Static Voltage Regulators

Performance and Design

Dissertation submitted in partial fulfilment of the requirements for the Degree of

MASTER OF ENGINEERING
IN
ELECTRICAL MACHINE DESIGN

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SYNOPSIS

Alternator regulation by varying the exciter field current with the help of voltage regulators employing electro-mechanical principles is well known.

This dissertation deals with voltage regulators of the "static" type i.e. those having no moving parts, the circuits comprising of static apparatus such as transformers, condensers , resistors, gaseous discharge tubes and transistors etc. Advantages of this type of regulator over the conventional type and limitations and difficulties experienced with the latter are discussed.

Static voltage regulators employing transductor and electronic principles are described.

The design and performance of a static voltage regulator employing transistors built by the author in the laboratory is discussed in the concluding chapters.

NOMENCLATURE

CAPITALS

A	Cross section of core
A_1, A_2, A_3	Numerical gain factors
B_o	Amplitude of sinusoidal flux density
B_m	Steady component of flux density
E	Pilot exciter armature voltage
I_{av}	Mean output current
I	R.M.S. output current
I, i	Input current of transistor 'A'
I_1 , i_1	Exciter shunt field current
I_2 , i_2	Control current
I_o	Initial transductor current
I_c	Signal current in control winding
K	Output constant
L	Exciter shunt field inductance
N	No. of field turns in series; self-excitation or feed back term.
P	Maximum useful transductor output power
P_i	Initial transductor output power.
R	Field circuit resistance; Resistance of transductor load resistor
R_o	Output resistance of transistor A
R_1	Resistance of exciter shunt field winding
R_2, R_3	Potentiometer arms.
R_4	Internal resistance of control source
R_c	Resistance of Control winding

T	Constant having dimensions of time
T_1, T_2, T_3	Time constants.
T_{AC}	Turns in a.c. winding of transductor element
T_c	Turns in control winding
T_{SE}	Turns for self excitation
V	Supply voltage
V_c	Signal voltage
V_g	Grid voltage
V_a	Anode voltage
V, v	Exciter terminal voltage
V_1, v_1	Output voltage of transistor A
V_2, v_2	Input voltage of transistor A
V_{2A}	Voltage across R_2 when transistor is disconnected from point A
V_3	Control source e.m.f.
Z	Constant in time lag equation.

SMALL LETTERS

a, r_b, r_c r[illegible], r_m	Parameters of transistor equivalent circuit
e	Main exciter armature e.m.f.
f	Supply frequency c/s
g	Constant relating r and T_{AC}
i	Field current
k	Output constant ; dV/dI_1
l	Magnetic length
m	Core constant
n	Ratio R/r
p	Power amplification

r	Internal resistance of transductor
s	Constant relating R_c and T_c
t_1	Time lag

<u>GREEK LETTERS</u> :

σ	Coefficient of dispersion
μ	Permeability ($= \mu_0 \mu_r$)
ω	Angular frequency of supply, rad/sec
ϕ_a	Air gap flux linking armature conductors
ϕ_f	Flux in each field core
ϕ_l	Leakage flux.

The abbreviations, not mentioned above are individually explained as and when necessary.

INTRODUCTION [1,2]

The successful operation of large systems depends on the correct application of efficient automatic voltage regulating equipment, and basically the aim is quick and efficient operation and the immediate restoration of stable conditions following system disturbances and transient load changes. The quick and accurate control of voltage and excitation permits the operation of the generator and the power system nearer to their steady state stability limits.

A number of regulators has been developed. The earliest ones - vibrating-contact type had reasonably quick response as there was no starting friction or inertia to overcome but there was an appreciable amount of maintenance connected with the adjustment and servicing of the mechanism and contacts. The continuous chatter of the contacts was, at times, a source of irritation in an otherwise quiet control room and this together with the maintenance factor, led to a preference for an alternative type - Rolling sector type with better features in these respects but unfortunately with a slower response. Very little maintenance was required and the regulator was silent in operation.

Next stage of development was normally in-active rheo - static type voltage regulators (i.e. no correction takes place until the voltage moves outside a certain range) with the particular object of reducing maintenance, since voltage control was recognized as a secondary role of the regulator, main role being defined as a form of protection standing by to deal with the effects of system disturbances. However, even this was not a satisfactory solution to the problem since it is well known that control is much more positive when the regulator is continuously active and has a small time constant.

