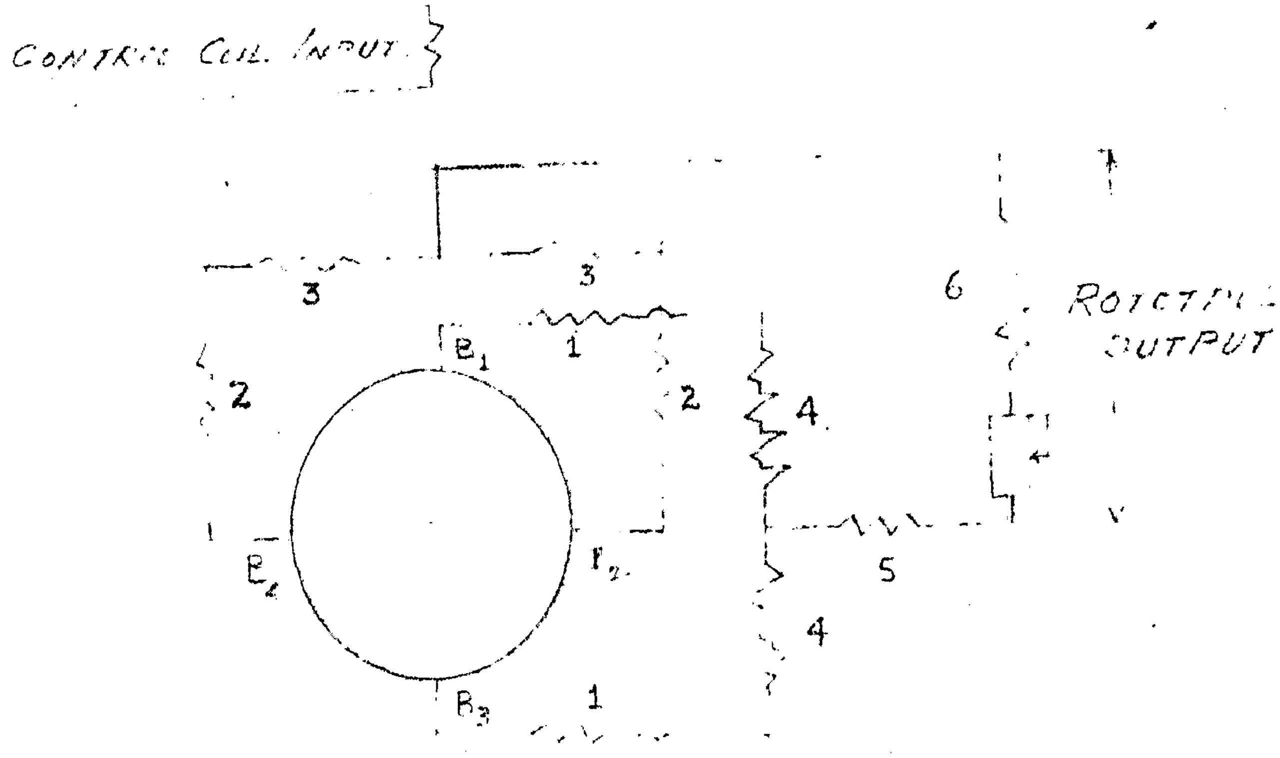
CHAPTER III.

PRINCIPLE OF THE STAGE ROTOTROL.

Fig. III-2 shows the normal winding used in a design for 2-stage Rototrol. Control intelligence is made to excite coils on poles L_1 and L_3, the coils being connected in such a manner as to have north-pole excitation on one pole and south pole excitation on the other. Flux produced generates a voltage between brushes B_1 and B_3, and this is used to excite coils on all poles. These act as control coils for the second stage of the Rototrol and are divided into two sections, each section having half the total turns of each pole.

One half of the section is connected in series with brush B_1 and the other half in series with brush B_3. One terminal [redacted] the output stage is taken from the common point of the connec between B_1 and B_3, and thus all effects of the output current are neutralised i.e. the current flowing from both B_1 and B_3 in the output circuit of rototrol will make excitation cumulative on one section and differential on the other. However as each section has an equal number of turns on each pole, the coils neutralise each other and result is no excitation.

The second stage consists of all poles and all brushes, and is self-excited in the usual way. The figure shows the series type of self-excitation, although shunt type could also be used. Output circuit and self-excitation are so designed as to be self-sustaining as usual. As the operation of rototrols normally is limited to the air gap portion of the saturation curve, the self-excitation is so determined as to coincide with the air gap line. In this way the Rototrol is able to supply sufficient excitation to itself to keep its output constant at any particular point on the straight portion of the saturation curve. Thus the function of control coils is limited to supplying the way of causing the rototrol to operate at a certain output, or to change from one value of output to another, as needed in operating the system under control.



Reference to Coil Numbers.

1. M_1 Compensating Coils on L_2 and L_1

2. M_2 Compensating Coils on Poles L_1 and L_3

3. M_3 Opposition Coils on Poles L_2 and L_4.

4. Control Coils For Second Stage

5 Series Type Self Excitation For Second Stage.

6. Shunt Type Self Excitation For Second Stage on all Poles.

Fig-III-3:- Diagram Of all Coils that must be Used in a Two Stage Rototrol

CHAPTER III.

NORMAL CIRCUIT FOR TWO STAGE ROTOTROLS.

Fig. III-3 shows the connections of all coils which may be used in such a machine. When only opposition is used to control M_1 and M_2, then coils M_1 and M_2 would be omitted. Again if one wants compensation for only M_2, then coils 1 and 3 would be left out. Experiments show that a design having nearly 80 per cent compensation for M_1 and M_2 in coils 1 and 2, and coils 3 opposing M_2 with nearly 65 per cent of the effective ampere turns per pole gave a minimum total coil space with satisfactory operation. Self excitation used in the second stage can be series, shunt, or a combination of the two. Both are used when output current is high and series excitation is preferred. It is usual to have slightly less than full amount of series excitation needed to produce a tuned output circuit, and a shunt field is added. The remaining excitation required is taken from the shunt field, and adjustments made with its rheostat.

Physically the two stage rototrol described above is similar to a conventional D.C. Machines. The commutator, armature, brushes, brackets, poles, air gaps and frame are of normal construction. For cases where control energy is low, special treatment is given to poles and frame to reduce the residual magnetism. When the frames are laminated, one gets a better speed of response.

CHAPTER III.

POSSIBLE NUMBER OF STAGES OF AMPLIFICATION.

Consider a rotating amplifier having n stages of amplification. It will have n magnetic circuits interlinked with one armature. These n circuits should have no saturation. The number of brush studs necessary for all magnetic circuits will be a minimum or equal to the number necessary for the magnetic circuit with the largest number of poles. Again the arrangement for good commutation would be simplest if the brush studs necessary for the different magnetic circuits are made to coincide.

A lap winding is used but without equalisers. The coil pitch is made equal to the pole pitch of the magnetic circuit with the largest number of poles. The winding is then chorded with respect to all other magnetic circuits. For a full pitch winding, the coil pitch is equal to 360/n mechanical degrees; the lower layer is moved with respect to the upper layer 360/n mechanical degrees, and the brush position for maximum voltage is shifted 180/n mechanical degrees with respect to the pole axis.

If the winding is chorded β mechanical degrees, the coil pitch is equal to $(\frac{360}{n} - \beta)$ mechanical degrees; the lower layer is moved with respect to the upper layer $(\frac{360}{n} - \beta)$ mechanical degrees, and the brush position for maximum voltage is shifted

$(\frac{180}{n} - \frac{\beta}{2})$ mechanical degrees from the pole axis.

Fig. III-4 shows a two-pole magnetic circuit and chorded winding. The upper and lower layers are shown of only one path. Chording is β degrees and brush position for maximum voltage is shifted $(90 - \frac{\beta}{2})$ degrees from the pole axis. For other positions of the brushes than that shown, the E.M.F. will be found to be less. Also when the brushes are in the position ab, the E.M.F. induced between them is zero i.e. the brush position for zero voltage is shifted with respect to that for maximum voltage by 2 $(\frac{180}{p} - \frac{\beta}{2})$ mechanical degrees.

In Fig. III-4 a chording β of 90 mechanical degrees has been assumed. Thus the brush position for zero voltage is shifted by $(\frac{180}{2} - \frac{90}{2})$ or 45 mechanical degrees from the position for maximum voltage. Fig.5 shows a two-pole magnetic circuit n_1s_1 superimposed on a four-pole magnetic circuit NSNS. As the winding has coil pitch of the 4-pole circuit, it is chorded 90 mechanical degrees with regard to the superimposed two-pole flux, and brush position for maximum voltage is $(\frac{180}{2} - \frac{90}{2})$ or 45 mechanical degrees with respect to the poles n_1s_1 i.e. the same for both magnetic circuits.

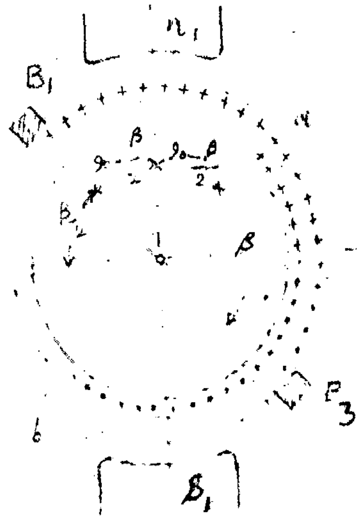


Fig.III-4:- Effect Of Chording On Brush Position For Maximum Voltage.

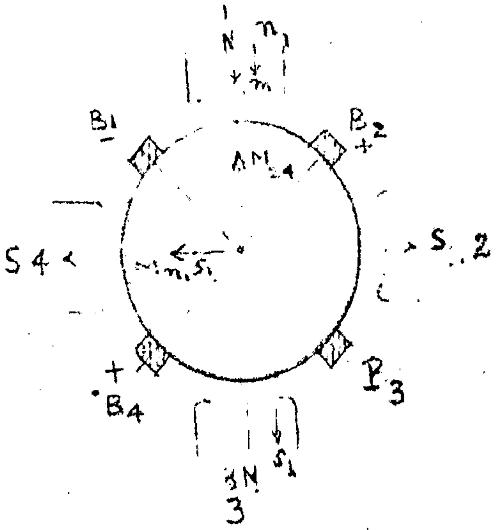


Fig.III-5:- Effect Of Super-Imposing Two-Pole Magnetic Circuit On Another Having Four Poles.

CHAPTER III.

POSSIBLE NUMBER OF STAGES OF AMPLIFICATION.

Now if polarity of brushes B_1 and B_3 is negative with regard to the 4-pole magnetic circuit, it is for these brushes negative and positive respectively with regard to the superimposed 2-pole magnetic circuit. The superimposed two-pole flux does not induce an EMF between brushes B_2 and B_4 as these are moved $2\left(\frac{180}{2} - \frac{90}{2}\right) = 90$ mechanical degrees with regard to brushes B_1 and B_3. Generally the least number of field coils are necessary in the amplifier, when each magnetic circuit induces voltage between as many brushes as it has poles i.e. when all magnetic circuits are symmetrical with regard to the armature winding or when for each magnetic circuit all armature paths have the same number of turns.

Assume the magnetic circuit with largest number of poles to have p_1 poles. Here the winding will be full pitched or $\beta = 0$, and distance from pole axis to brush axis for maximum voltage is $\alpha_1 = \frac{180}{p_1}$ mechanical degrees. In each layer the width of armature path $b_1 = \frac{360}{p_1}$ mechanical degrees.

CHAPTER III.

POSSIBLE NUMBER OF STAGES OF AMPLIFICATION.

For any magnetic circuit p_2 for which armature winding is symmetrical, in each layer the width of armature path $b_2 = \frac{360}{p_2}$ mechanical degrees.

Chording $\beta_2 = (b_2 - b_1) = 360 \left(\frac{1}{p_2} - \frac{1}{p_1}\right)$ mechanical degrees and distance between pole axis and brush axis for maximum voltage for this magnetic circuit is

$$\alpha_2 = \frac{180}{p_2} - \frac{\beta_2}{2} = \frac{180}{p_2} - 180 \left(\frac{1}{p_2} - \frac{1}{p_1}\right) = \alpha_1 .$$

This shows that chording for any magnetic circuit is the same as that for circuit with lrgest number of poles.

A voltage is produced between brushes B_1 and B_3 by the superimposed two pole flux $N_1 S_1$. The load is connected to brushes B_1 B_3 and B_2 B_4. A circulating current is induced through the armature and these brushes. The axis of the armature M.M.F. $M_{N_1 S_1}$ coincides with the axis of pole 2 and 4 and produces another superimposed two-pole flux. This induces an E.M.F. between B_2 and B_4, which are brushes having same polarity with regard to the four

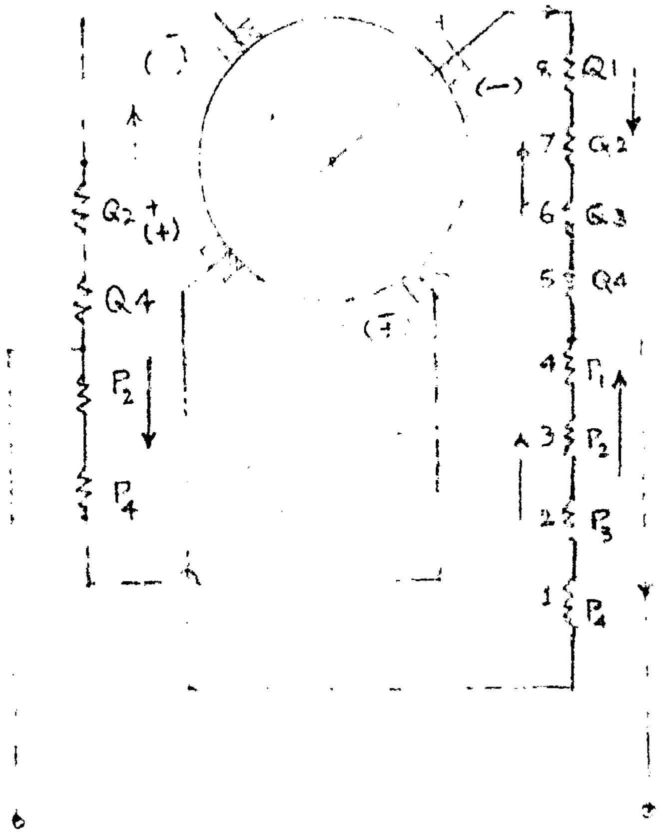


FIG. 11-12:- ARRANGEMENT FOR THREE-
- STAGE ROTOTROL

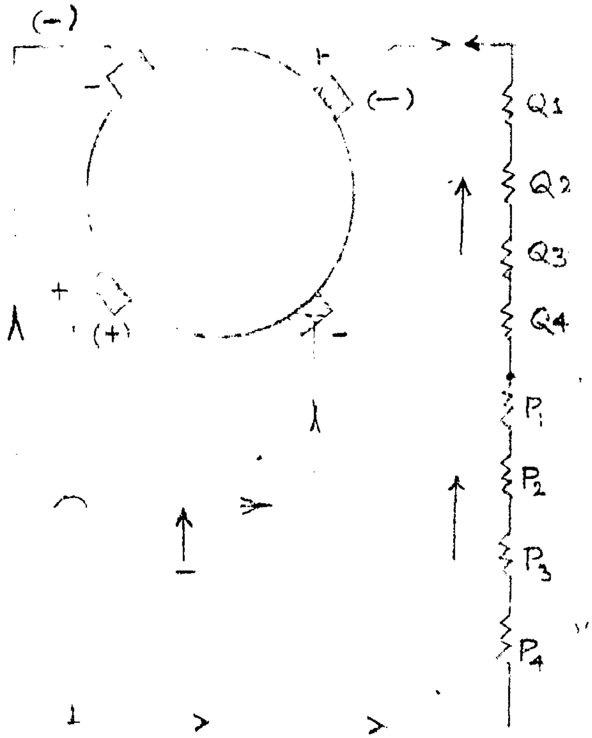


FIG IV-13:- ALTERNATIVE ARRANGEMENT FOR THREE-STAGE ROTOTROL pole flux NSNS and the load circuit. Hence a second circulating current shall flow through the armature, but over the brushes B_2 and B_4. Armature M.M.F. M_{24} produced has its axis along that of flux n_2s_2 and opposes this flux. It is necessary to compensate M_{24} as exactly as practicable.

Referring to Fig. III-12 if the circulating current between the brushes B_2 and B_4 is used to excite the field coils of the four pole magnetic circuit, the 4-pole machine of Fig. III-6 can operate as a three-stage amplifier, having the following three amplification stages:-

i. Control coils inducing the two pole flux n_1s_1 and the armature between B_1B_3.

ii. Two-pole flux produced in the pole arms 2 and 4 by the circulating current between B_1 and B_3 and the armature between B_2 and B_4.

iii. Four-pole flux excited by the circulating current between B_2 and B_4 and the armature between B_1, B_2, B_3 and B_4.

Connections of field windings have been shown in Fig.III-12 and III-13.

CHAPTER III.

THE THREE STAGE ROTOTROL.

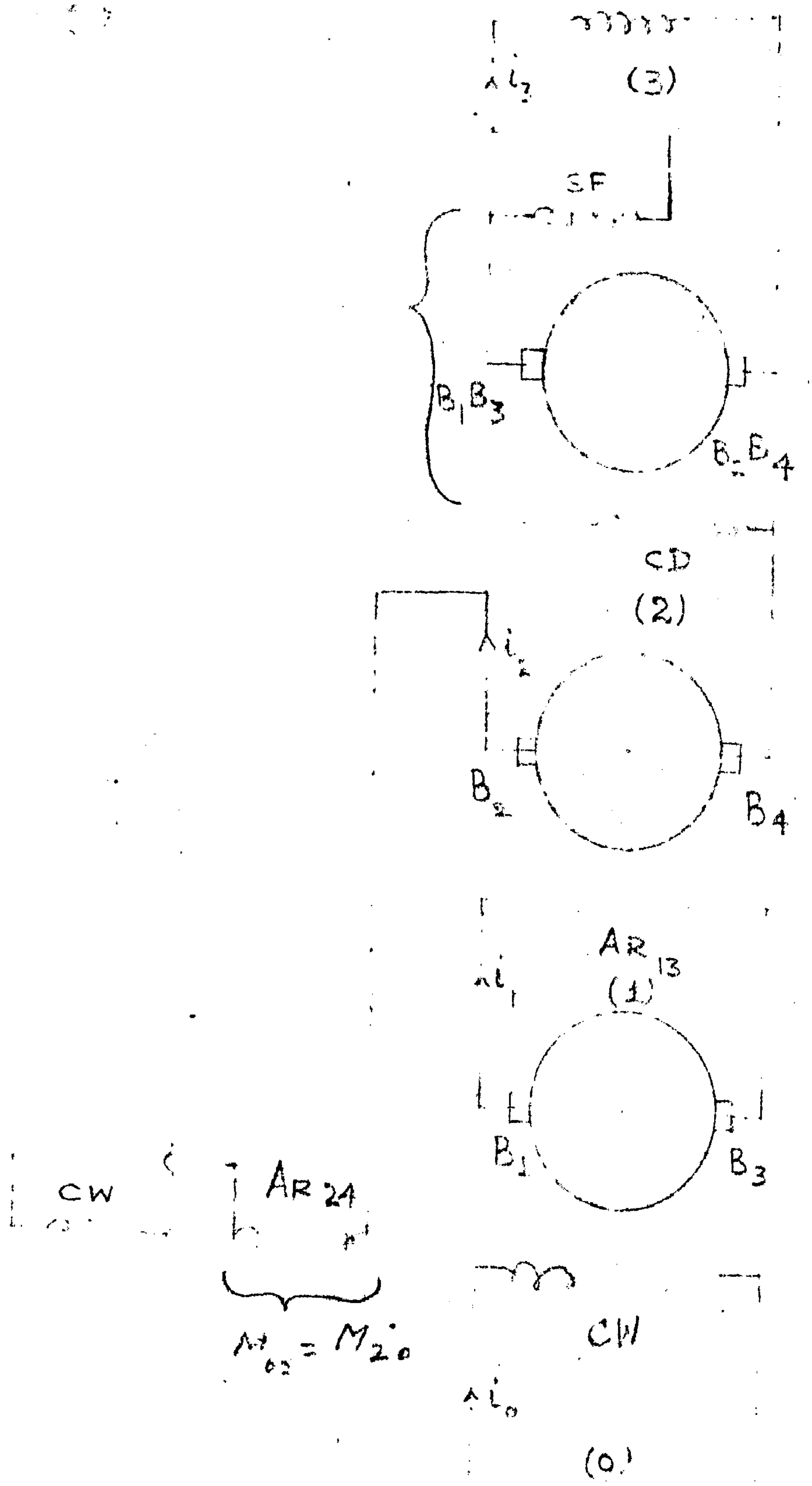
In one arrangement, the field coils are arranged on diagonally opposite poles and fed by the circulating current. This would increase the armature reaction flux produced by this current.