Static Voltage Regulators :

The use of such regulators is now-a-days being greatly extended as the absence of electro-mechanical motions and their attendant advantages leads to appreciably reduced maintenance and simplicity of operation and control. The use of bridge circuits with saturating reactors as a variable reference makes the regulators continuous in operation and the absence of contactors and relays leads to increased speed of operation. Also a reduction in stability margins is possible with this type of regulators.

A static voltage regulator usually forms a part of the complete excitation system so that the present day excitation and voltage regulating systems are first discussed and salient features of various schemes brought out.

This is followed by a detailed discussion of different types of static voltage regulators - Transductor, Electronic and Transistor in Chapters 4, 5 and 6.

Theoretical analysis developed in Chapter 6 for Transistor type voltage regulators leads to design in Chapter 7 which also gives the steady state and transient performance of a regulator circuit assembled and tested in the laboratory.

Salient points have been brought out in the Conclusion.

CHAPTER - 1

DIFFERENT TYPES OF VOLTAGE REGULATORS

1.1. CLASSIFICATION :

The different types of voltage regulators which have been developed employ different basic principles.

Voltage regulators for generators can be classified into :

(i) Electromechanical Regulators

(ii) Static Regulators.

1.2. ELECTROMECHANICAL VOLTAGE REGULATORS:[3,4,5]

1.2.1. Vibrating-contact type (or Tirril) Regulators:

This type of regulator connects a fixed amount of resistance in and out of the field circuit and the average exciter voltage depends on the on-off ratio of the contacts. This ratio is controlled by the position of a beam which is normally held in balance by a solenoid fed from the generator terminal voltage. Any departure of the generator voltage from the set value causes the beam to move, altering the on-off ratio and hence the exciter voltage so as to restore the correct value of gnerator voltage.

1.2.2. Rheostatic type Regulators:

In this type the regulating resistance is varied continuously or in small steps instead of being first completely cut in, then completely cut out. Under steady conditions, all parts of the regulator are at rest; therefore the wear is small.

Rheostatic regulators can be classified into direct acting and in direct acting types. In the direct-acting type, the voltage-sensitive element of the regulator controls the rheostat through a direct mechanical connection. In the in-direct acting type, the voltage-sensitive element operates contacts which, in turn, control a motor to drive the rheostat.

(a) Direct-Acting Regulators:

One of the simplest voltage regulators is the direct acting rheostatic type. In this regulator the voltage sensitive element is an electromagnet the armature of which is balanced against a spring. The resistance element which is in the exciter field circuit is connected directly to the armature and is a part of the regulator assembly. When there is a change in the controlled voltage, the armature will change position and adjust the resistance element in such a way as to restore the controlled voltage. This type of regulator is compact and simple to install, operate and maintain. At present it is not designed to handle high exciter field currents and, therefore, its use is limited to small and medium sized machines. This regulator is af the continuously acting type and has a narrow band of voltage regulation.

(b) Indirect-Acting Regulators:

The in-direct acting rheostatic type voltage regulator is well suited for use in excitation systems having both a pilot and a main exciter. The voltage sensitive element of this regultor may be a polyphase torque motor the torque of which is proportional to the approximate average 3 phase voltage. The torque of the motor is balanced against the pull of a spring so that for each value of voltage there is a definite position of the motor rotor to which is attached a contact assembly. The contact assembly has two sets of contacts, the first set operates intermittently for small changes in voltage to control the pilot motor of the motor-operated Wheatstone-bridge rheostat which in turn adjusts the resistance of the rheostat. Both sets of contacts operate for large changes in voltage, the second set controlling the temporary switching of all the regulating resistance in the rheostat, while the first set of contacts controls the final position of the rheostat. Thus, for large changes in voltage, there is an extremely rapid change in the excitation field resistance which increases the response of the entire excitation system.

This type of regulator is rugged. When used with Wheatstone-bridge-type rheostat, rapid response is obtained, and practically no limit need be placed on the field currents it will successfully control. For some applications where severe fluctuating loads are encountered the dead band principle in conjunction with the intermittent control feature is not the ideal type of regulator.