The field coils on these two poles and the Armature Reaction flux provide the excitation for the second stage of amplification. For avoiding effect of load current on this excitation, two coils P_2 Q_2 + P_4 Q_4 with equal number of turns are placed on each of the two poles. The two coils P_2 P_4 are connected in series as also the coils Q_2 Q_4, and the load for the load is connected between the P coils and the Q coils, as indicated in Fig. III-12.

These 4 coils are in the same direction so that they cancel each other's effect on each pole with respect to the load current, while all of them add together for the excitation current. For the third stage of amplification as shown in Fig. III-13, the coils P_1 to P_4 and Q_1 to Q_4 are connected in the same manner as P_2 P_4 and Q_2 Q_4 were connected for the second stage.

If the P coils and the Q coils in the circuit have the same number of turns, the machine operates as a pure amplifier, and all circuits have no current under steady-state conditions. When operation as a generator under steady-state conditions is required either the coils P_1 to P_4 and Q_1 to Q_4 have to be given a different number of turns or a special coil has to be placed on each of the four poles to provide self-excitation. Special coils may be shunt connected.

An alternative arrangement omits the coils on the two diagonally opposite poles, and excitation for the second stage is provided only from armature flux due to circulating current between the other set of diagonally opposite poles. We use a distributed compensating winding in the pole shoes of 2 and 4, or by a concentrated winding on the poles 1 and 3. In both cases the coils must be fed by the circulating current. As amplification of the 3-stage amplifier is very high, compensation of armature reaction is not so critical as in a 2-stage amplifier.



C.F - Control Field
C.W - Compensating Winding
S.F - Series Field

Fig-III-6:-Circuits of Two Stage Rototrol
Transient Calculations

CHAPTER III.

THE THREE STAGE ROTOTROL UNDER TRANSIENT CONDITIONS.

For transient conditions refer to Fig. III-13 it being assumed that special series coils are used for self-excitation in the steady-state. As the control coils on poles 1 and 3 make the poles north and south, while the P and Q coils and series field coils make them north and north, there is no mutual induction between the control coils and P and Q coils or the series coils.

Mutual induction does exist between control coils and the portion of the armature between B_2 B_4 and the compensating winding, if the compensation is not perfect. Again mutual induction exists between the P and Q coils and the series field coils. In Fig. III-6 the different circuits are shown as 0, 1, 2 and 3. Fluxes caused by armature reaction are shown by the coils AR_{13} and AR_{24}, CF is the control field, CW the compensating field and SF the series field for self-excitation. Assuming that compensation is not perfect, the voltage equations for no load are

$$e_0 = R_0 i_0 + L_0 p i_0 - M_{02} p i_2 , \qquad (1)$$

$$G_0 i_0 - G_c i_2 = R_1 i_1 + L_1 p i_1 , \qquad (2)$$

$$e_1 i_1 = R_2 i_2 + L_2 p i_2 - M_{20} p i_0 \tag{3}$$

$$e_2 i_2 = e_3 \; ; \tag{4}$$

where $e_0 i_0$, $e_0 i_2$, $e_1 i_1$ and $e_2 i_2$ are rotational E.M.F's. For load conditions equations (3) and (4) become

$$e_1 i_1 = R_2 i_2 + L_2 p i_2 - M_{20} p i_0 + M_{23} p i_3 \tag{5}$$

$$e_2 i_2 + e_3 i_3 = R_3 i_3 + L_3 p i_3 + M_{32} p i_2 \tag{6}$$

Again there is a relation between e_0 and i_3 depending upon the application of the Rototrol. If it is used for voltage control, this relation is assumed as

$$e_0 = - A e_4 = - A e_3 i_3 \; . \tag{7}$$

where A is a constant and e_4 is the deviation of the generator voltage from normal. Equations 1, 2, 5 and 6 can be solved for i_3. Now

$$T_o = \frac{L_o}{R_o} \,,$$

$$T_1 = \frac{L_1}{R_1} \,,$$

$$T_2 = \frac{L_2}{R_2} \,,$$

and $$t_{32} = \frac{M_{32}}{c_2} \,.$$

∴ The current i_3 becomes

$$i_3 = \frac{\left[c_o c_1 + R_1 M_{20} p \,(1 + T_1 p)\right] c_2 (1 - t_{32} p)}{D(p)} \, e_o \,, \qquad (8)$$

where

$$D(p) = R_0 R_1 (1 + T_0 p)(1 + T_1 p) \times \Big[C_2 M_{32} p (1 - t_{32} p) + R_2 (1 + T_2 p)$$

$$\times (R_3 - C_a + L_3 p) - (R_3 - C_a + L_3 p) \Big] \times \Big[c_0 c_1 M_{20} p - c_a c_1 R_0$$

$$\times (1 + T_0 p) + (M_{20} p)^2 R_1 (1 + T_1 p) \Big] \qquad (9)$$

When perfectly compensated, armature reaction due to circulating current $I_{B_2 B_4} = M_{03} = M_{20} = c_a = 0$, and

$$i_3 = \frac{c_0 c_1 c_2 (1 - t_{32} p)}{D'(p)} e_0 \qquad (10)$$

where

$$D'(p) = R_0 R_1 (1 + T_0 p)(1 + T_1 p) \times \Big[c_2 M_{32} p (1 - t_{32} p)$$

$$+ R_2 (1 + T_2 p) \times (R_3 - c_a + L_3 p) \Big] \qquad (11)$$

CHAPTER III.

THE MULTI STAGE ROTOTROL UNDER TRANSIENT CONDITIONS.

Thus an excitation system includes all equipment required to regulate the A.C. voltage and excitation to the field of the A.C. Machine. These may be said to consist of three parts:-

i. Voltage Regulators and its auxiliaries,
ii. D.C. Machines for supplying excitation to the A.C. machine, and
iii. Provision for manual control of the A.C. machine output.

The improvement of the Rototrol amplifier as a part of the A.C. machine excitation system has made vast changes in all three parts of the system. Use of one stage or two-stage amplification depends on the energy available in the control circuit, and the total power output required. The two-stage Rototrol produces sufficient power to excite the field of the largest steam-driven generator, with nearly the same control energy as used with a single stage machine. It may be used either as a pilot exciter or as a main exciter.

In mechanical construction a Rototrol is the same as a conventional D.C. machine of similar rating and speed. However the physical size may be slightly bigger, due to more field windings in the stator structure and due to operation with an unsaturated magnetic circuit. The air-gaps are of normal size for both types of machines. We can supply one or two stages of amplification in a four pole machine, so that it can be connected directly to the shaft of any generator operating at say 3600 RPM. For providing excitation to machines with slower speed, the Rototrol must be separately driven at higher speed to obtain a smaller unit, which may not require excessive control energy.

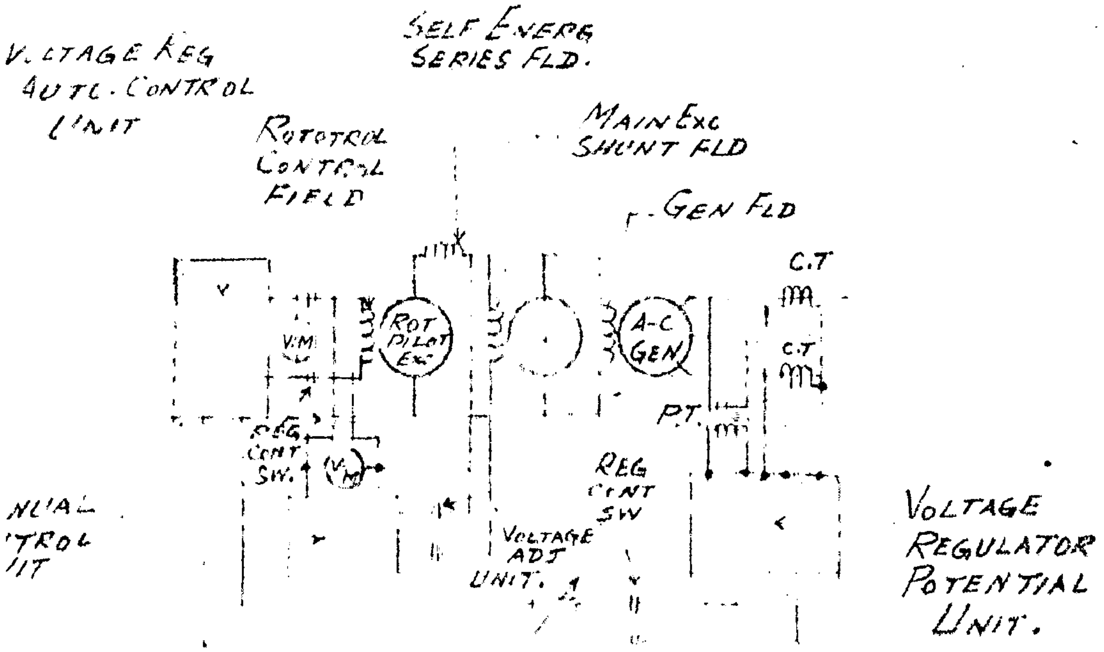


Fig. III-7:- Excitation System With Pilot Exciter And Single Field Main Exciter

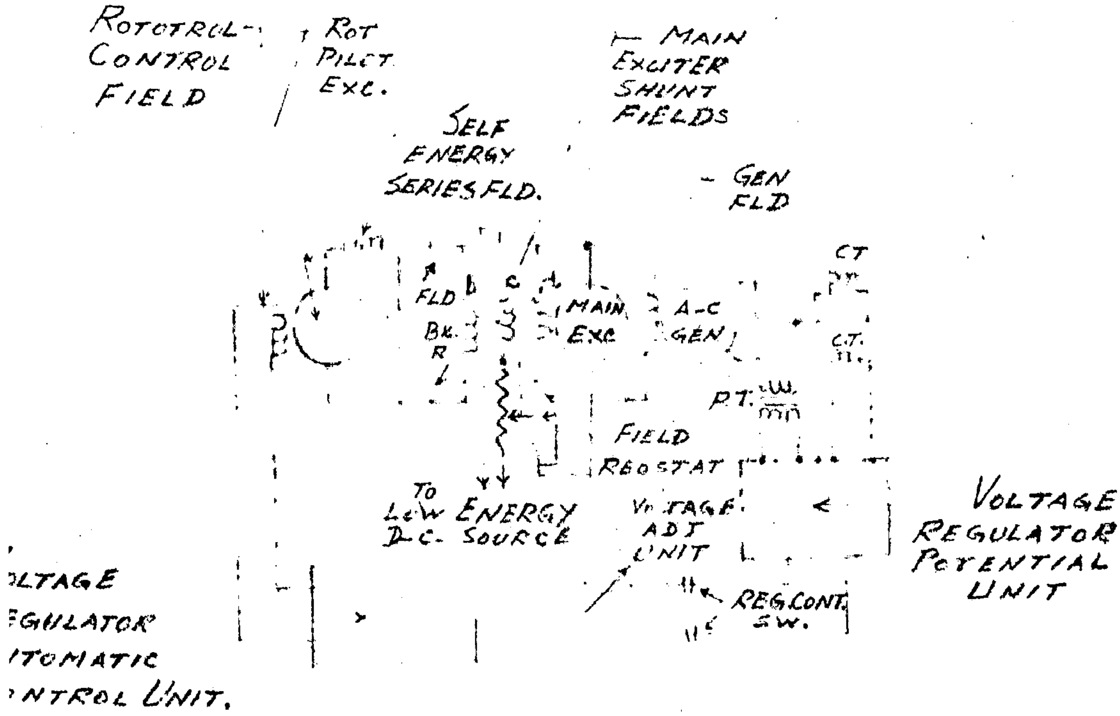


Fig. III-8:- System With Buck Boost Exciter And Three Field Main Exciter.

CHAPTER III.

SIMPLE TYPE OF PILOT EXCITER SYSTEM.

Fig. III-7 shows the simplest type of rototrol pilot exciter for use with a turbine generator. The rototrol is a conventional D.C. machine having a high speed, the A.C. generator and main and pilot exciters are all run by the same shaft at 1200, 1800 or 3600 R.P.M. for a 60-cycle generator. In a normal excitation system, the pilot exciter is a constant voltage generator. However the rototrol pilot exciter is a variable voltage pilot exciter, and the operation is similar to that of a normal exciter-rheostat system. But in the new arrangement, no regulator-controlled motor-operated exciter-field rheostat is used. A variable voltage is supplied to the main exciter field by the rototrol pilot exciter which is directly connected to the field and is controlled by the voltage regulator automatic control unit or the hand control unit. A potential unit measures the voltage at generator terminals, making the regulator regulate the polyphase voltages.

The regulator automatic control unit is different from previous control units; which used a contact-making voltage measuring unit to control the main-exciter field rheostat through normal and quick raise and lower contactors. In that arrangement it was necessary to use several moving parts and contactors. The automatic control unit used here avoids all contactors and all moving parts, and is a static device. This system usually uses impedance type of static voltage regulator.

CHAPTER III.

SIMPLE TYPE OF PILOT EXCITER SYSTEM.

The physical control unit has a bridge circuit excited by main-exciter field voltage drop. In this bridge circuit, the rototrol control field is connected differentially. Any change in the shunt field voltage of the main exciter from the hand-set value creates an unbalance in the bridge circuit, and current flows in the rototrol control field to correct the voltage. The physical control unit hence regulates the shunt field voltage of main exciter, to keep it constant at any set value which needs no further attention by the operator. Depending upon the energy requirements one may have one or two stages of amplification. The rototrol's self-excited series field provides all the excitation needs of the pilot exciter, if the A.C. generator is operating with regulated voltage. As the rototrol operates on the straight portion of the saturation curve, the control field has a stabilising effect and keeps the rototrol voltage at constant value.

Constructional changes in the rototrol can give response and ceiling voltages either equal to those with conventional D.C. generators as shown in Fig. III-7 or better than in the old systems. The series-tuned circuit can utilise the induced transient current in generator field and in main exciter field, due to A.C. short-circuit or sudden changes in load. This flows through the self-excited rototrol series field. Pilot exciter shown in Fig. III-7 gives all the main-exciter excitation, and is identical with the older systems using pilot exciters.

CHAPTER XXX.

SIMPLE TYPE OF PILOT EXCITER SYSTEM.

A great advantage is the elimination of the intricate exciter-rheostatic regulator with moving parts, and of the motor-operated field rheostat of the main exciter. Similar to the case with the exciter-rheostatic excitation system, a short-circuit or open-circuit results in loss of rototrol pilot exciter, and hence loss of excitation on the A.C. generator. However experience shows conventional pilot exciters to be very reliable. In the same way, rototrol pilot exciters are mechanically and electrically equally reliable, as standard parts are used in both types, and standard multiple fields in addition in the rototrol. In both systems, the main exciter is similar in construction.

CHAPTER III.

ROTOTROL PILOT EXCITER WITH THREE FIELD MAIN EXCITER

Fig. III-8 shows another system which is better than the one already described. It is known as the buck-boost rototrol excitation scheme using three field main exciter. The potential unit and automatic control unit are identical with those in the previous system. The pilot exciter is the same type as before, except that it operates in a different manner. It can be better understood by analysing the working of the main exciter. The main exciter has a normal construction, except that it has three shunt field windings instead of one. Field (a) is a self-excited shunt field and supplies most of the field excitation for main exciter, getting its energy from the armature circuit in the usual manner for a self-excited field. Field (c) is a separately excited shunt field fed from a station battery, and capable of giving 10 per cent of the total excitation required by the main exciter. Its purpose is to give stability at low voltages, under physical control.

This is used rarely whenever the speed of response voltage output range makes it necessary. Rheostats are provided in the energising circuits of fields (a) and (c), their rheostat arms being coupled together in such a way that when resistance is added to one field, it is removed from the second. This combination can either be hand-operated or motor-operated. Also the rheostat for field (c) gets open circuited at nearly half voltage on the main exciter and remains so, as the voltage of exciter is increased. Thus one observes that field (c) stabilises the main exciter at low voltage output under physical control, by shifting the total saturation curve so that a positive intersection of the saturation curve with any field resistance line is secured.

As the stabilising effect at higher exciter voltages is not required, the open circuiting of field (c) has no bad effects and drain on station battery for this field is avoided.

Field (b) is a shunt field excited by the buck-boost pilot exciter. In operation with this excitation system, the rheostat for field (a) is set so that it alone provides a base field current e.g. enough to keep steady-state stability at full load on the A.C. generator. The voltage regulator controls the buck-boost pilot exciter output for polarity and magnitude, so that excitation supplied by field (b) either adds to or subtracts from the base excitation. This helps to maintain the set A.C. Voltage although load keeps changing on the A.C. machine.

Under regulator control, the rototrol excited field of main exciter is itself a stabilising field. The buck-boost pilot exciter can supply sufficient energy to the rototrol-excited field on main exciter, so that the net excitation can be controlled, over the normal range of A.C. generator, by the voltage regulator.

CHAPTER XXX.

ROTOTROL PILOT EXCITER WITH THREE FIELD MAIN EXCITER.

As the base excitation is supplied by self-excited field, if there is any trouble in the rototrol buck-boost pilot exciter or static type voltage regulator, complete excitation is not lost nor load supply is disturbed. This is an advantage over the older systems and the previous one. For a short-circuit or open-circuit in pilot-exciter circuit, the set base excitation remains unchanged. When a circuit fails as A.C. generator is carrying a load different from that used for the rheostat setting, the A.C. generator continues to carry its load, but at a different power factor.

CHAPTER III.

PILOT EXCITER WITH THREE FIELD MAIN EXCITER DESIGN FOR HYDROELECTRIC GENERATORS.

The hydroelectric generators are of low speeds while rototrols have high speeds, so it is not practicable to have a direct connection to generator shaft. The buck-boost pilot exciter must be driven by a small motor, which creates the problem of reliable power supply for this motor. Three field main exciter system is workable for slow-speed generators, as shown in Fig. III-8. For normal operation of the A.C. generator, the excitation system will operate as described previously i.e. the self-excited shunt field gives the base excitation and the rototrol gives buck-boost action to adjust for the changes in voltage of the generator. For starting the generator, when no outside source is available for driving the rototrol M.G. set, the main exciter is self-excited and provides excitation for the main generator. As soon as the A.C. voltage is available, the rototrol may be started and the voltage regulator connected up.

When there are short circuits on the A.C. system, the system should be able to supply full-excitation to the generator field. In the system shown, this is achieved by creating sufficient inertia in the rototrol m.g. set to carry it through disturbances without much change in speed. Otherwise the rototrol motor generator set is made only of three-units with an A.C. and D.C. driving motor. For normal operation, it is driven by the A.C. motor, with the D.C. motor floating on the battery and acting as

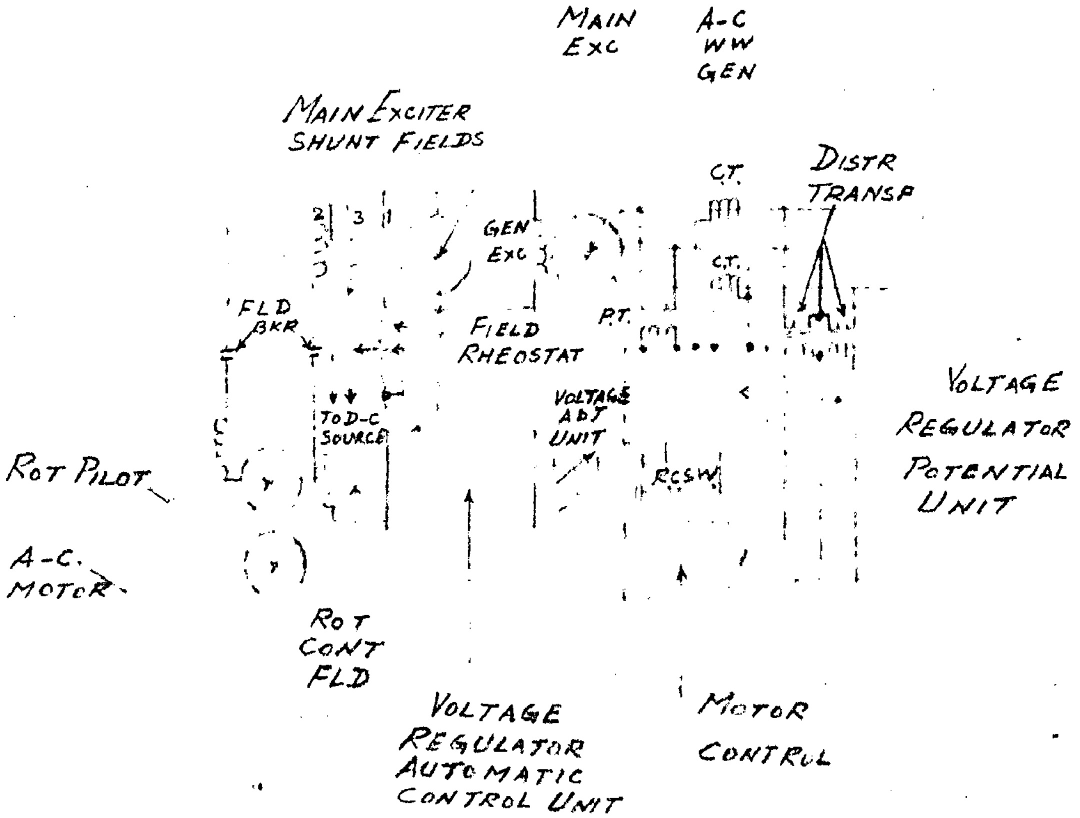


Fig III-9:- Excitation System For Hydroelectric Generators

D.C. generator. If there is a disturbance on the A.C. system, the D.C. machine shall automatically take up the driving function, when the A.C. voltage falls. After the restoration of A.C. voltage, the A.C. motor would again drive the M.G. set.

The rototrol can be driven by an entirely independent source of A.C. energy, which should be reliable or automatic transfer provision should be made. Any trouble on this A.C. source would upset operation of the excitation system. The system shown in Fig. III-9 is most reliable, where supply to the rototrol driving gets disturbed only when there arefluctuations on the main A.C. system. However enough inertia in the rototrol m.g. set allows it to overcome the disturbance.

CHAPTER III.

MAIN EXCITER ROTOTROL.

A two-stage rototrol can be constructed for big power output by using a small control field energy, which may be supplied by instrument transformers. It can be direct-connected to the shaft of turbine generator, as it has a high speed and the same air gap as an ordinary D.C. machine.

The direct-connected rototrol of this type simplifies turbine-generator construction and maintenance by avoiding use of a pilot exciter. The potential unit and voltage regulator automatic control unit are the same as used for buckboost pilot exciter. Its performance is similar to that from ordinary excitation systems.

By using Rototrol pilot exciters, direct connected for new installations, and separately motor driven for older installations, and using static networks for voltage regulation the overall excitation operation has improved.

A good way to avoid failure of any apparatus is either to eliminate it, or make it simpler. We eliminate the Regulator with its contacts and the pilot exciter in the Main exciter Rototrol excitation for Turbine generators. Thus we accomplish with one main exciter; complete excitation, stability and regulation with the addition of only a static voltage regulating network. So our purpose has been served in one exciter, without use of additional brushes, short circuited windings, or other constructions requiring adjustment. As the amplification is produced in the main exciter itself, it is constructed as a two-stage rotating amplifier, in order to need only a small amount of control energy from the static network.

One of the sizes of main exciter rototrols used is 200 KW 250-Volt 3300 R.P.M. for exciting a 60,000 KW 13,800-Volt three-phase 60-cycle 3300 R.P.M. turbogenerator at a power factor of 0.85. Its principle is the Westinghouse construction and gives a closed machine for normal operation. When the cover is removed, it gives better accessibility for inspection and replacement of brushes than in a D.C. machine of similar size. The brush holder is of double-type, and without using any tools the brushes can be replaced while the machine is in operation, by employing standard shunted brushes. The arrangement and number of brushes is normal and same as on an ordinary 200 KW 3600 R.P.M. exciter.

No shutdowns are necessary for replacing brushes, but a depressed bedplate is used for convenience of brush replacement. Owing to the high speeds, shrink rings are used and the shrink ring commutator is of the Westinghouse floating type. Armature winding is the ordinary lap winding without cross connections. The openings between commutator necks are filled with insulating material, and the winding is kept behind the necks and under extensions of front coil to avoid creepage paths. The only livecreeping surfaces on the armature are the insulation near the bands on extensions of front coil and near the shrink rings, and these can be cleaned by compressed air while the unit is operating.

The stator is conventional, except for modified brush holder cross connections and additional field windings to get two amplification stages. The frame used is laminated to reduce hysteresis; avoid eddy currents and give a faster response. Windings of series field, shunt field and commutating pole are insulated for the full length to avoid creepage paths. The bearings used are of pedestal-type, as they need no members for tying to the frame and allow better accessibility regarding oil seals around the shaft, hence reducing leakage of oil.

A flexible coupling is used on the A.C. generator shaft to drive the exciter from its commutator end. A fan is provided on end of turbine generator shaft and gives separate ventilation for the A.C. exciter and A.C. generator collector rings. Baffles projecting inwards from the cover and rubber seals provide partitions in the housing of exciter to direct the ventilating air for efficient cooling. The direction of air flow is from rear of machine towards the commutator and fan, such that there is no possibility of drawing in carbon dust from worn brushes. The baffle at front end of commutator makes the air pass over the commutator, thus cooling it and the brushes. Air for collector rings is carried from the rear of exciter in hollow tubes to the A.C. generator field collector rings and brushes. Filters are used at the air entrance into the exciter unit. Air is discharged directly below the fan, which is placed at the end of the A.C. generator shaft.

Inspection openings are built in the cover and lights provided for illumination, so that working can be observed with the cover is closed. The cover is mounted on rollers, which can be moved by a handle at the end of the cover. Pulling of this handle depresses the rollers and the cover can be rolled away from the exciter. This can be done even when the unit is working.

CHAPTER IIV.

VOLTAGE REGULATION OF THE MAIN EXCITER ROTOTROL.

Several regulating circuits can be used. Electro-mechanical means have the advantage of fixed reference such as coil spring tension, but have the drawback of moving and wearing parts. Direct-acting rheostatic type regulators with spring mounted moving parts have overcome the disadvantages of moving and wearing parts.

A better way is to use a reference consisting of intersection of non-linear and linear impedance characteristics. The regulating circuit is balanced at the point of intersection of the two characteristics. For changes from the voltage level for which the intersection is meant, a current difference is set up in the static network to provide energy of one polarity (or its opposite) to energise the rototrol control field. Fig. IV-1 shows these characteristics. The curve OAB is non-linear and indicates relation of A.C. applied voltage and the current flowing through the saturated reactor, and OAH is a straight line showing the relation between the applied voltage and current through the capacitor. Usually the voltage value chosen for the intersection of the impedance characteristic is a bit less than the value of normal voltage generated after reduction through potential transformers. For getting a range of adjustment of voltage level, a rheostat is connected in series with the circuit which gives the reference level. The operator can change the rheostat position to vary the resistance of the circuit and thus the voltage to a desired level.

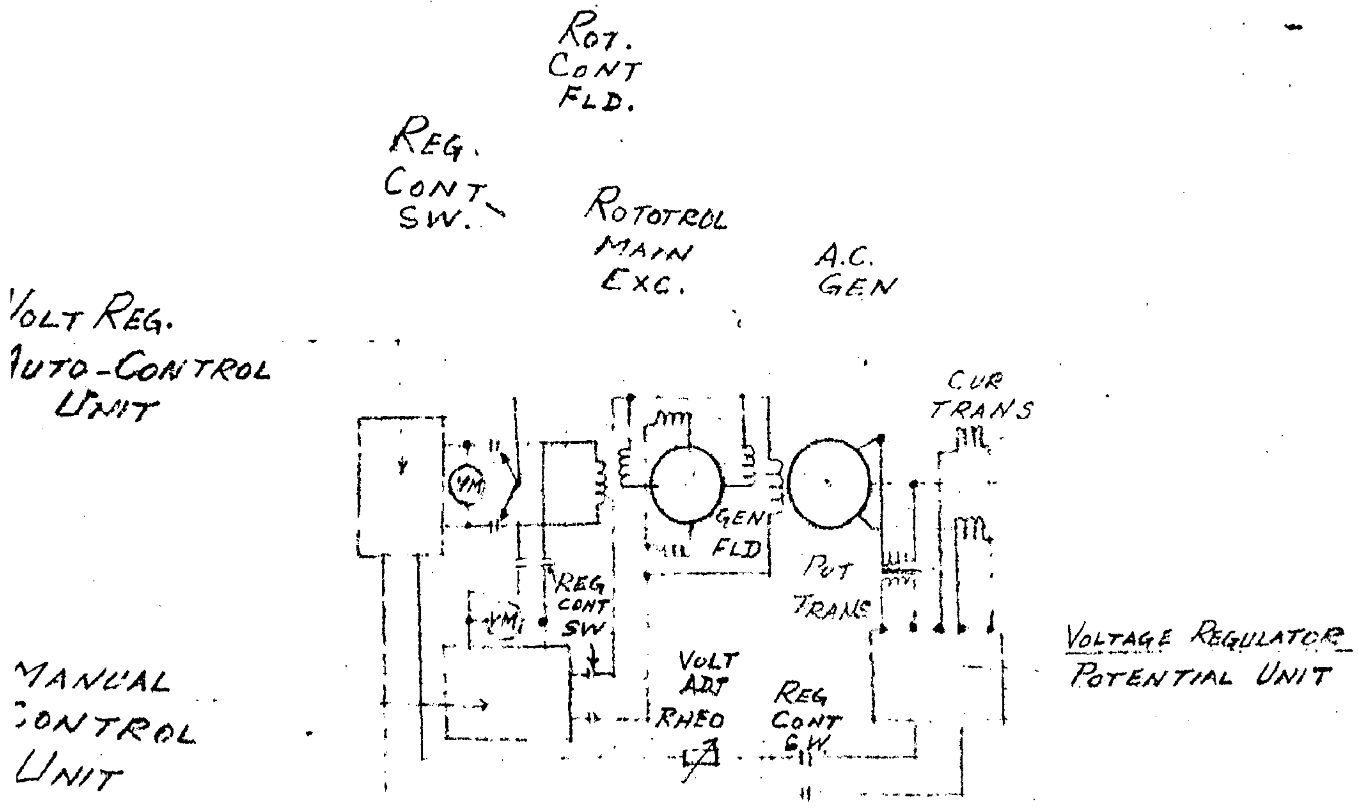
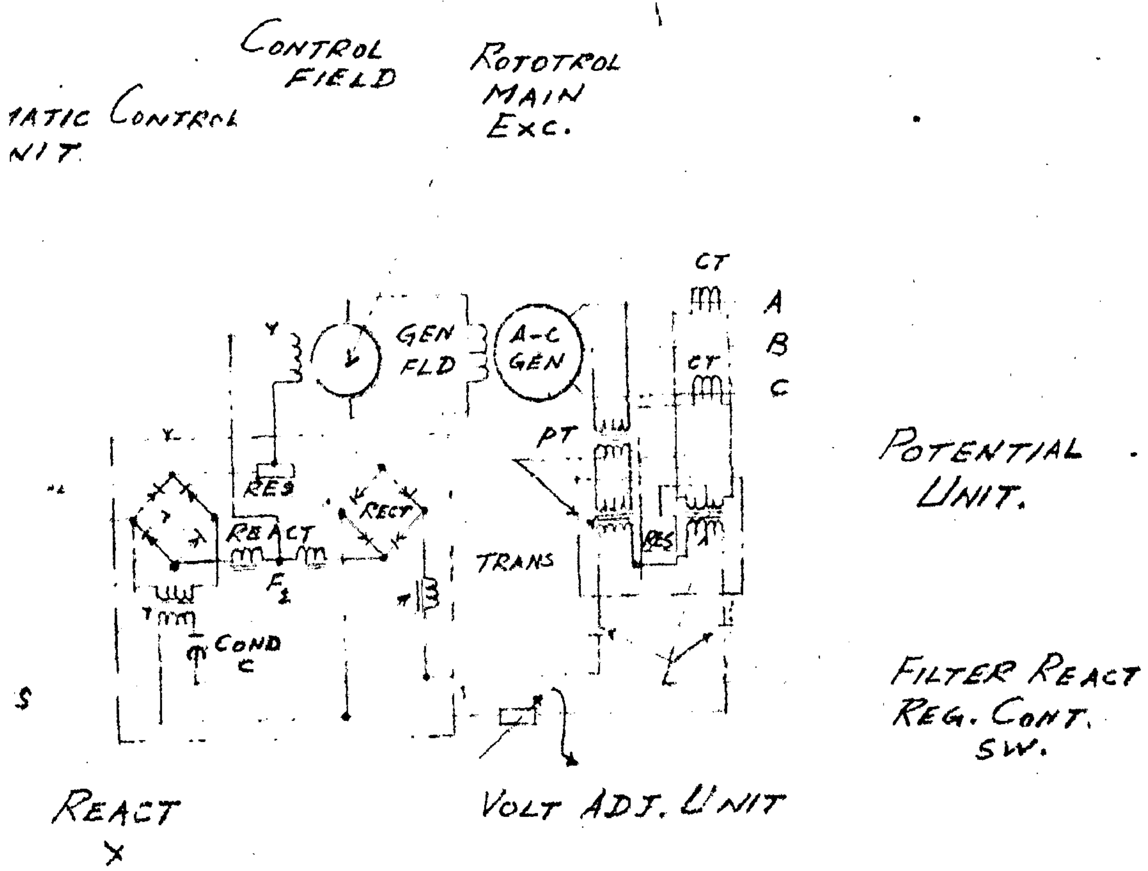


Fig-III-10.-System With Impedance Type Voltage Regulator.



ig-III-11 - Internal Connections Of Automatic Control Unit And Potential Unit Of An Excitation System.

CHAPTER III.

VOLTAGE REGULATION OF THE MAIN EXCITER ROTOTROL.

Fig. III-10 shows a system with a static regulator network. The regulator automatic control unit includes the capacitor and saturating reactor. Another part is the potential unit in which A.C. Voltage and current are used to supply positive-sequence voltage for the automatic control unit, and adjustment for equalising reactive load between the A.C. generators which operate in parallel. There is a control switch to switch the regulator in or out of circuit, and a physical control unit for controlling the rototrol exciter manually when the voltage regulator is not in service.

The internal connections of potential unit and automatic control unit are shown in Fig. III-11. In the control unit, the input A.C. voltage feeds direct to the capacitor circuit and to the reactor circuit, each of which energises a dry-type rectifier. The rectifier outputs are connected in a series relation through a tapped resistance. The control field is connected from the centre of the resistance to the opposite side of the rectifier circuit. At the point of intersecting impedance, the current and voltage output of each rectifier is identical and no difference current reaches the rototrol control field. When there is a fall in A.C. voltage, the current becomes less in the reactor circuit and causes some current to flow in the control field, with the same polarity as the capacitor rectifier. This flow in the 'raise' direction will make the rototrol increase the output and hence restore the A.C. generator voltage to its normal value.

If A.C. voltage increases, the current becomes more in the reactor circuit and results in flow of difference current in the output of rectifiers of same polarity as reactor circuit. Polarity now is reverse of that when the A.C. Voltage had decreased and the rototrol control field is energised in the 'lower' direction. This decreases the rototrol's output and again restores the A.C. generator voltage to normal. The hand control unit has a bridge circuit and variable resistance energised from the rototrol output, and includes dry-type rectifier and resistance connection to the control field. If setting of rheostat is fixed, the circuit is self-regulating to control the output voltage and keep it constant at a predetermined value. A change in rheostat setting alters the rototrol output voltage as desired, and controls the terminal voltage.

A control switch is used to change from hand control to regulator control, and this has four positions; physical, regulator test, physical test and regulator. For changing from physical to regulator control, it is first turned to the regulator test. Then the automatic control unit output is varied by the adjusting unit and checked by voltmeter till it matches the voltage of physical control unit. Now it is turned to the regulating position and the regulator takes control of the A.C. Voltage.

On the other hand, when changing from regulator to physical control, the switch is adjusted to physical test position. The output of physical unit is changed by a rheostat and checked by voltmeter till it matches that of automatic control unit. Now it is turned to the physical position. If the exciter voltage changes from the setting while the physical control is being used, then the bridge circuit energises the rototrol control field in such a direction as to return the exciter voltage to the physical setting at which the system is being maintained.

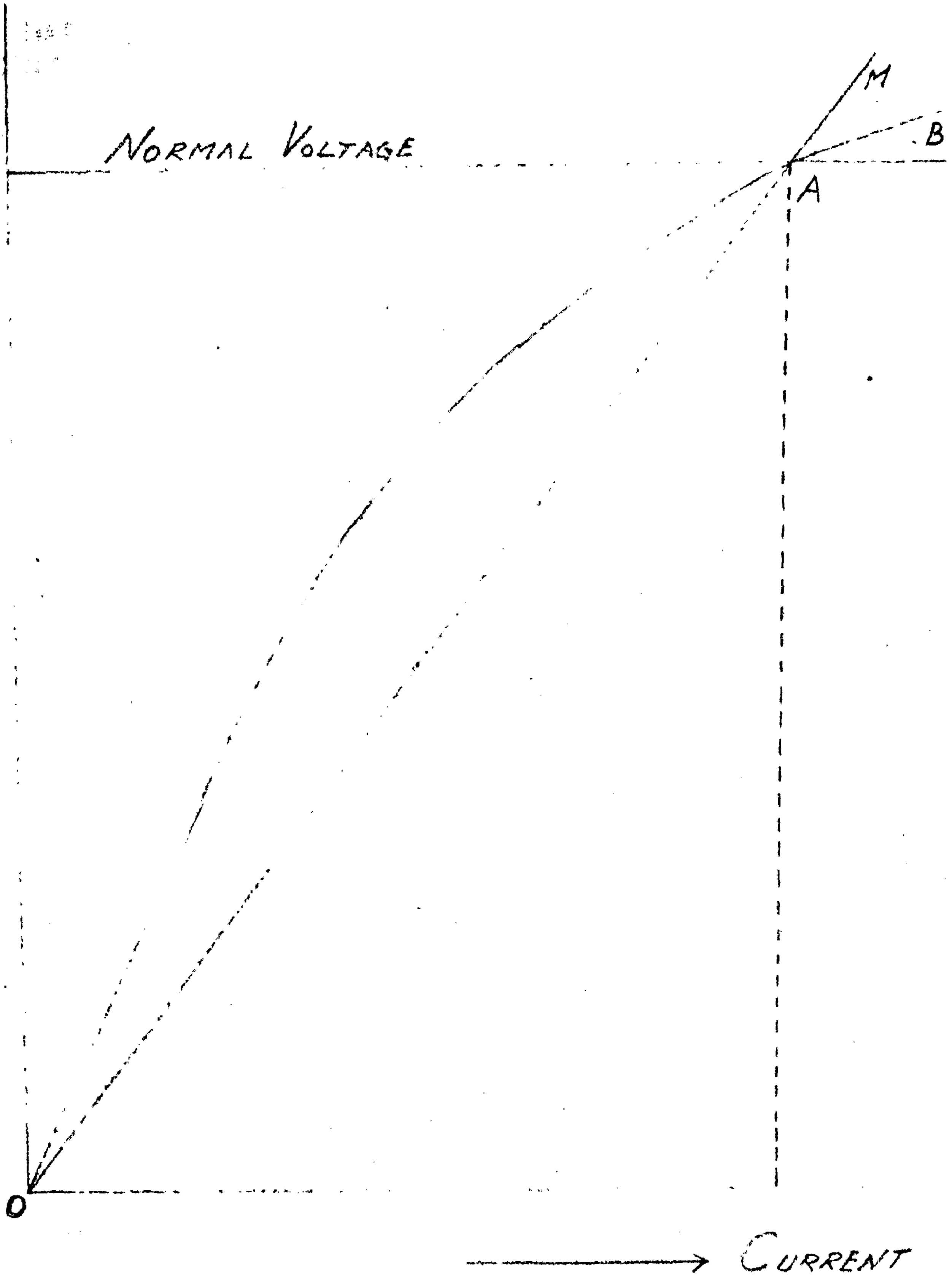


FIG-IV-1:- Interacting Impedance

[illegible]

CHAPTER IV.

STATIC VOLTAGE REGULATORS INCLUDING ELECTRONIC TYPE.

STATIC REGULATING SYSTEMS.

Usually a generator voltage regulator produces a greater correction in the field for a small deviation in the normal voltage. In direct acting type of regulators, this amplification is partly obtained in the exciter and partly in the regulator. One can either have two or more stages of amplification or use a single machine with high amplification, such as a rototrol exciter. Regulation can be obtained by arranging the control field of exciter or rototrol to alter the response to any deviation in voltage from the standard voltage.

In one arrangement there is a D.C. Generator operating on the linear portion of its saturation curve and self-excited by shunt and series fields. There are a number of control fields to vary the voltage as required to keep it stable for operation at any point. Here it is assumed that a battery cannot be used as a standard voltage and also that vacuum tubes can not be used. There should be no moving parts except for the rotating machine, and they should have air gaps as large as in ordinary D.C. generators.

It is very common now to use voltage reference having interesting impedance characteristics depicted in Fig. IV.1, and explained earlier in Chapter III under the sub-heading "Voltage Regulation of the Main Exciter Rototrol". All currents before comparison are rectified.

As already mentioned, voltage regulating circuits using Rototrols for amplification can be used as illustrated in Fig. 2(a). There is a resistance path Z_R and a saturating reactor path Z_X with the current rectified of each path and fed into the control fields of the Rototrol. Such a circuit uses a Rototrol pilot exciter, the Rototrol exciter, and an A.C. Generator. The control fields are connected in such a way so as to be equal and opposite magnetically, at the moment when the A.C. generator voltage is normal at the regulated value. The Rototrol output voltage is maintained by its self-exciting shunt and series fields. If the A.C. Voltage varies, the control fields adjust the Rototrol as required. Figure IV-1 shows the intersecting impedance characteristics, the resistance branch being shown by R and the reactance circuit by X. Means are provided for altering the point of intersection or normal voltage, so that adjustment is possible of the value the regulator is set to maintain.