It is important to note that electromechanical types of voltage regulators suffer from wear and friction and require fairly regular attention. Friction reduces the sensitivity and causes a dead zone of between 1/2% and 1% within which no control action is obtained. The contacts of the vibrating type require regular attention due to erosion caused by sparking. The rate of response of both types is restricted by the mass of the parts that have to be moved. Even when giving full corrective action they order to restrict generator over-voltage on load rejection (an important consideration for hydro electric stations) - as can a regulator employing magnetic or rotating amplifiers.

1.3. STATIC VOLTAGE REGULATORS:[3,4,5]

1.3.1 Impedance Regulators:

The impedance regulator is one of the more recent developments in the voltage regulation field. It is a static-type regulator and is normally used with a rotating amplifier. The function of the rotating amplifier is to respond to changes in the controlled voltage as detected by the regulator and modifying the voltage in the field circuit of the main exciter in such a manner as to restore the controlled voltage.

The impedance of voltage regulator consists of a linear and non-linear impedance. The 3 phase voltage to be controlled is passed through a positive sequence network and the resulting single phase voltage which is the approximate average of the three phase voltage, is impressed on both the linear and non-linear impedances. The linear impedance supplies rectified current to the control field of the rotating amplifier in such a direction as to lower the output voltage. The volt-ampere characteristics of the two impedances are such that they intersect at some value of control voltage at which point there is no net current in the control field of the rotating amplifier. For a change in the controlled voltage there will be a net current in the control field which is in the direction to restore the controlled voltage to its previous value.

The impedance voltage regulator is simple in operation, has no moving parts and no inherent dead band, and is of the continuously acting type. Special control features can be added readily to this type of regulator by the use of additional control fields in the rotating amplifier. The use of this type of regulator results in fast and smooth response of the excitation system with a narrow band of voltage regulation.

1.3.2. Electronic Regulators:

Another static type of voltage regulator is the electronic regulator. It can be used either with a rotating amplifier in an excitation system with rotating exciters, or directly with an electronic exciter to control the grids of the firing tubes, which in turn control the firing point of the main power tubes.

The electronic regulator consists essentially of a constant voltage glow tube and the necessary rectifier and control tubes. The 3 phase voltage is rectified and compared with the voltage across the glow tube. Any difference in these voltages is amplified and produces a change in the grid of the tubes supplying power to the control fields of the rotating amplifier. The tubes used are thermionic type and, to give reliable operation two tubes in parallel are used so that tubes can be checked or changed without shutting down the regulator.

The electronic regulator has the same features as the impedance regulator. In this type of regulator special control features can be added directly to the regulator. Its use will also result in fast and smooth response of the excitation system with a narrow band of voltage regulation.

CHAPTER - 2

MODERN EXCITATION SYSTEMS FOR SYNCHRONOUS MACHINES

2.1. INTRODUCTION

An excitation system consists essentially of an exciter and means for its regulation. In the earlier period manual control of voltage was used widely. With the development of power systems using modern apparatus, automatic control in general, has come to play an important part in the progress of electric power industry. Therefore, it is in keeping with this progress that voltage regulators have been used increasingly and have become an important factor in making possible further economies and improvements in system stability.

The physical size of the generating element for a given capacity is determined largely by its Short Circuit Ratio. Reduction in S.C.R. makes more desirable the use of automatic regulation, and at the same time increases the importance of the excitation system reliability.