Figure 2(b) shows the static regulator with only a Rototrol exciter, omitting the pilot exciter used in the previous circuit. This main exciter has a higher amplification, and thus the required output to the field of A.C. Generator is controlled by a small amount of energy in the control field. There can be other static circuits as shown in Figure 2. The terminal voltage is balanced by a standard voltage, and the difference voltage which appears when the generator voltage varies from normal is applied to the Rototrol fields. A separate D.C. or A.C. source can be used as the standard voltage. Alternatively a constant potential device can be used, energized by the voltage of the generator with which the regulator is used. The design of this device is such that it supplies constant A.C. voltage at its output, inspite of large changes in the input.

In Figure 8(a) is shown a regulator controlling a Rototrol exciter with two control fields. These are so connected as to have equal and opposite magnetic effect when the A.C. generator voltage is at the predetermined normal value. When the load on the generator is increased causing the terminal voltage to drop, the "raise" field is more prominent and the Rototrol armature voltage rises, bringing the A.C. Voltage to normal. Thus the Rototrol control fields reach a balance. When the load is decreased, the 'lower' field predominates and again the armature voltage is brought to normal. In Figure 8(b) is shown a balanced-voltage circuit with a single control field. Normally there is no current flowing through the control field, and hence there are no losses and no heating in this field as long as the A.C. generator voltage remains at the normal regulated value. Thus here one may use a minimum of material in the Rototrol frame, as winding space and winding losses are less.

New Regulating Circuit.

By this means generators having ratings greater than 1300 KVA at 1250 R.M. can be controlled, and for mechanical reasons it is better to have conventional air gaps, such that one can fix the energy needs of the control field. It is

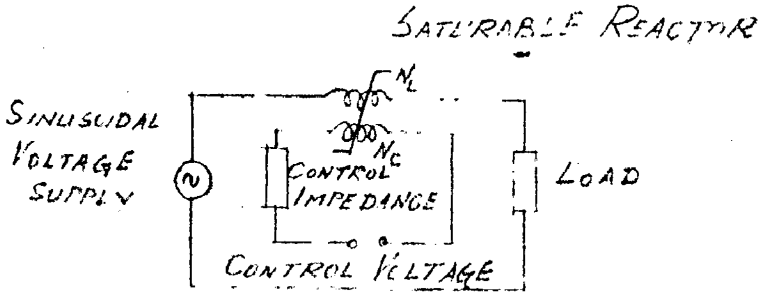
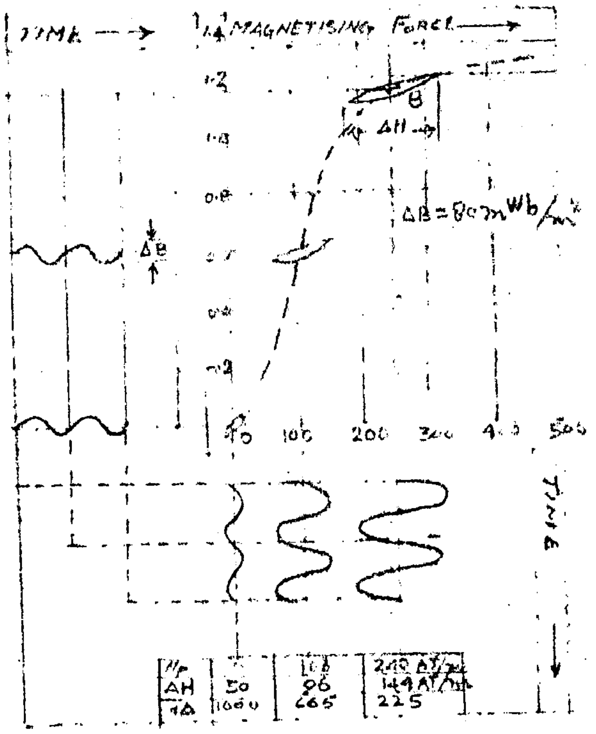


Fig. IV - 2:- Saturable Reactor Control Circuit.



IV – 3:- Change Of Permeability With Polarizing Field.

necessary to analyse thoroughly the previous designs of static regulators (of large size and losses) to obtain maximum energy output for a given deviation from normal voltage. Positive sequence or average three-phase voltage response was needed and thus the energy requirements were increased, as such a net work should be sufficient to carry the larger power of the measuring circuit. One solution was to first deduct the negative-sequence voltage from the line voltage, before filtering the voltage.

Previously large errors due to frequency were tolerated, but in this circuit it is aimed to regulate within plus or minus five percent departure from normal frequency. For this purpose a static regulator of high efficiency was designed and the theory and performance of the Circulating Current Static Network are given in the following paragraphs.

The diagram for the new regulating circuit is given in Fig. 3 (a) which uses a magnetic amplifier. The operation of the magnetic amplifier is as follows-

Fig. IV-2 shows the simplest type of saturable-reactor circuit. It is a basic circuit which explains the action of saturable reactors, and practical applications though complicated have this circuit as a basis. Its operation depends on control voltage and impedance, supply voltage, load impedance and the magnetization curve.

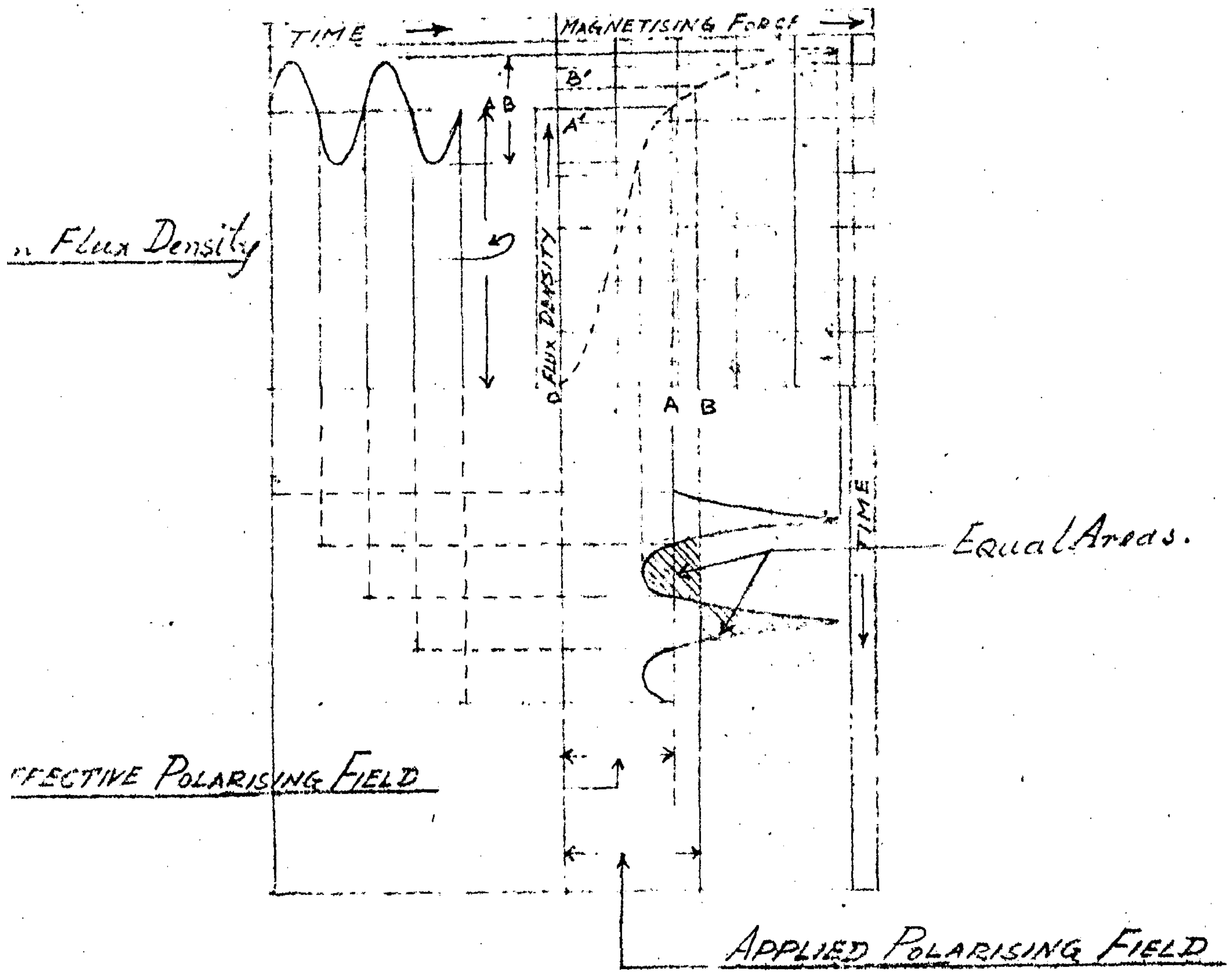


Fig. IV-4:- Change Of Magnetising Curve Non-Linearity With Polarizing Field.

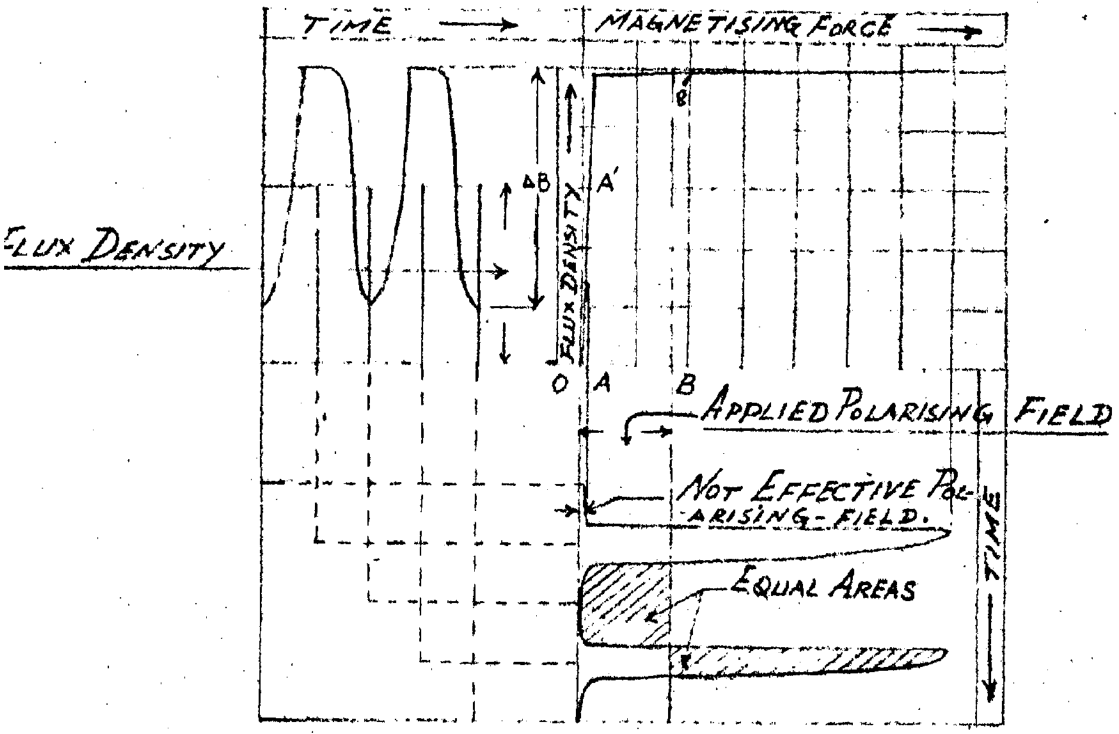


Fig IV – 5 :- Magnetising Curve Showing Large Non Linearity With Polarising Field.

Effect of small and large changes in flux density is shown in Fig. IV-3, IV-4 and IV-5. It has been assumed that the voltage and impedance of control circuit are very large resulting in constant current, inspite of transformer action effects of the saturable reactor. Also it is assumed that the amplitude of A.C. Voltage and impedance are small so that sinusoidal flux changes cause sinusoidal load current changes. The effect of variation on control voltage is shown in Fig.IV-3. It is observed that when the magnetic cycle is linear, a change in field produces a corresponding change in the average flux density.

Looking at Fig. IV-4 we find a different result if change in flux density ΔD is large and placed about an average flux density, so that there is a non-linearity of the magnetisation curve. Under linear magnetisation the average flux-density OA' requires a field OA. In the non-linear condition shown a field OB is required. The extra field AB is needed to satisfy the fundamental fact that for a complete cycle, the average value of a non-sinusoidal current should be zero. i.e.

$$\int_0^{\frac{2\pi}{\omega}} i_L \, d_t = 0 \qquad (1)$$

The above effect is important for control and working of saturable reactors.

Fig. IV-5 shows the effect of a pronounced non-linearity and is found in amplifiers used in modern practice. The ratio between applied and effective fields is ten to one in the figure shown, but it can be greater. The effect of equation (1) is shown by equal areas of Fig. IV-8.

By Ampere's Law for magnetic circuits, the sum of excitations along a closed magnetic circuit is zero.

$$\text{or } (HL) = i_c N_c + i_L N_L \qquad (2)$$

where i_c, i_L and (HL) are instantaneous values.

$$(HL)_{av.} = \frac{1}{2\pi} \int_0^{2\pi} (HL)\, d\theta = I_c N_c \qquad (3)$$

This is an important equation as it shows the control characteristics of the circuit.

Compared to electronic valves, relays or rotary amplifiers, the saturable reactor has a slow response to control signals and is unfavourable regarding weight, cost and size. They usually have low impedances upto 2000 ohms and are more reliable than other devices. This is so because saturable reactors are static in nature and have no moving parts with a limited life. They are robust and reliable like transformers.

Saturable reactors require no regular maintenance. The usual failures are of associated rectifiers or relays.

However, their servicing is a specialised work and if faults cannot be easily detected, the equipment has to be returned to the makers.

The output is fed into a magnetic amplifier, whose output side has two circuits in parallel. One of these is linear and the other has a saturable reactor or is non-linear. The difference of voltage drops in these two circuits is fed to the control field, and would be positive or negative depending on the magnitudes of voltage drops in these two parallel circuits.

Considering Fig. 3(a) we observe that at normal voltage the voltages in the resistor RR and the voltage in the saturable reactor X are equal. Thus the voltage difference of the two circuits is zero and there is no control field voltage. In the same manner Fig. 3(b) shows the voltage gradient when there is an over voltage. Here voltage in the resistor RR is greater and so the control field becomes positive, as the voltage across saturable reactor has the property of being nearly constant. The effect of positive control field voltage will be to lower the resultant voltage.

Fig. 3(d) shows the case of voltage gradient for an under voltage. Now the voltage in the resistor RR gets reduced when the voltage across X remains constant. The control field voltage becomes negative and its effect will be to raise the regulated voltage. Thus the voltage is kept constant, by neutralising deviations from the normal regulated voltage.

ELECTRONIC EXCITER SYSTEMS.

The static regulators explained above were in use before Rotating Amplifiers became popular. The latest type of Non-rotating exciters used are Electronic Exciters, which offer several advantages, such as no moving parts, controlled voltage and reduced maintenance. However, their cost is more than for an ordinary main exciter, thus while rototrols are in general use, electronic exciters have a limited use for A.C. synchronous machines.

Electronic exciters consist of a power rectifier fed from an A.C. source and having necessary controls, protection and regulating equipment. The different parts have to be co-ordinated to meet the excitation requirements of large A.C. machines. Ignitron type power rectifiers have been used in industry since many years, and are reliable and efficient.

Rectifier output can be only as reliable as the source of A.C. input power, which is therefore considered a part of the rectifier. The source of A.C. power input may be taken directly from the terminals of the A.C. generator being excited; from a separate A.C. generator being excited from a separate A.C. supply which is independent of the A.C.generator; or lastly from a separate generator supplying power only to the rectifier, but which uses the same turbine (that drives the main A.C. generator) as its prime mover.

It is observed that in the first case the electronic exciter is self-excited while in the second and third cases it

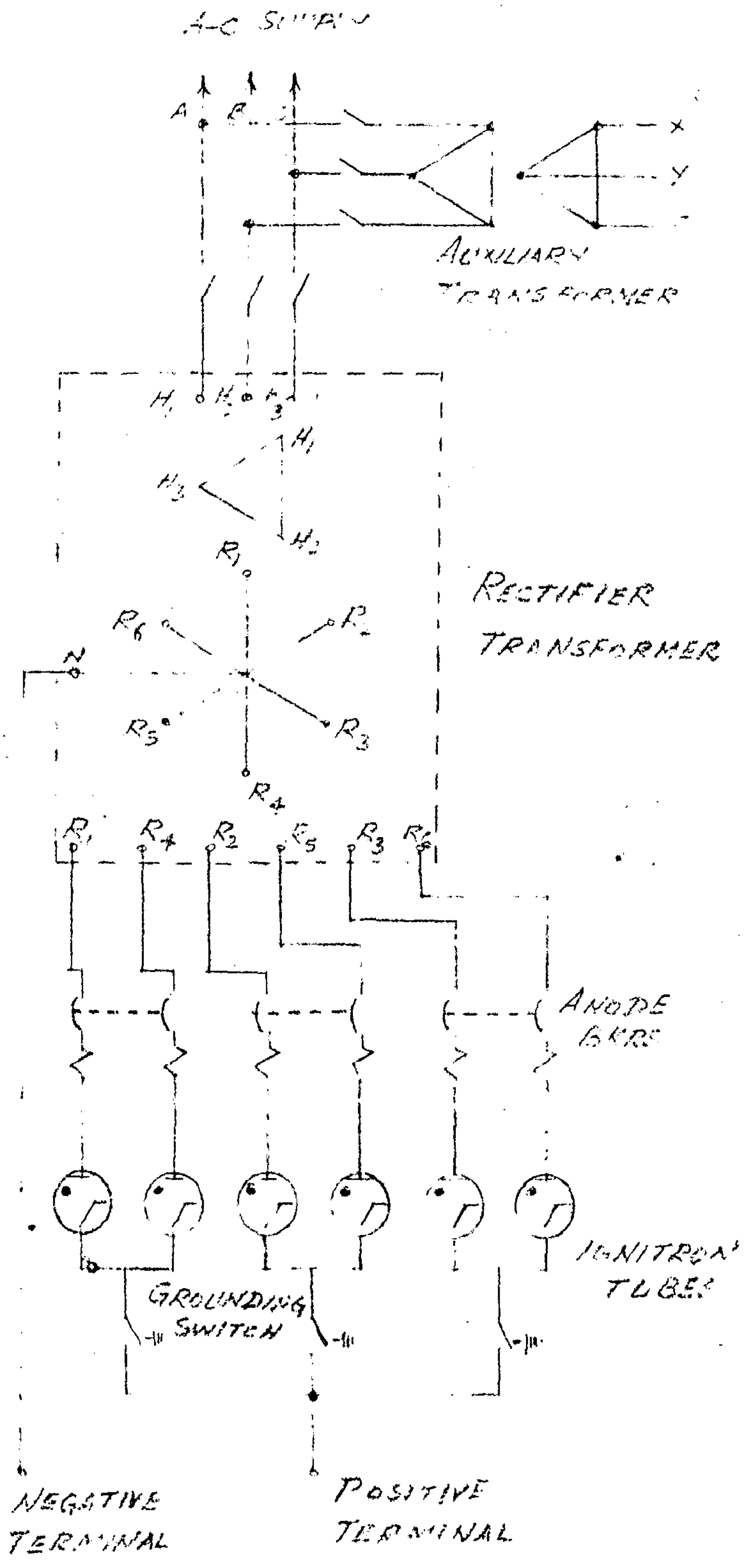


Fig. IV-6:- Electronic Main Exciter Fed Through a Rectifier Transformer from A.C Generator - Terminals -

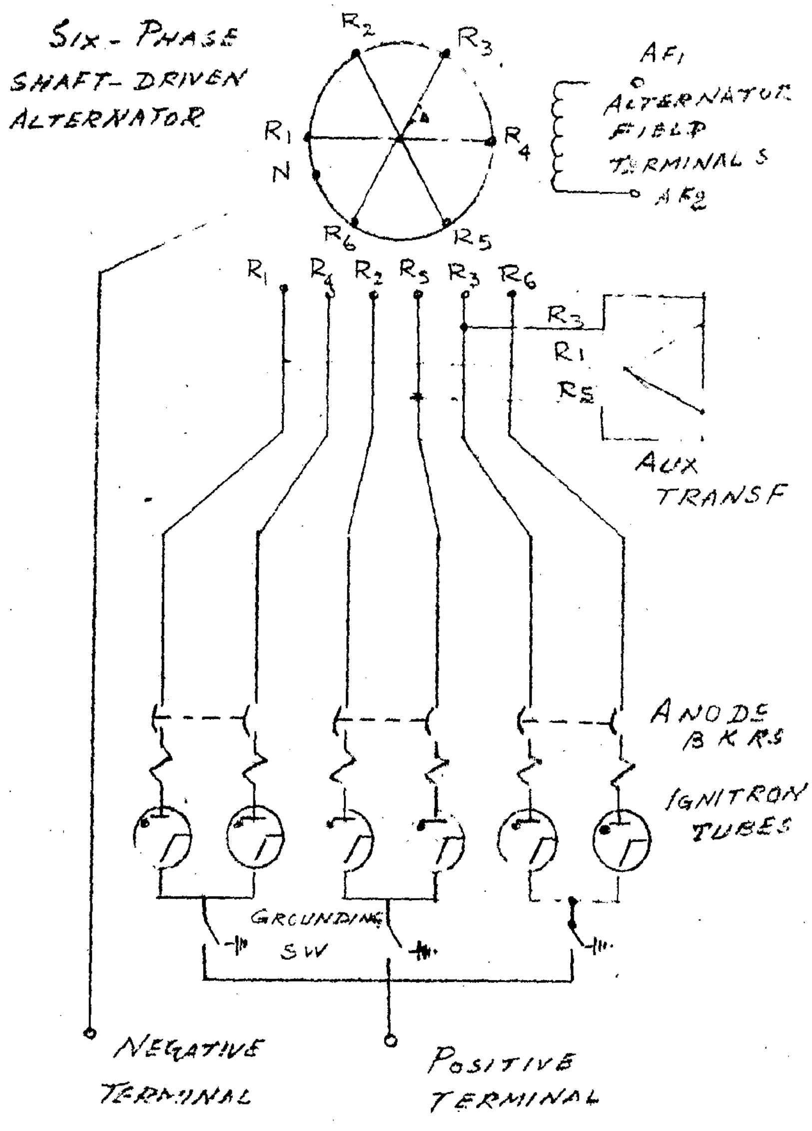


Fig-IV-7:- Electronic Exciter Supplied from a 6-Phase alternator Connected directly to the Main Generator Shaft.

is separately-excited. If rectifier is being supplied from a high-voltage source such as alternator terminals, a transformer is needed to reduce the voltage to desired value for the rectifier. Connections of transformer are delta on the high tension side, and six-phase star on the low tension side. The circuit for such an arrangement is shown in Fig. IV-6. The primary of the transformer may be energised from the terminals of main A.C. generator, or from an auxiliary power supply, or from any independent source. The rectifier consists of three groups of two Ignitron tubes each, the two tubes of each group being connected to opposite phases of the six-phase secondary through a two-pole anode circuit breaker. Opening of a breaker de-energises both tubes of a group. These breakers are of high speed, and are equipped with reversed-current trip arrangement for automatic reclosing. With the occurrence of an Ignitron arc-back, the circuit breaker is automatically opened at high-speed. If however a second arc-back occurs in a short duration, the anode circuit breaker now opens and locks the breaker for detailed inspection of the unit.