2.2. TYPES OF EXCITATION SYSTEMS: [3,4]

2.2.1. Self-excited main exciter and direct acting rheostatic type regulator :

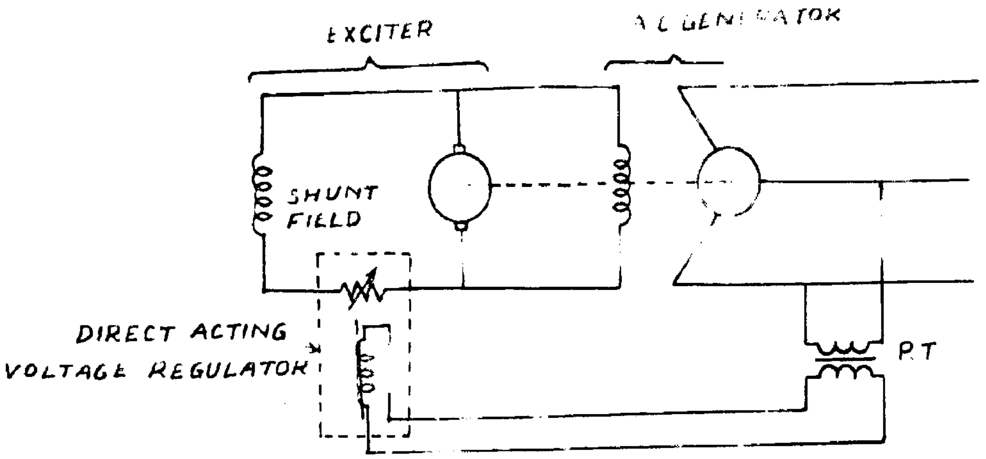
In this arrangement the voltage regulator changes the resistance in the field circuit of the exciter. As shown in Fig. 2.1 the voltage-sensitive element of the regulator (for example, a solenoid) acts directly on the rheostat to vary its resistance. This system is commonly used on the smaller a.c. generators.

2.2.2. Main and Pilot exciters and indirect-acting rheostatic type regulator.

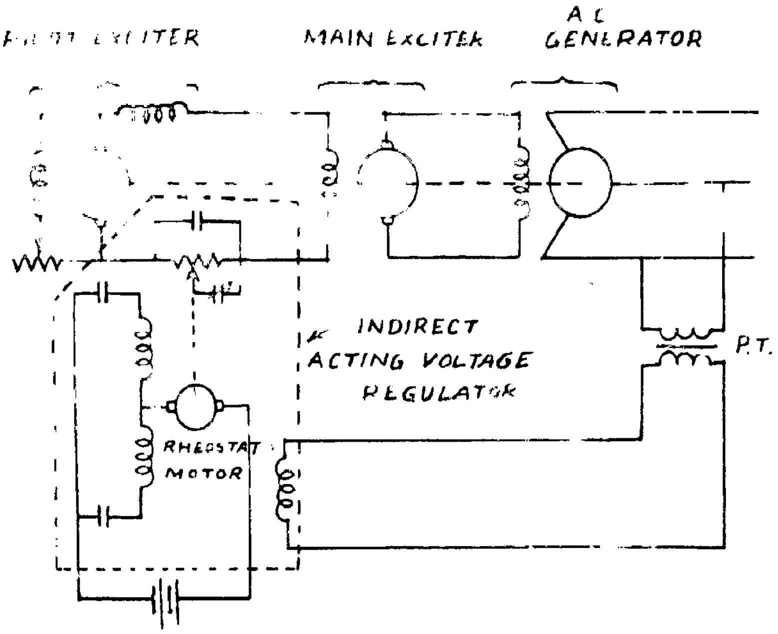
Referring to fig. 2.2 when a small deviation of voltage occurs, the voltage-sensitive element of the regulator closes contacts which control a motor-driven switch which raises or lowers the resistance of the field rheostat of the main exciter. If the voltage deviation is greater, additional contacts are closed which short-circuit the field rheostat to produce a rapid build-up of the alternating voltage or contacts are opened which introduce the entire resistance of the rheostat to produce rapid build down. This regulator has the dis-advantage of a "dead band" that is a small range of voltage in which no corrective action is produced. This dead zone reduces the accuracy of voltage regulation and prevents the regulator from increasing steady-state stability. Until recently this has been the standard scheme of excitation for large machines.

2.2.3 Main exciter, rotating amplifier, and static voltage regulator:

This is one of the most recent developed excitation system and the main exciter is either an ordinary shunt-wound machine or a shunt-wound machine with additional field windings. The rotating amplifier is a d.c. machine specially designed as a power amplifier. The important feature of such machines is that a large output may be controlled by a few watts' input, which can be supplied by


EXCITER
A.C GENERATOR
SHUNT FIELD
DIRECT ACTING VOLTAGE REGULATOR
P.T

2.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INDIRECT ACTING VOLTAGE REGULATOR
RHEOSTAT MOTOR
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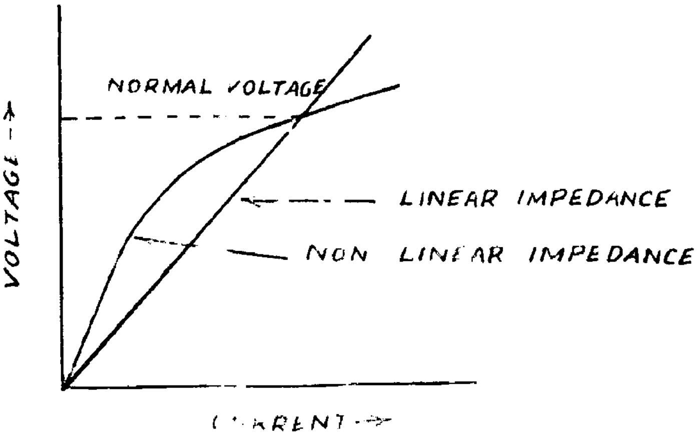
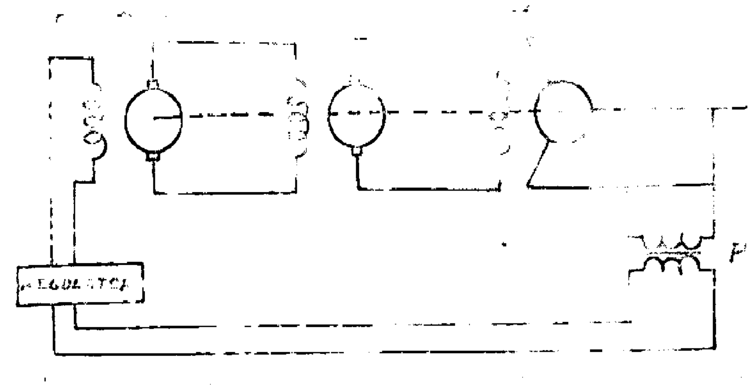

NORMAL VOLTAGE
LINEAR IMPEDANCE
NON LINEAR IMPEDANCE
VOLTAGE →
CURRENT →


REGULATOR
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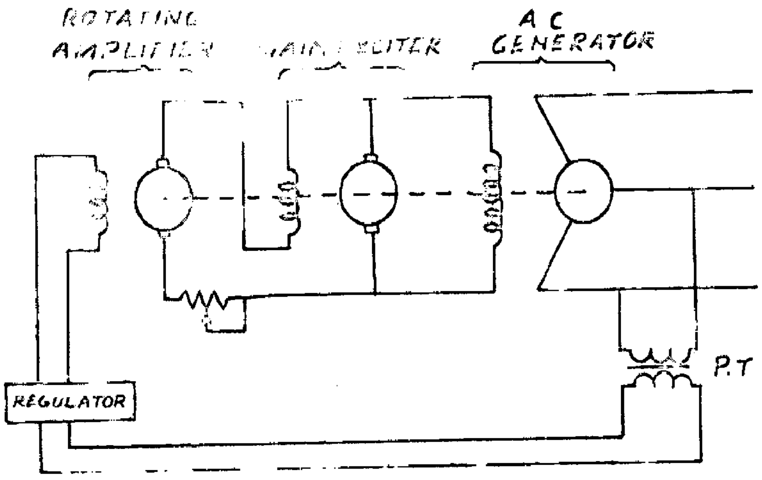
ROTATING AMPLIFIER
MAIN EXCITER
A.C GENERATOR
REGULATOR
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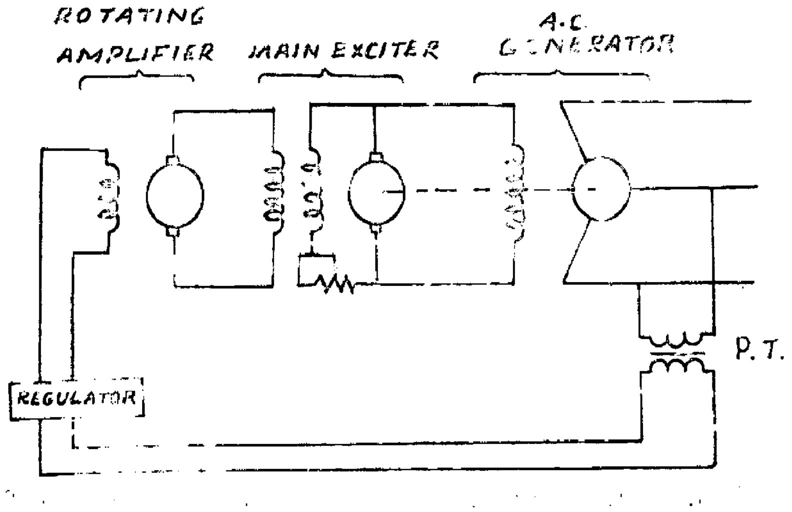
ROTATING AMPLIFIER
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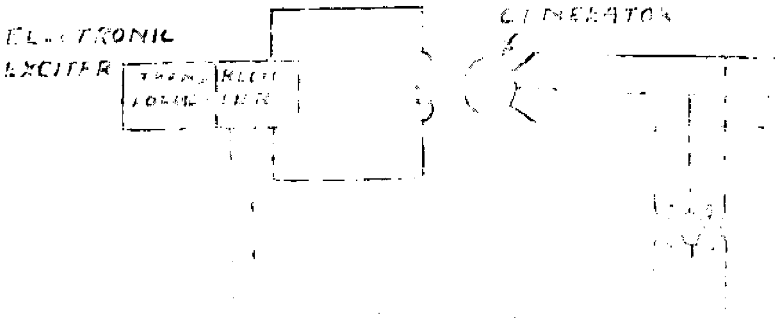