There is nothing special about the third case; which is separate excitation by another generator, using as its prime mover the same turbine that drives the A.C. generator. Now we shall deal in detail the second case of separate excitation from a separate A.C. supply entirely independent from A.C. generator being excited. Fig. IV-7 shows a six-phase alternator supplying an electronic exciter.

As regards the Main Exciter rectifier the details

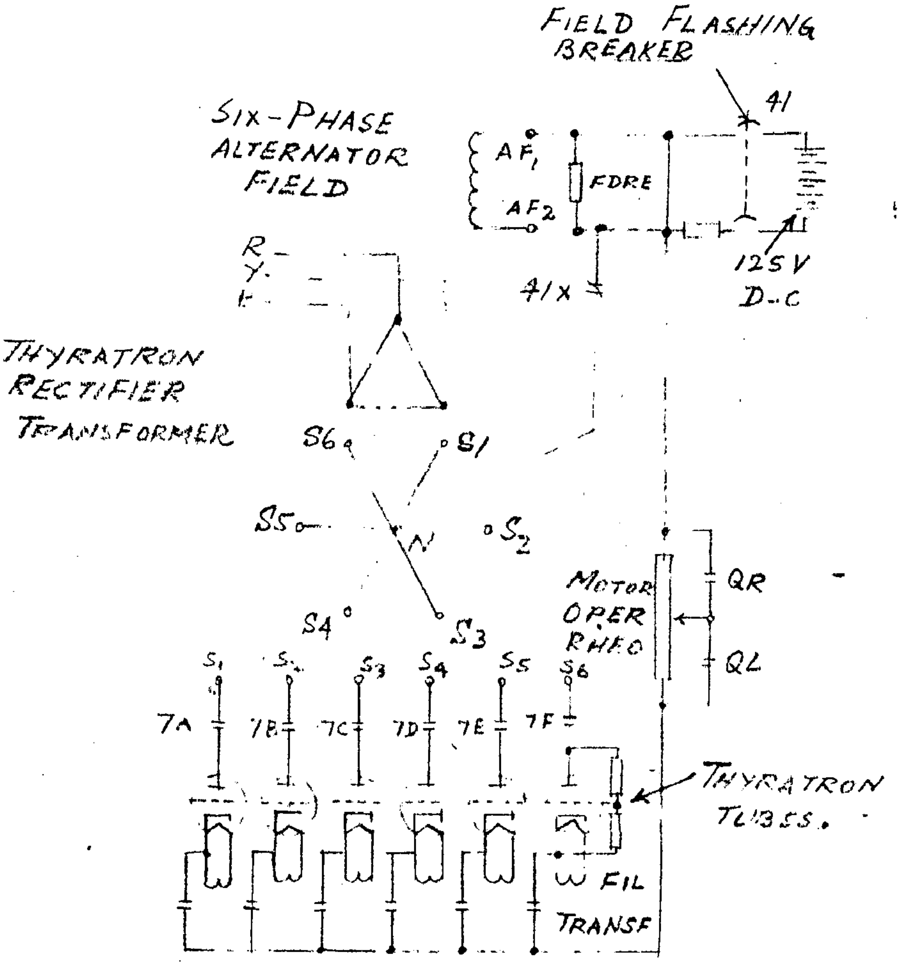


Fig-IV-8:- Self Excitation from a 6 Phase Alternator Through a Rectifier Transformer Using a Thyratron Rectifier.

FDRE = FIELD DISCHARGE RESISTOR

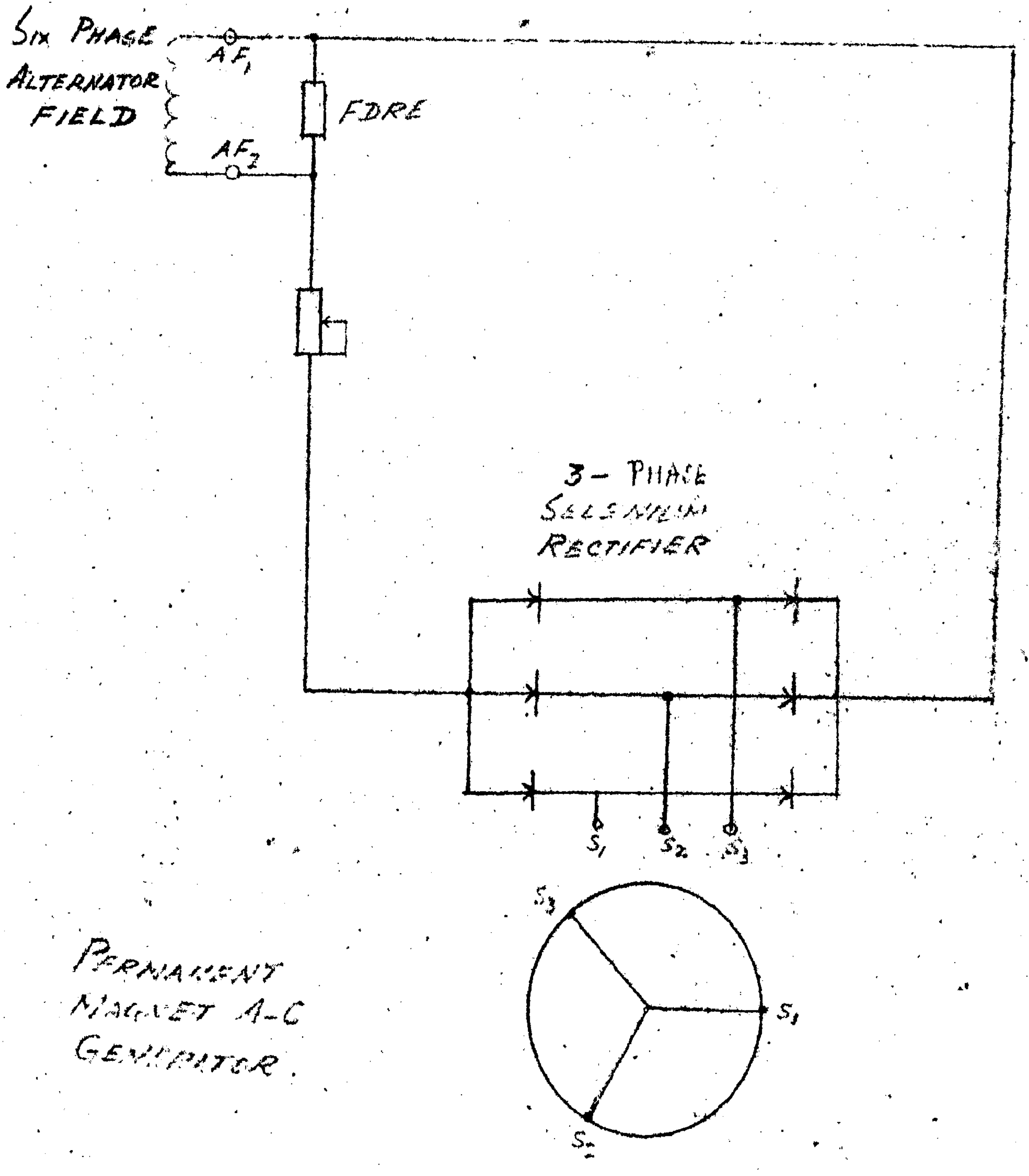


Fig-IV-9-Three-Phase Permanent Magnet Generato
And Rectifier To Provide Separate Excitati

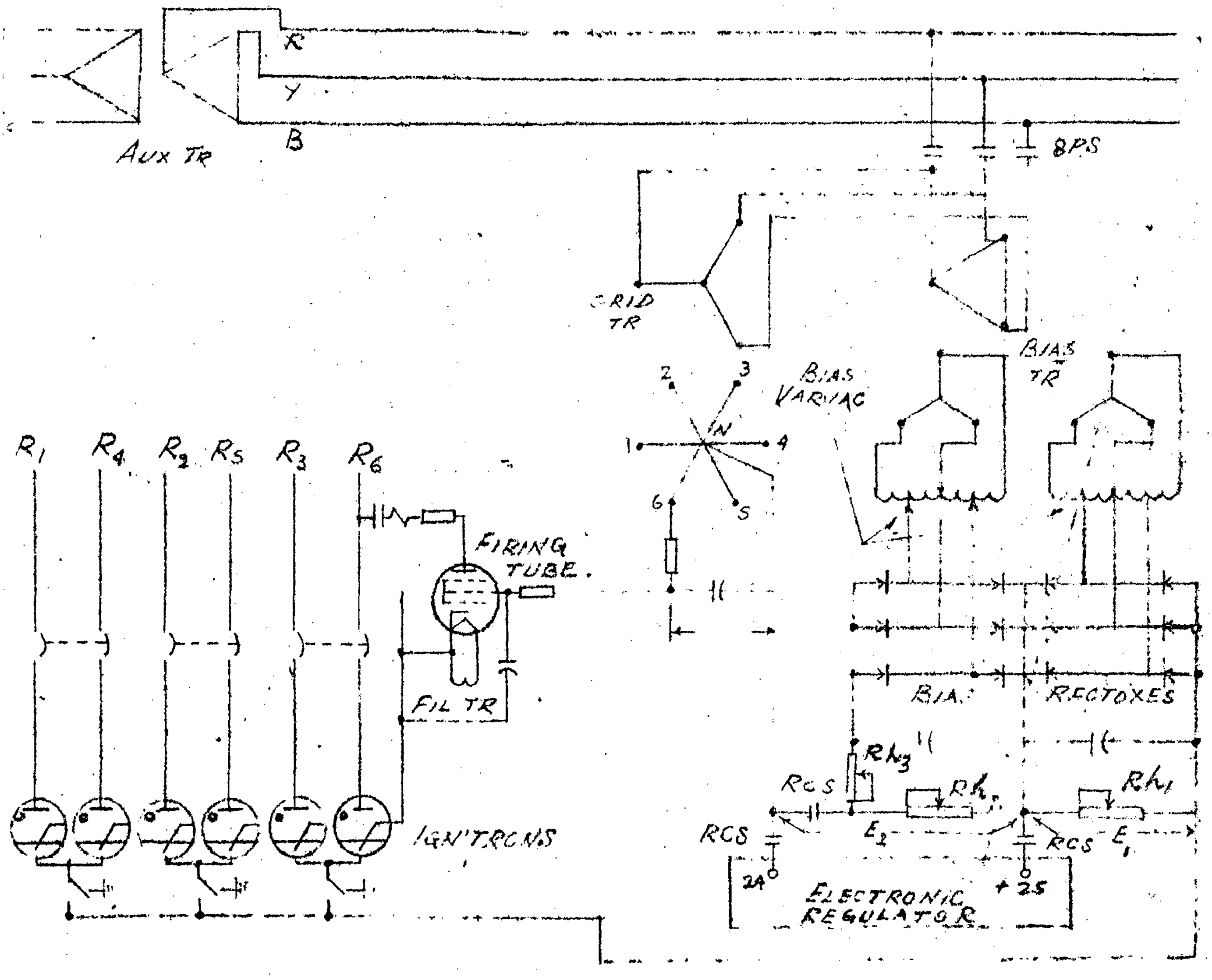


Fig. IV-10: Circuit For Controlling Release Of Thyratron Firing Tube To Adjust Main Exciter Voltage are the same as in Fig. IV-6. There are some complications due to the necessity to provide excitation for the six-phase alternator. One of the ways in which it can be provided is shown in Fig. IV-8. Here a six-phase alternator supplies a thyratron rectifier through a rectifier transformer. The field voltage of the alternator is kept constant by a voltage regulator. A 125-volt battery is used to start operation of the alternator field. The thyratron rectifier transformer gets its supply from the same source as the supply to the main exciter rectifier.

An alternative method for providing excitation to the six-phase alternator is shown in Fig. IV-9. This uses a three-phase permanent-magnet A.C. generator as power supply. The good quality permanent magnets are fixed on the same shaft as the main A.C. generator to serve as the rotor, and there is an ordinary three phase armature winding on the stator. Output of this permanent-magnet A.C. generator is rectified by a 3-phase selenium rectifier of bridge type, and fed into the field of the six-phase alternator.

It is possible to have a standard three-phase alternator in place of six-phase unit shown in Fig. IV-7. However in that case a rectifier transformer is used to convert the Ignitron Rectifier input to six-phase.

Each ignitron tube is of the anode firing type and the firing circuit is indicated in Fig. IV-10. A thyratron

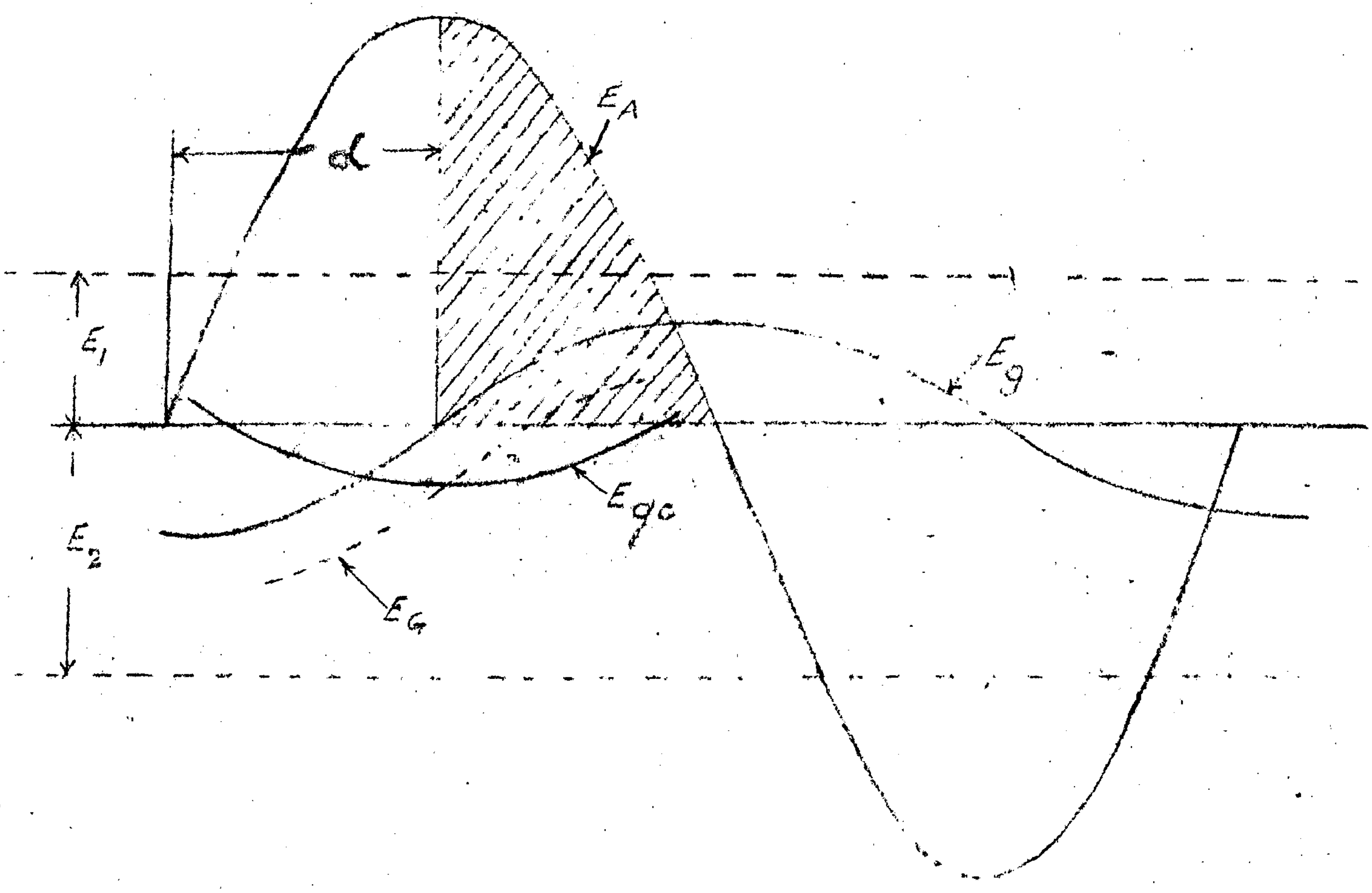


Fig. IV-11- Control Grid Voltages Applied To Thyration Firing Tube.

tube and its ignitor are connected in parallel with the ignitron. It is conductive when anode voltage is positive with respect to its cathode and its grid is released. As current flows through the ignitor, this initiates a cathode spot and fires the ignitron.

For any reason if the ignitron fails to conduct, the thyratron tries to carry the load current, but it is cut cut off from the circuit by the anode breaker. The output voltage of the electronic exciter is varied by regulating the point on its anode voltage wave, at which the ignitron tube becomes conductive. Looking at Fig. IV-10 we observe that this point is found by releasing the control grid of the firing thyratron, which is controlled by a sine-wave grid transformer, a rectox for fixed positive bias, a rectox for variable negative bias for manual control, and an electronic regulator supplying variable negative bias for automatic control. The voltage E_1 across rheostat Rh_1 is a positive grid bias, while the voltage E_2 across Rh_2 is a negative grid bias.

The sine-wave voltage E_3 on the grid of the thyratron is delayed by 90° from the anode voltage, and is connected in series with the positive bias and the negative bias. This is shown in Fig. IV-11. Initially Rh_1 and Rh_2 are adjusted to give the required value of positive and negative biases. Control of exciter voltage is secured by altering the setting of rheostat Rh_2, which changes the negative bias.

The biases E_1, E_2, and E_g addeup to give the total grid voltage shown by E_G, and changing the negative bias locates the point where the total grid voltage is more positive than the critical grid voltage E_{cg} of the firing tube releasing it for conduction. Then the ignitron becomes conductive by current in the igniter, and remains so for the remainder of the positive half-cycle of the anode voltage. Angle α of Fig. IV-11 is called the angle of grid delay. In the above use of a positive and a negative grid bias we get a wide range of control of the angle α, and hence for a large range of control of the exciter output voltage. When the voltage is controlled by the automatic electronic regulator, the negative grid bias E_2 is substituted by a varying negative bias voltage from the regulator.

Application and Response of an Electronic Exciter.

Main exciters and excitation systems should be able to operate continuously for long periods and replacement of parts that wear out should be possible without any shutdown or unloading. This is required because A.C. generators have shown capability of continuous operation without any shutdowns for long durations. Ignitron and thyratron tubes in electronic exciters get deteriorated and have to be replaced, but it is essential that this should be possible without affecting the excitation of the A.C. generator. Electronic main exciters are therefore so designed that they can supply full excitation even with two of the six ignitron tubes out of service. Thus , with all six tubes in service, the capacity is one and a half times the actual requirements.

Again the overload capability of ignitron tubes is such that for a short duration the rectifier can supply full excitation with only two of the tubes in service. When replacing any tube, the anode breaker, grounding switch, and firing tube anode breaker are opened to enable replacement of ignitron or firing thyratron of any group. This is possible without affecting the operation of the remaining two tube groups.

To overcome the effects of faults on neighbouring lines or voltage drops due to other causes (if self-excited from the terminal of the main A.C. generator) it is necessary to increase the generator excitation. One method to compensate for this low voltage is to design the rectifier to produce normal ceiling voltage when input voltage is 75 percent of normal. Thus for normal load, the voltage has to be reduced by controlling the firing point. For this we need a bigger rectifier and therefore delayed firing during normal operation.

In the case of separate-excitation the rectifier power supply is made very reliable, for which the best is the shaft-driven three-phase or six-phase alternator. Sometimes the supply used for power house auxiliaries is used as standby for the rectifier.

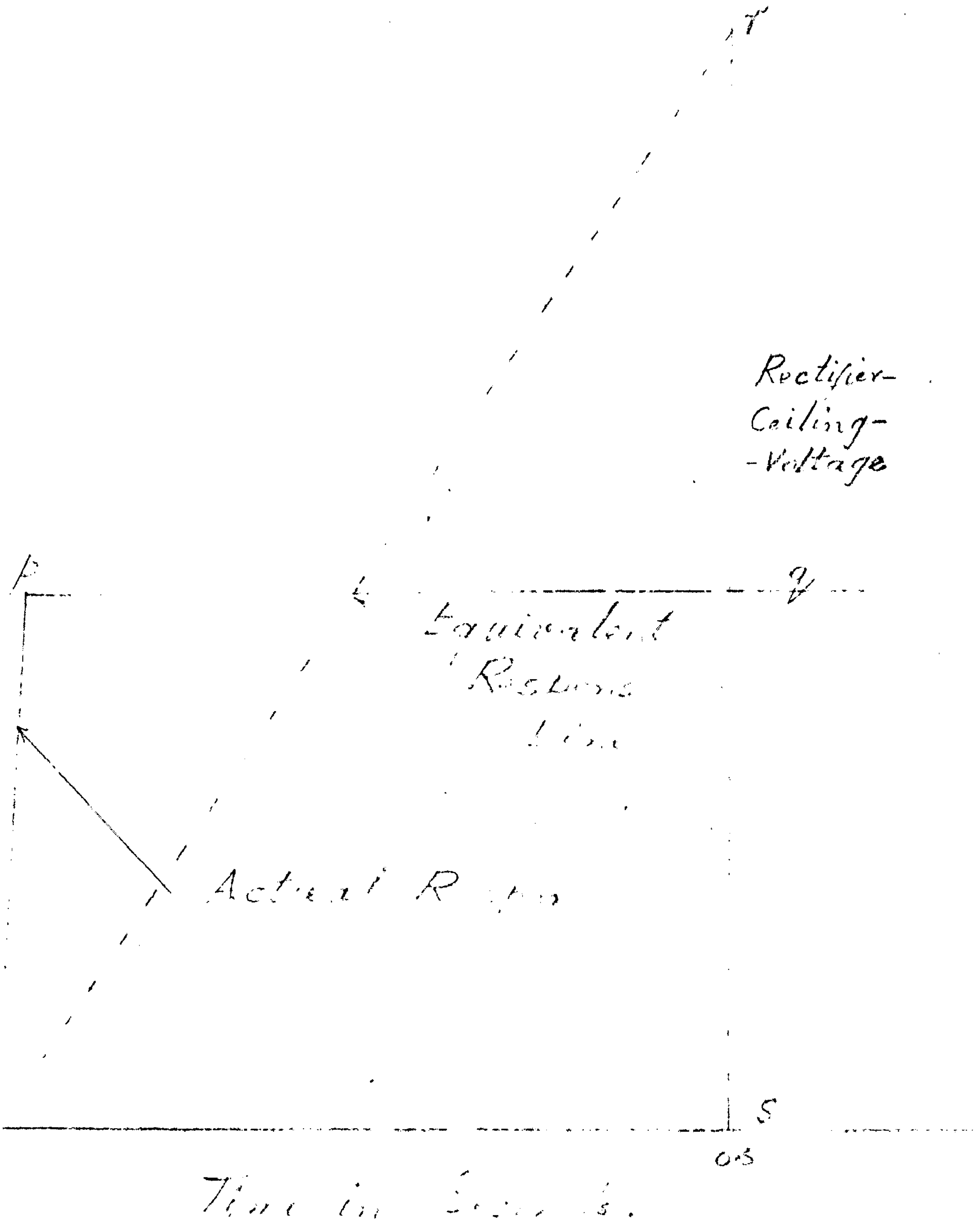


Fig. IV-12:- Electronic Main Exciter Response.

Response.

The ignitron rectifier is able to increase or decrease its voltage output with practically no time delay. Referring to Fig. IV-23 the line Op shows the actual voltage response, and pq the ceiling voltage. Line Or has been so drawn that area Ors = area Opqs under the response curve during an interval of 0.5 second.

By definition, the rate of response is the slope of line Or. Thus exciter voltage has not reached the ceiling value at the end of 0.5 second interval. When Op is assumed to be 1.0 per unit, Or is nearly 2.0 per unit, and rate of response of $\frac{2.0}{0.5}$ = 4.0 per unit per second. As the actual time for increase of voltage from 0 to p is less than 0.1 second, so the actual rate of voltage increase is more than 10.0 per unit per second.

CHAPTER V.

HARMONIC EXCITATION SYSTEM.

GENERAL.

In commercial synchronous machines, the flux wave has a fundamental and all odd harmonics which are caused by slotting of stator and rotor, saturation of the rotor teeth and in salient-pole machines also by the shape of pole head. Similarly the wave shape of generated voltage has harmonics of different amounts, depending upon the chording and distribution of the stator winding in relation to the harmonic waves. These harmonic voltages in single phase can be made to do work. As practically all alternating energy is transmitted as three phase power, the third harmonic and its odd multiples are in phase with each other in all phases, and hence will not cause any third harmonic current to flow between phases in the external circuit. Thus, a four-wire system is necessary for harmonic voltages to do useful work.

Now if some of the third and odd multiple harmonics in the flux can be converted to useful power in an additional stator winding, we get this power without appreciable change in the excitation of main generator field. This winding can be provided in a machine whose stator is so slotted that it can accommodate

a separate balanced stator winding, having number of poles equal to order of harmonic multiplied by number of rotor poles. It will also cancel all fundamental components and harmonic voltages, except those of third harmonic and its odd multiples.

For utilizing the harmonic power to self-excite the generator, the following design and performance considerations are required to have reliable controls-

i) Substitution of rotating amplifiers and driving motors requiring auxiliary power.

ii) Control unit should be such that voltage regulating equipment of static type already found could be used for automatic voltage regulation.

iii) Such regulating equipment should provide regulation of terminal voltage, line-drop compensation, and reduced excitation for under-excited conditions.

iv) Arrangements for changing over from one source to another without disturbing service for cases where a number of excitation sources are available.

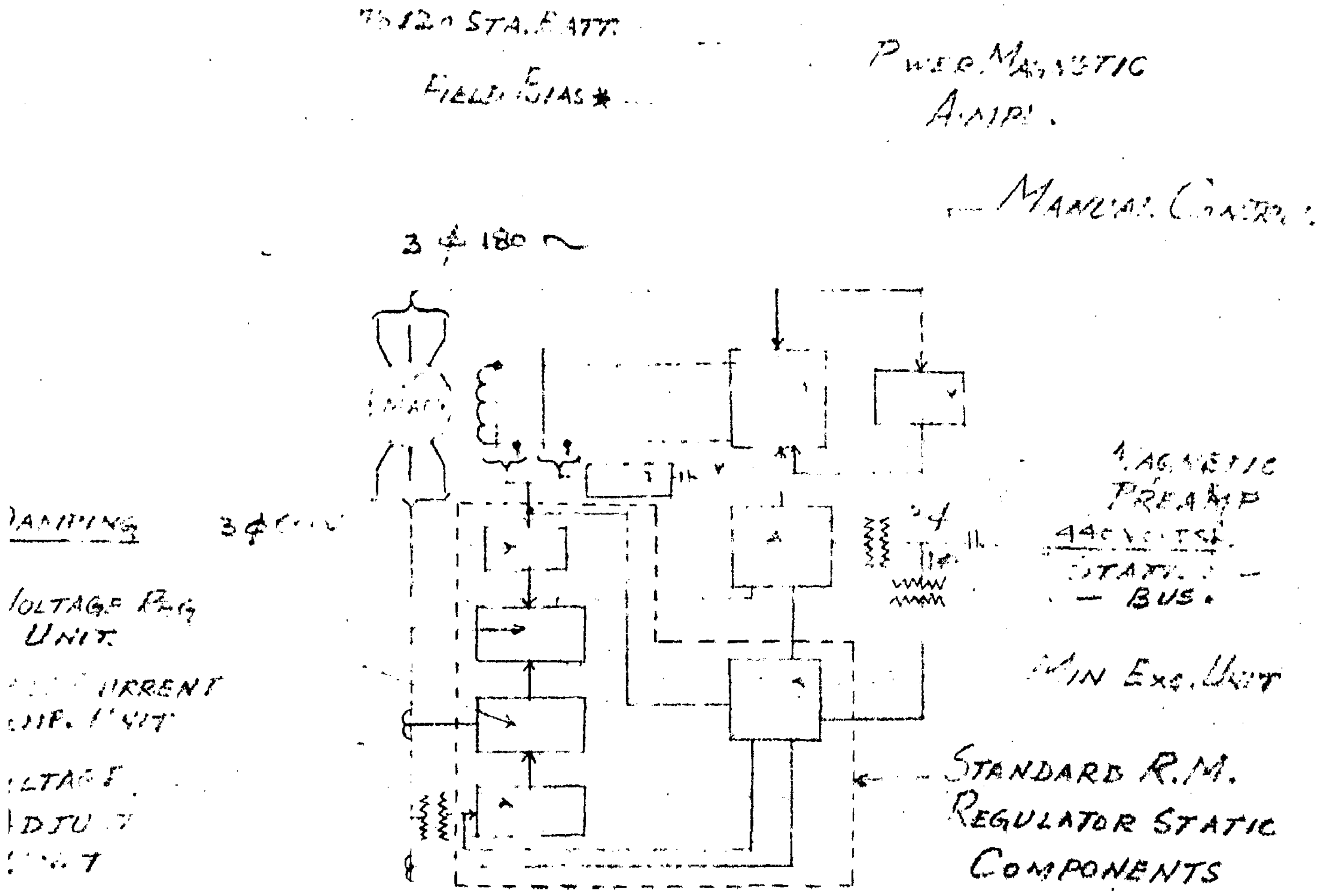
v) The design should provide enough excitation during fault conditions to produce a sustained high armature current.

vi) Some arrangement for manual control of the excitation which can be used if the automatic voltage regulator fails.

vii) It should be possible to change the location of the control unit, and the site should not be permanently fixed.

viii) For changes of generator load, the equipment should have far better response speed compared to rotating exciters and voltage regulators.

ix) It should have a flashing circuit in the generator field for initiating excitation.



* Gen Field Bias Used To Establish a Residual Flux When starting Only.

Fig-V-1:- Block Diagram of Regulation And Excitation System.

ARRANGEMENTS FOR HARMONIC POWER CONTROL.

Fig. V-1 shows an automatic control system for fulfilling all design considerations mentioned above, and to control harmonic power. It consists of a static voltage regulator, a magnetic pre-amplifier of push-pull type, a power magnetic amplifier having silicon rectifiers, and essential protective devices.

This equipment is housed in two cubicles. One of them has the static voltage regulator components and magnetic pre-amplifier, and in the second cubicle are mounted the saturable reactors and power rectifiers. The second cubicle is meant for operation by remote control. They can be kept at any convenient site in a power house, but forced-air cooling should be provided for power rectifiers and saturable reactors.

It is possible to locate the excitation unit at the end of the generator, where forced-cooling by a fan on the generator shaft is convenient or it can have convection cooling. In the excitation cubicle in addition to the power magnetic amplifier there is a static hand control unit, maximum excitation limit circuit, fuse in each rectifier branch of a three-phase bridge, non-linear resistance to reduce surges, and a flashing circuit for generator field. Each branch of the 3-phase-rectifier is mounted on a draw-out trolley for ease in maintenance without affecting the generator load. Draw-out trolleys have fuses, shunts, testing jacks and signal lights to make checking of rectifier simple and safe.

ARRANGEMENTS FOR HARMONIC POWER CONTROL.

The capacity of rectifiers is so designed that they take full load when one branch in each of the three phases is not in service. If a rectifier fails, the fuse will eliminate the faulty unit from the system. Then the draw-out trolley can be taken out and the rectifier repaired, but the unit keeps operating on full load, and there is neither any danger to human life nor any disturbance on the power system. Out of the currents induced from the generator field during fault conditions, the positive currents are carried by the rectifiers themselves, and the negative currents are absorbed by a non-linear resistance connected across the field winding.

In order to provide hand control of the generator voltage independent of the voltage regulator and any external power source, there is the manual control unit. With this the generator voltage can be adjusted by adjusting a small rheostat on the control board. Each setting will hold the voltage constant for a particular load and power factor. This hand control circuit is energized from the harmonic voltage, and a constant source of D.C. power is used to control the power amplifier output by the rectifiers and saturating transformers. A maximum excitation limit circuit is also combined with the above circuit, to limit the excitation during fault conditions to a safe value in the case of a fault at the machine terminals.

Tests and analysis are necessary to find the characteristics of harmonic voltage and power under both steady-state

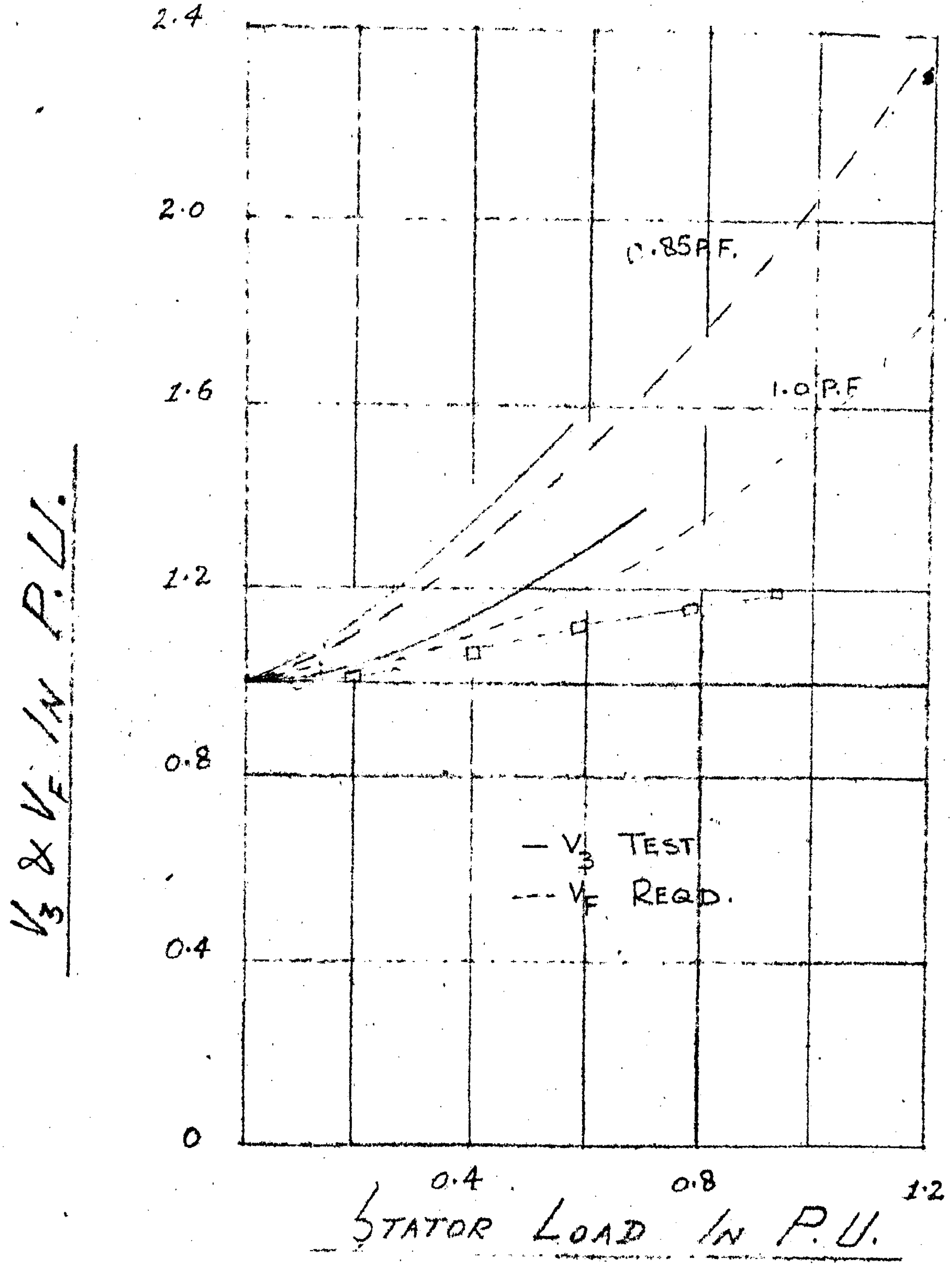


Fig V-2:- Variation Of Third-Harmonic Voltage As a Function Of K.V.A. Loading

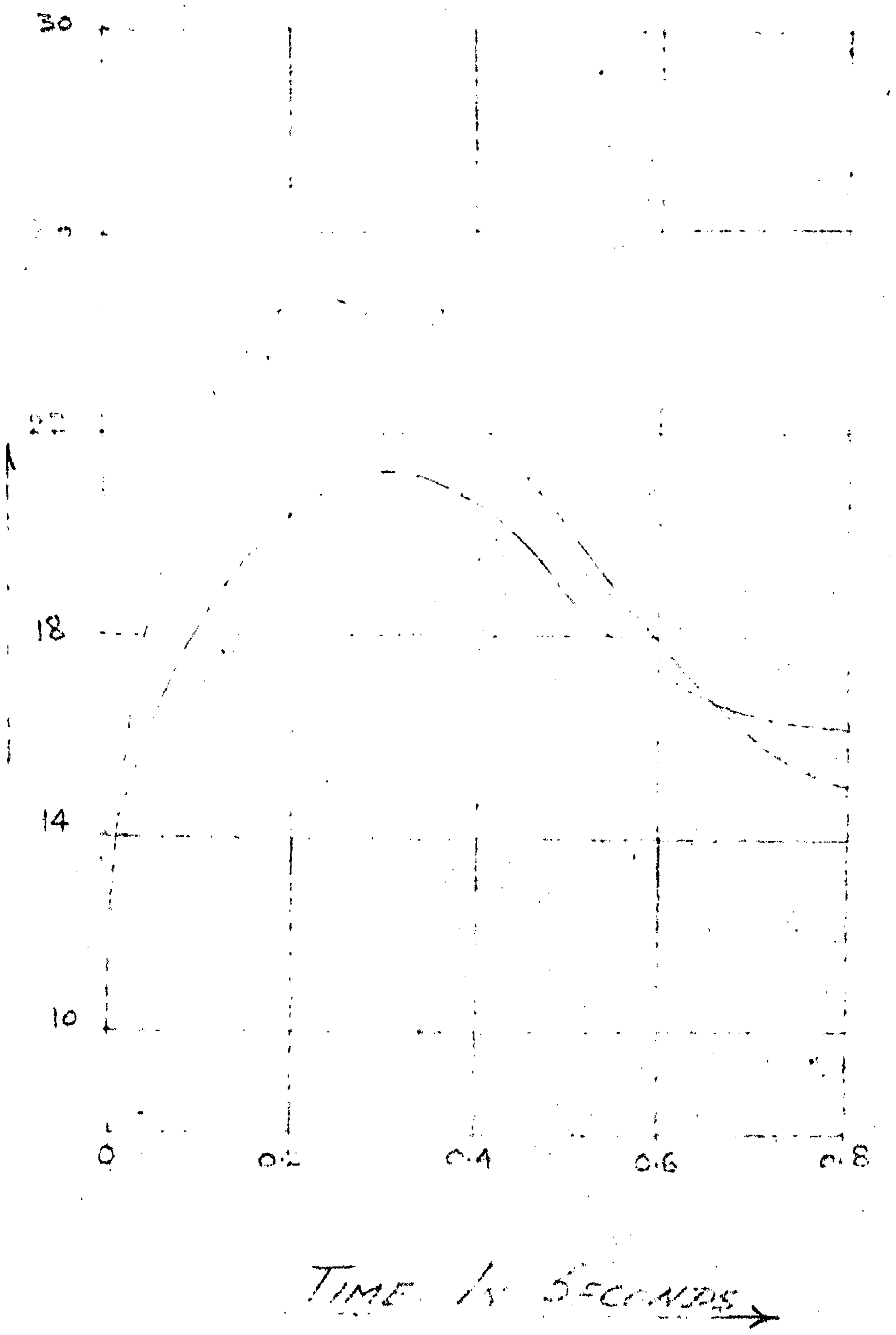


Fig-V-3:- Effect Of Short Circuits On

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and transient conditions. This helps in creating a good system for harmonic power control. Results are shown in Fig. V-2 and Fig. V-3, as also the generator excitation requirements in Fig. V-2. Careful scrutiny of these figures will show-

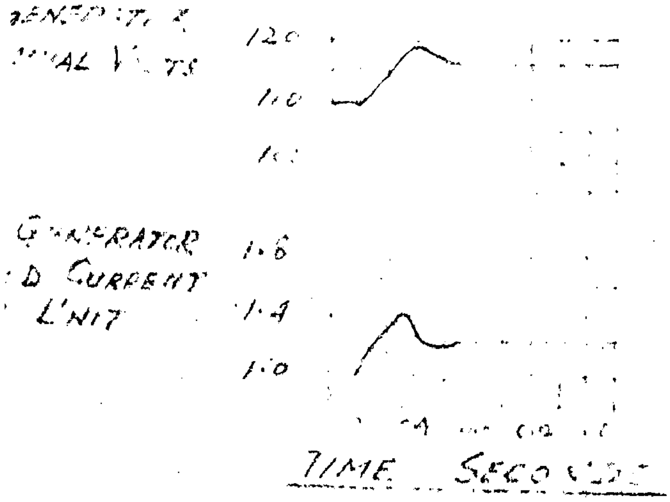
a) For power factors of 0.88 to 0.95 in Fig. V-2 from experimental results showed that the harmonic voltage increases with stator load at roughly the same rate as the machine excitation requirement.

b) For main-winding short-circuit conditions, the harmonic voltage and power are enough to produce a sustained large armature current needed for proper function of the protective relays.