ELECTRONIC EXCITER
TRANSFORMER
RECTIFIER
GENERATOR

a static type of regulator having no dead band and no moving parts. Such regulators are accurate and reliable. They are of either of two types, electronic or impedance. The electronic regulator compares the constant voltage drop across a glow tube or across a resistor in the plate circuit of a pentode with the rectified alternating voltage being controlled, the difference being applied to a control-field winding of the amplifier, or each voltage being applied to one of a pair of such windings, the m.m.f's of which are opposed. The impedance- type of regulator compares the current through a non-linear impedance-usually an iron-cored inductor, with that through a linear impedance-usually a capacitor (Refer Fig 2.3) When the alternating voltage is correct, the currents through the two impedances are equal. When the voltage is high or low, one current or the other predominates and, after rectification, excites the control-field winding (or windings) of the rotating amplifier . In some cases, where more power gain is required, a magnetic amplifier has been placed between the voltage regulator and the rotating amplifier.

Figs. 2.4, 2.5 and 2.6 show some of the typical methods of exciting the main exciter, the latter two using combination of self- and separate excitation of the main exciter. The advantage obtainable with the latter schemes is that the rotating amplifier can be removed from service for maintenance without shutting down the generating unit. In Figs. 2.5, and 2.6 the voltage of the amplifier either bucks or boosts that of the exciter armature, as required for proper control of the alternator voltage. Arrangement of fig. 2.5 requires a transfer switch for mannal control while that of fig.2.6 has the special type of exciter.

2.2.4. Electronic Exciter and Electronic Voltage Regulator:

The essential elements are shown in fig. 2.7.

The electronic exciter is a power tube rectifier, complete with its required control equipment and supply transformer, and supplies excitation to the field of the main synchronous machine through anode breakers which act as a field breaker. In normal operation the voltage regulator detects changes in the controlled operating voltage and adjusts the firing time of the tubes to give the required exciter output voltage. Provision also is made for operating the electronic exciter on hand control.

This type of arrangement has operated very satisfactorily but is not widely used because both their first cost and their maintenance cost have been found to be greater than for other types of excitation systems.

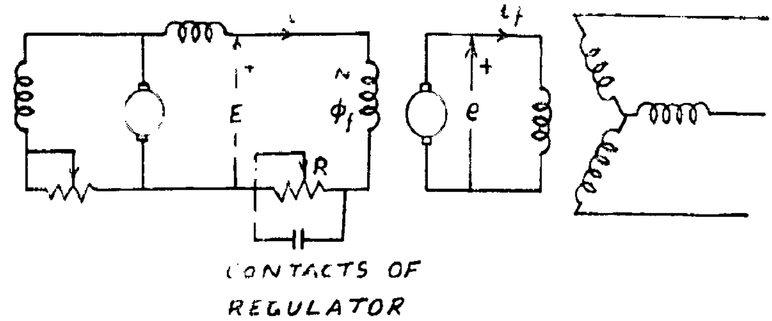
2.2.5.