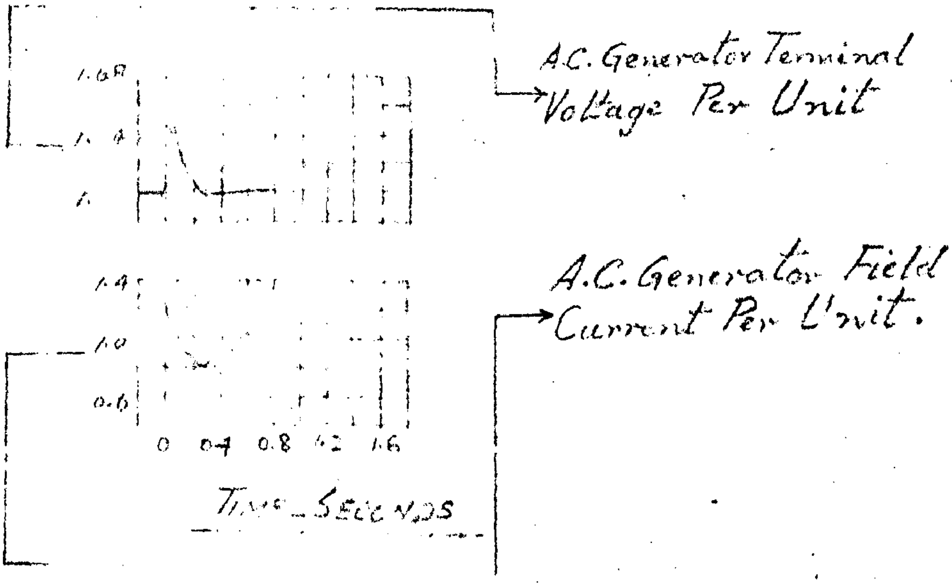
Referring to Fig. V-3, a fault makes the harmonic voltage to rise and increase the generator excitation. This will increase the fault current and the harmonic voltage. By limiting the excitation under fault conditions, one can limit the maximum harmonic voltage. A rectifier voltage varying according to the harmonic voltage is balanced against a zener diode reference. If the harmonic voltage rises to a pre-determined value above normal, the zener diode conducts and permits sufficient current to flow through the control windings of the power amplifier in a direction to reduce the power amplifier output and limit the machine excitation. When the voltage regulator is operating and compensating and limiting circuits are disconnected, the voltage is maintained within ± 1/2 per cent for all loads and power factors.

ARRANGEMENTS FOR HARMONIC POWER CONTROL.

Looking at Fig. V-2, due to the rising nature of the harmonic voltage with load paralleling the excitation requirements, small action is required by the regulator to maintain constant voltage. However, the voltage regulator is needed to reduce response time under sudden changes of load, and to trim the action of the rising harmonic voltage curve. As the residual harmonic voltage magnitude is nearly zero, a flashing circuit for the generator field is required to start excitation of the generator. This circuit gets its power from a 125-volt station battery, so that excitation power for starting is available in an emergency when A.C. power is not available. When the start switch is operated, the field bias circuit gives excitation power as long as the generator open-circuit voltage rises to rated value. At this time an automatic transfer to self-excited condition takes place. All this takes about 10 seconds, so the current drawn from the station battery is negligible.



g-V-4:- Response Of Excitation System To a Step Change in Reference Voltage.



ig-V-5:- Excitation System Behaviour During Rejection Of Load.

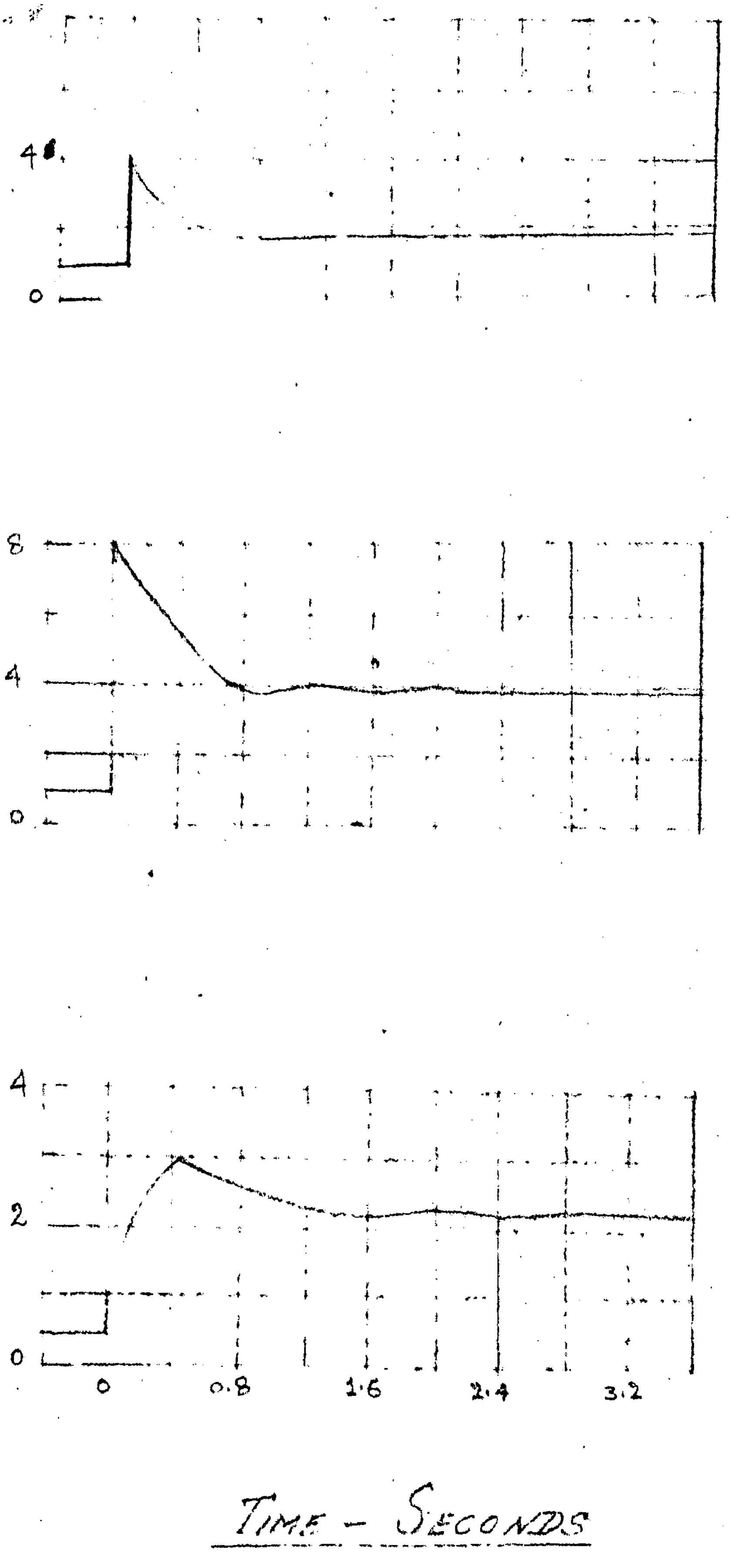


Fig V-6:- Three-Phase Fault Response Of A Excitation System.

IMPORTANT TEST RESULTS.

In order to find out the effect of disturbances on the system, three tests were conducted on a 25,000 KVA 13,200-Volt steam turbine-generator, and the results are shown in Figs. V-4, V-5, and V-6.

Fig. V-4 shows the response when a step change of 5 per cent is made in the A.C. regulator, when the generator is at no load. Here the voltage was forced to the value in less than 0.3 second and settled within 1/2 percent of the final regulated value in nearly 0.6 second. Fig. V-5 shows the effect of rejection of a reactive load of nearly 4,500 KVA on the system performance. Oscillogram indicates a recovery time of 1/2 per cent of the normal generator voltage in less than 0.3 second.

The effect of a 3-phase fault on generator terminals on the system is shown in Fig. V-6. This fault suddenly applied induces a high field transient which makes the harmonic voltage rise about three times the original value before the field transient decays. Increase in harmonic excitation voltage causes a sustained large armature current, and this is needed to make relays of the system function properly.

The above tests show that harmonic excitation is possible and gives an outstanding performance. By using this system in preference to the conventional system with a D.C. exciter, one can reduce building and foundation costs. This advantage holds good both for salient pole and non-salient pole machines.

CHAPTER VI.

EXCITATION SYSTEMS FOR SMALL GENERATORS.

GENERAL.

During the last several years due to demand of small generators for military and aircraft use, there has been a great development in excitation systems for A.C. generators upto 2000 KVA. Now this experience along with new materials has helped the designer to produce new techniques for several excitation systems for commercial generators. Upto 1948 excitation for all automatically regulated generators was obtained by rotating exciters controlled mechanically by regulators. For some applications these regulators are still being used in present times. However, in 1948 the use of square-loop materials and selenium rectifiers made it practicable to use magnetic amplifiers in voltage regulators and excitation systems. Due to higher cost they were used only for military and aircraft purposes but not for general purposes.

The use of silicon rectifiers and other semiconductor devices and reduction in cost of magnetic materials helped in great development in static excitation equipment. At present there is an increased use of magnetic amplifier and semi-conductor types of regulators and excitation systems for commercial applications on A.C. generators upto 2,000 KVA; the important uses being as follows:-

i) All types of aircraft.

ii) Power equipment on land according to military requirements.

iii) Service generators for ships according to Navy specifications.

iv) Power and portable equipment for commercial use.

v) Standby power for commercial use.

vi) Standby power and service for Marine ships.

vii) Power supplies for computer and other special applications.

The generator design and excitation system for commercial and military aircrafts, Navy service and power equipment for military use are dependent upon detailed specifications for the particular use. Other applications have equipment built to commercial practice instead of military needs. Here one finds that due to lower cost, if standard products meet the industry's needs, special designs are not considered.

When used for standby power, or marine-ship service, one requirement is to start stand-by motors, while keeping the voltage high enough to keep motor starters energized. Steady-state accuracy is ± 2 per cent for load, temperature and drift changes. Where the generator is connected to a complex distribution system, sufficient output is needed during distribution system faults to give selective tripping of breakers. In the case of portable power there is severe vibration for the excitation system, regulator and motors, which are mounted on the generator. For such general applications to have low maintenance, it is better to have simple and reliable circuits.

GENERAL.

The loads at some military installations are combinations of motors, lighting and electronic equipment. Hence requirements for voltage changes with load need the use of generators with low reactances with co-ordinated excitation systems. In computer power supplies accuracy requirements are ± 1/4 to 1/2 per cent for steady-state; and the problems for voltage modulation, harmonic distortion and wave shape changes and transient conditions become important.

STEADY STATE AND TRANSIENT PERFORMANCE OF A REGULATING SYSTEM.

(a) The voltage accuracy with paralleling means inoperative should be within ± 1 per cent when the load changes from no-load to full-load, and a frequency variation within ± 4 percent.

(b) If load is kept constant, the voltage accuracy should be within ± 1/2 per cent for an ambient temperature range from 10°C to 40°C.

(c) Voltage drift should not exceed ± 1 per cent for a one hour period, when load and ambient temperature are kept constant.

One can combine the above three requirements into one by demanding an accuracy of ± 2½ per cent for change from no-load to full-load, with a frequency variation of ± 4 percent and including drift and ambient temperature changes from 10°C to 40°C. A variation of ± 1 per cent should be expected for load changes. So the following transient specification would be reasonable.

When full load is applied or rejected, the voltage should not vary more than 20 per cent from starting voltage, and should recover and remain within ± 1 per cent of the initial voltage within one second.

ADDITIONAL CONSIDERATIONS.

(i) Modulation of Voltage.

This is the magnitude variation of consecutive sine waves in the generator voltage. If the excitation system source frequency is different from generator frequency, voltage modulation can be produced by the excitation system. However this is no consideration, when the generator output voltage is used for voltage-regulated power.

(ii) Harmonic Distortion.

Excitation systems which get power from generator terminals (through magnetic amplifiers or controlled rectifiers) may introduce notches in the generator wave, due to high rate of change needed by the excitation system. This is called harmonic distortion, and can be suppressed when necessary.

(iii) R.M.S. Peak or Average Voltage.

The wave shape of a small generator changes with load, so the three types of voltage do not remain in the same proportion. As there is no simple means to permit the sensing of R.M.S.Voltage, hence either peak or average voltage can be regulated, and this is important when accuracy of the order of 1/2 to 1 per cent is required. It is observed that polyphase rectifier loads are more sensitive to peak voltage, while motor torque is more sensitive to average voltage.

(iv) 3-Phase or Single Phase Voltage Sensing.

With balanced loads it is common to sense one phase of the generator, rather than the average of line to line voltag in the case of unbalanced loads, if one regulates the most loade phase it will result in overvoltage on the other phases, so it would seem reasonable to take the average of the three line to l voltages. In this case accuracy of a particular phase to narrow limits would become difficult to obtain.

v) Paralleling generators.

Such circuits are needed to get satisfactory distributio of reactive KVA among paralleled generators. Paralleling circui ense reactive current and give a signal to the regulator to lowe he voltage if over excited reactive KVA increases, and to raise t if overexcited reactive KVA decreases. Each generator usually as its own compensator. When specifying steady-state accuracy, s mentioned with paralleling means disconnected.

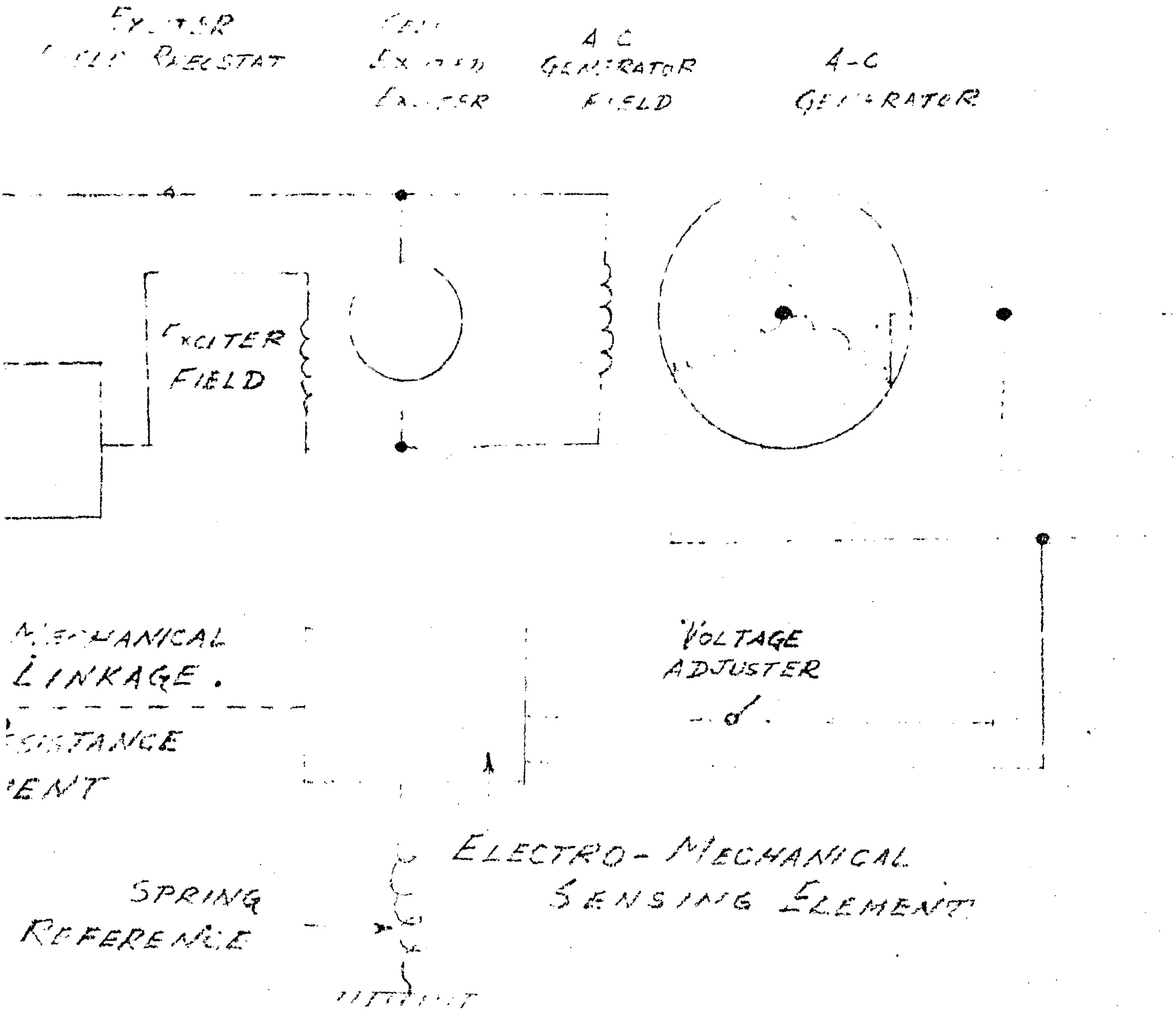


Fig. VI-1. Voltage Regulator

Mechanical Type

DIFFERENT TYPES OF EXCITATION AND REGULATING SYSTEMS FOR SMALL GENERATORS.

There are three types of exciters usually used

(i) The static type supplying excitation direct to the A.C. generator field through magnetic amplifiers. The voltage regulator gives power to the static power amplifier.

(ii) D.C. Rotating commutator exciter. This supplies excitation to the A.C. generator field and is driven by the same prime mover as the A.C. generator. The voltage regulator controls excitation to the D.C. exciter, which is usually self-excited.

(iii) A.C. rotating brushless exciter. This supplies excitation to the A.C. generator field through silicon diodes from the A.C. exciter armature. As the diodes and exciter armature rotate with the generator field, no brushes are required. The voltage regulator supplies excitation to the separately excited A.C. exciter stationary field winding.

Fig. VI-1 shows a regulator of mechanical type. Voltage from A.C. generator is fed to an electro mechanical sensing element. As the A.C. voltage rises, by comparison of magnetic pull to a spring, a change in position of a mechanical linkage is achieved. This effect is transmitted to the voltage regulator rehostat element in series with a self-excited exciter field. Due to change in resistance value, the field current of self excited exciter changes, thus a change in A.C. machine excitation, returning the A.C. generator voltage to normal.

The most modern devices use electrical-sensing and amplification. The use of electronic circuits is being superceded.

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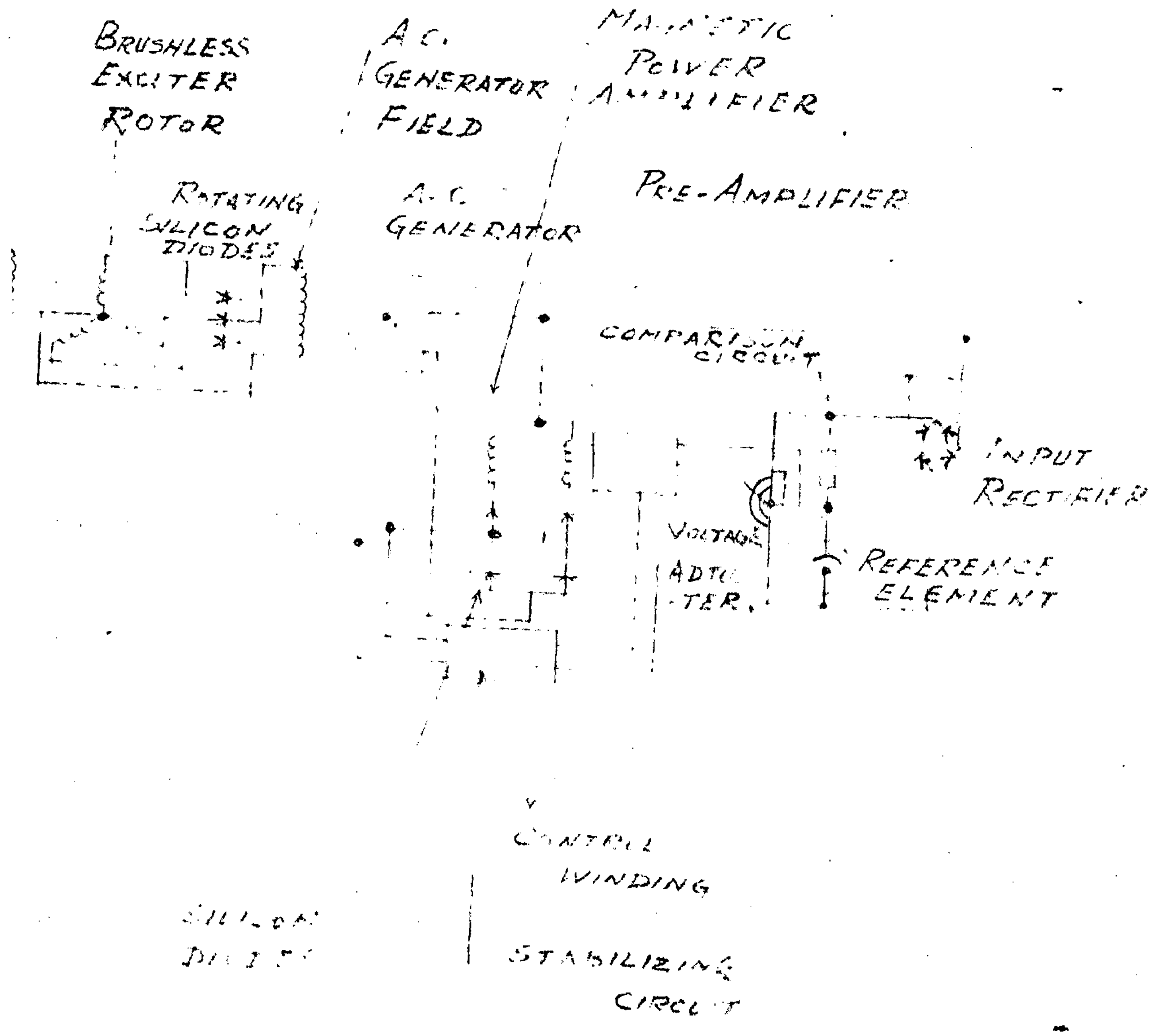

Fig. II-2- Voltage Regulator Of Magnetic – Amplifier Type.

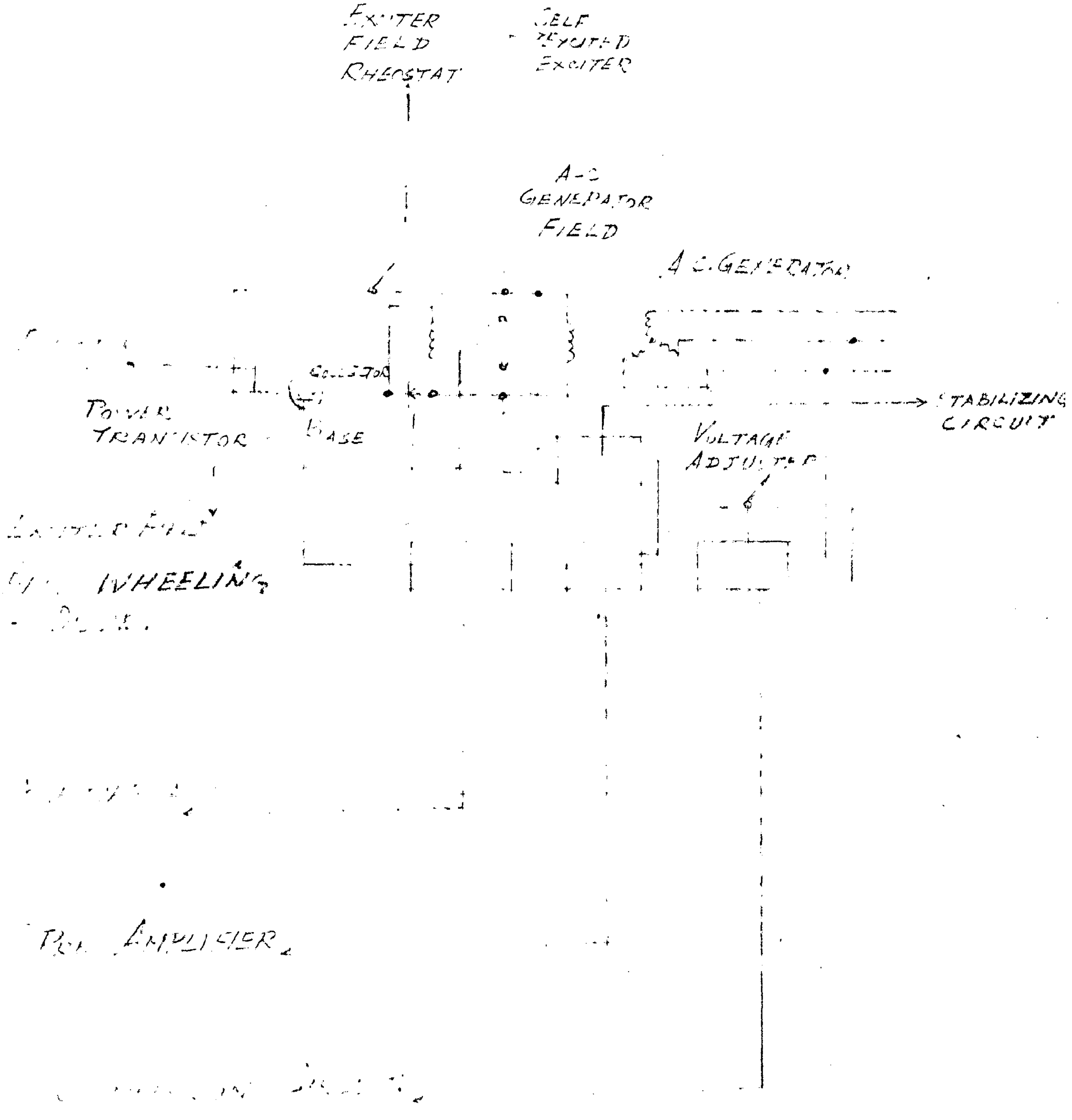

Fig VI-3:- Voltage Regulator, TRM Transistor Type.

by magnetic and semi-conductor circuits, which have no filament type tubes and need negligible maintenance. The following are four types of static regulators and static exciter regulators normally used:-

1. Magnetic Amplifier Type: Fig. VI-2 shows a diagram of this type which is frequently used as a static regulator to control an exciter field, or as a static exciter regulator to directly control the field of an A.C. generator. It has an output from 10 to 10,000 watts. In the figure, the excitation system consists of a brushless exciter whose field is excited by a magnetic amplifier regulator. This has a comparison circuit, producing an output signa varying according to the difference between rectified generator voltage and a reference voltage, a pre-amplifier, and a power magnetic amplifier to supply the exciter field.

R-C networks or stabilizing transformers are used to achi stabilization. These fields back power amplifier output voltage to the pre-amplifier. The reference elements are cold-cathode gas tubes or zener tubes. The amplifier is a combination of semicondiactor diodes and a saturable reactor. Power to the magnetic amplifier is supplied by the main A.C. generator. For a static exciter regulator of this type, the power amplifier directly supplies the generator field.

2. Transistor Type: Fig. VI-3 shows a semiconductor T.R.M. type regulator for use with rotating exciters to provide better performance than mechanical type for large machines. A power transister is used (instead of rheostat in the mechanical regulator) and it can be switched on and off at a rapid rate. By controlling the on-off ratio one can control the

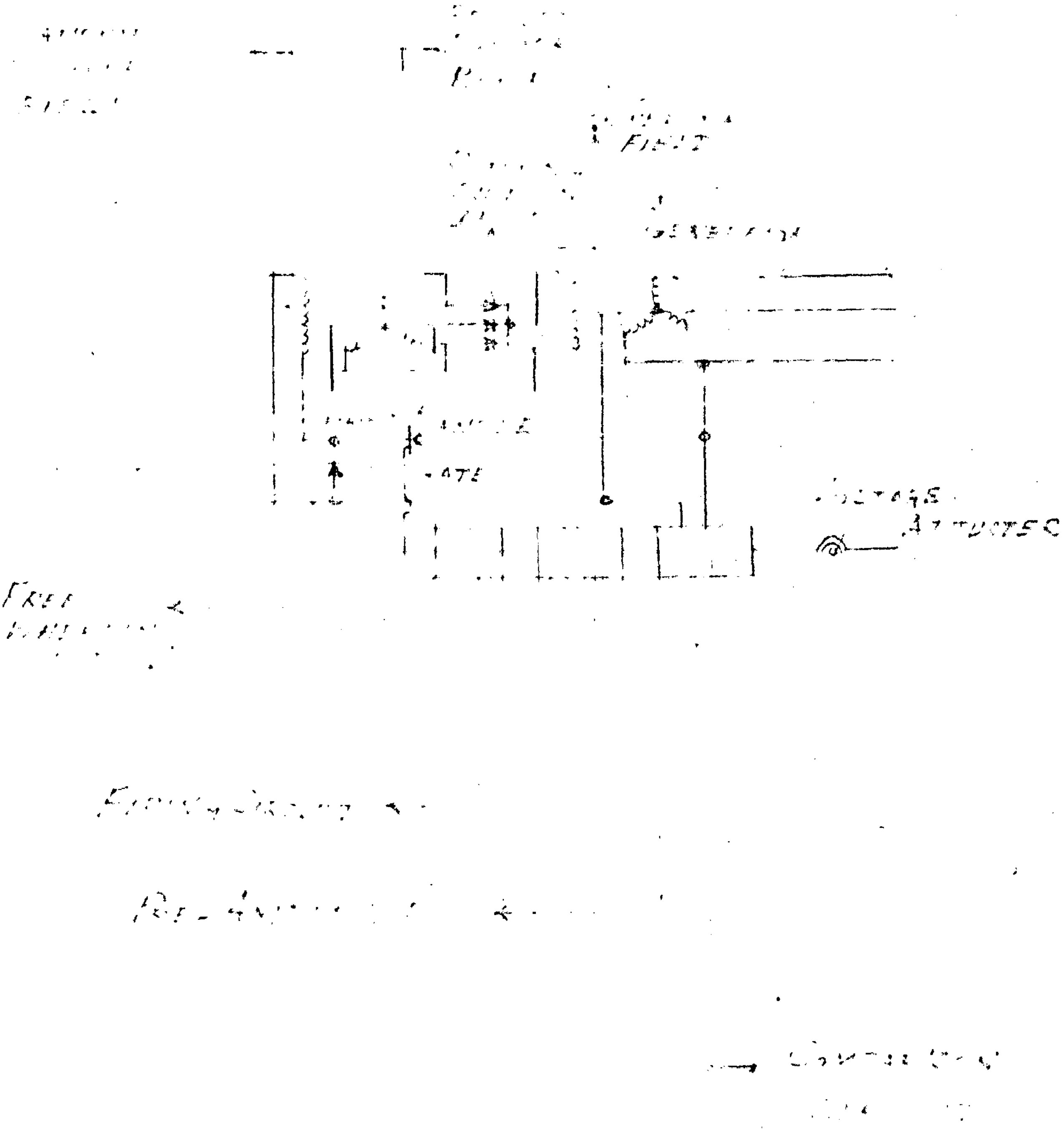

Fig-IV-5: Voltage Regulator, Half-Wave SCR Type.

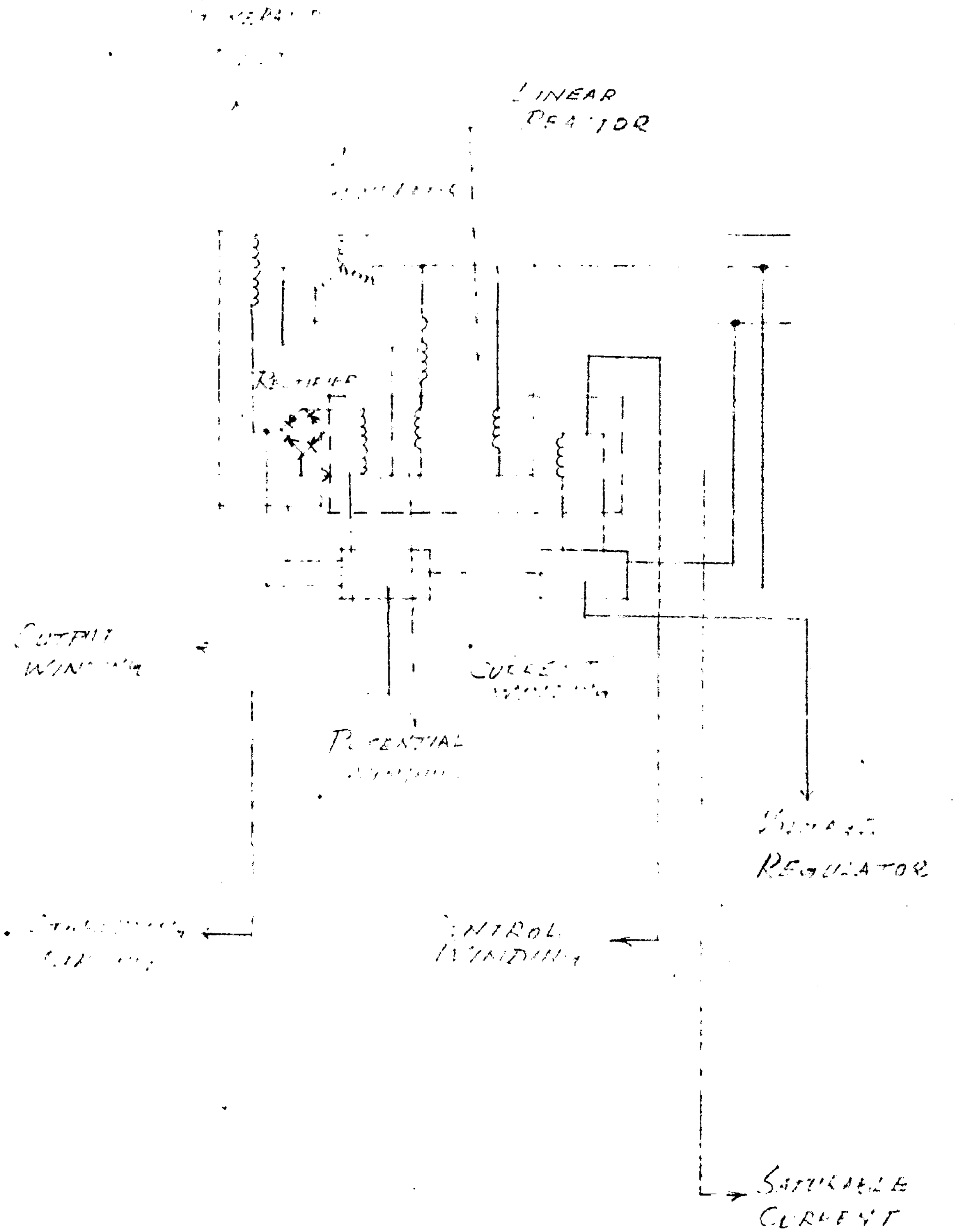

Fig-VI-4:-Saturable Current And P.T. Voltage Regulator.

exciters and hence also the average field current. The T.R.M. regulator can be used only with a direct voltage. When used on a brushless generator or as a static exciter, the direct voltage for the transistor is taken from a separate source or rectified output voltage of the alternator.

3. Saturable Current P.T. type: This type of voltage regulator is depicted in Fig. VI-4. The major element is a saturable transformer whose A.C. output is rectified to supply power to the generator field. The exciter field could also have been supplied power from the rectified D.C. output.

The saturable transformer has a potential winding to give excitation for no load condition of the generator and a current winding for the additional excitation required when the generator is loaded. The design of linear reactor and the current winding is such that the system adjusts itself for changing excitation requirements as the machine is loaded. The voltage regulation portion of the circuit controls saturation of the SCPT, and change excitation to correct inaccuracies in current compensation due to saturation and heating of generator. Regulator has a comparison circuit, reference, pre-amplifier, power amplifier, and stabilizing circuit.

4. Silicon-controlled Rectifier Type: Fig.VI-5 shows a half-wave silicon controlled rectifier. A brushless exciter excite the A.C. generator field. It has a stationary field getting power from the regulator. The controlled rectifier becomes conducting

after a firing pulse is applied. The SCR remains conducting thereafter until the applied alternating voltage becomes zero. By controlling the phase of the firing pulse applied to the SCR, the average voltage applied to the exciter field and hence the average field current can be controlled. When the SCR is not conducting for a portion of the cycle, the field current flows through the diode.

Magnetic or semi-conductor components are contained in the firing circuit, which converts the comparison circuit and pre-amplifier signal to a phase-shift signal. Silocon controlled rectifiers (SCR) depending upon power required, may be full wave or three phase. It is expected that the S.C.R. regulator or exciter will become the most popular, due to small size, efficiency, fast response and ability to handle large power.

CONCLUSION

CONCLUSION

The performance of any excitation system is limited by the contribution of generator, exciter and voltage regulator. Usually the regulator characteristics limit the steady-state performance, and the A.C. generator and the exciter limit the transient performance of the system.

The regulator or exciter regulator should provide enough increase in exciter field voltage to counteract the effect of loading the generator and heating effects of generator and exciter. Also the effect of changes in ambient temperature and drift should be within predetermined accuracy limits. The voltage drop seen after application of load is the minimum drop of voltage, and time-constants of exciter and generator limit the recovery time.

The three winding exciter gives better stability and more reliability than the conventional D.C. generator using only one winding. As one of the three shunt windings is excited from a separate variable voltage source, the control of exciter terminal voltage is partially lost for a defect in the field circuit. On the other hand for a defect in the variable voltage source circuit, the exciter will continue to operate depending upon the rheostat setting of the self-excited field circuit. The best prime mover for the main exciter is the prime mover which drives the A.C. machine, and this arrangement was used for several years.

The operation of any machine is unstable in the unsaturated portion of the magnetization curve. If the resistance line is raised and made to coincide with the air gap line, the output voltage can be established at any value from zero to the point where the no-load curve begins to bend away from the air gap line. One solution was the use of a cross-field machine having negative feedback to improve the transient response of the machine and give a more linear output. The error can be reduced but at the expense of a tendency to instability.

The use of rotating machines for regulating purposes was made for the first time in 1932. Any number of rotating machines can be used according to the amplification required. Such machines are used in industry and are called Rototrols and test results show high sensitivity and response which means a requirement of low control energy.

With Rototrols it is necessary to measure the output and compare it with a predetermined standard. The system should be able to correct the output when there is any variation, and take no action at the correct output. Comparison can be made inside the machines or externally, but at the correct output some other means such as self-excitation by shunt, series or compound field is provided. Due to this condition, the operation of rototrols is limited to the air gap portion of the saturation curve. In this system it is possible to obtain three amplification stages from one machine.

A modification used for hydroelectric generators is the

Rototrol Pilot Exciter with Three Field Main Exciter. A later development was the elimination of regulator and pilot exciter, and to use only one main exciter and static voltage regulating network. In this case we avoid the use of additional brushes and short-circuited windings.

The voltage regulation is achieved best by the method of intersecting impedance characteristics. This has one linear and one non-linear circuit in parallel, the circuit being balanced at the point of intersection. voltage in non-linear branch remains almost constant but there is a net effect of fluctuations due to the linear branch causing a corresponding correcting action.

Extensive use of Rotating Amplifiers encouraged engineers to find a more sensitive and more reliable method, and the result was the use of electronic exciters. Additional advantages of this system are elimination of moving parts reduced maintenance and no risk of instability of the exciter system. However, due to being more expensive compared to rototrols, their use is limited.

A further improvement in the excitation system is the use of brushless exciters and static exciter regulators. Their designs are economical, give similar performance and due to the absence of time-constant of exciter field, static exciters have better transient performance than mechanical regulators with rotating self-excited exciters. This performance can be equalled by separately excited commutator exciters or brushless exciters, owing to the high values of forcing voltage that can be obtained from the regulator at a low power level. The effect of exciter field inductance is minimised due to high value of forcing voltage.

Of all the systems discussed in this work, harmonic excitation appears to be the best though it is still in the experimental stage.

As the harmonic excitation system is being developed, improvements expected are the replacement of the 180-cycle magnetic amplifier with controlled rectifier, and omission of the magnetic pre-amplifier. The result would be a system having only two time constants, one with generator field, and the other with the small device to control the firing angle of the controlled rectifiers. These two time-constants will differ by several orders of magnitude, so very small stabilising signal will be needed. Thus, the best in regard to dynamic performance can be achieved in an excitation system.

The variation of harmonic voltage with load and use of a 180-cycle power amplifier gives an excellent transient performance. The advantage of better reliability and less maintenance shall be confirmed by further experience with static components including silicon rectifiers. A complete analysis of harmonic voltage curves on salient-pole synchronous generators, condensers and motors should be made before harmonic excitation can be used. Plenty of field testing and analysis is to be done to find these characteristics.

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