In addition to the 4 principal types mention may be made of the following three excitation schemes namely,

(1) Rotating main exciter with electronic pilot exciter and electronic regulator.

(2) Rotating amplifier as main exciter and static voltage regulator.

(3) Main exciter, mangetic amplifier and static voltage regulator.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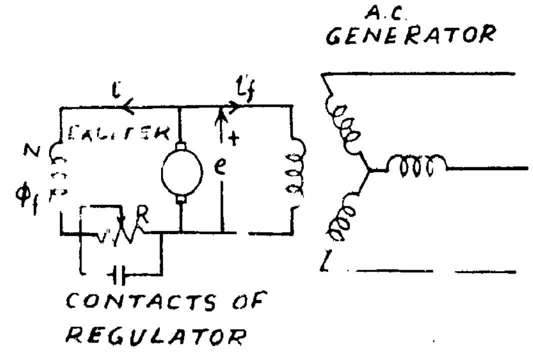
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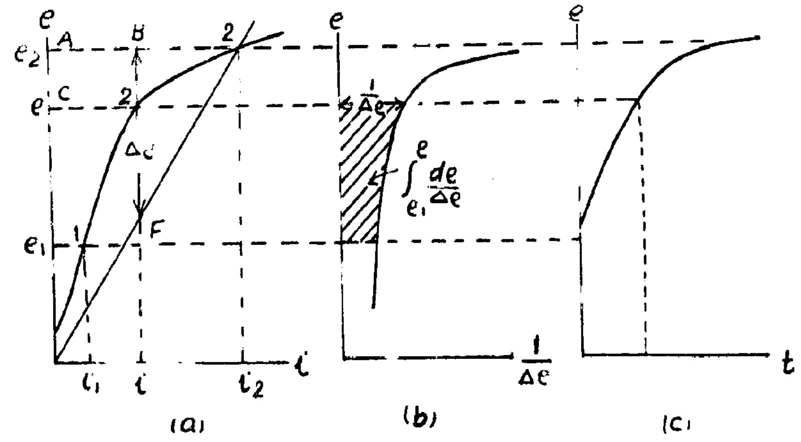
e
e_2
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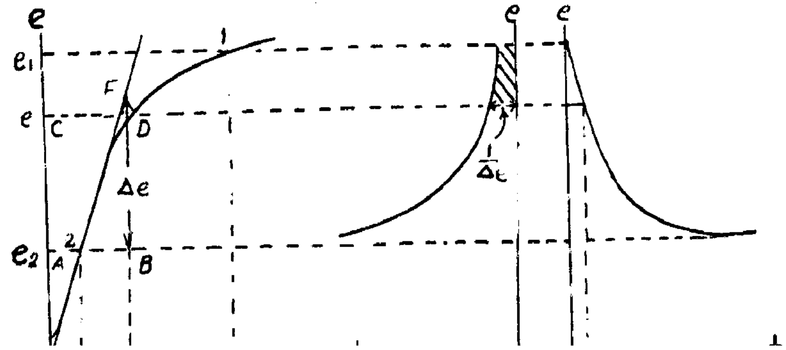

e
e_1
1
F
e
C
D
Δe
e_2
2
A
1
B
e
$\frac{1}{\Delta e}$
e

2.3. Quick-response Excitation:[4]

Quick-response excitation, in addition to raising stability limits, diminishes the disturbance to voltage caused by such events as a short circuit, the opening of a transmission line, swinging of machines, or the disconnection of a generator, and thus improves the quality of electric power service.

The recent trend towards the use of turbo-generators of lower short circuit ratio, and hence of lower inherent steady state stability , has aroused interest in the use of of quick-response excitation. Even though the generators are normally stable when operated with hand control of excitation, the use of suitable voltage regulators increases the margin of stability.

To be effective in increasing the steady-state stability limit, the excitation system should have a voltage regulator with no dead band.

2.4. Response of unloaded Exciter:[4]

The circuit diagrams for separate excitation and self-excitation of the main exciter are shown in Figs. 2.8 and 2.9.

The equation of voltage around the field circuit of the main exciter, whether separately or self- excited, is

$$N \frac{d\phi_f}{dt} + Ri = E \text{ or } e \qquad (2.1)$$

where N = number of field turns in series.

ϕ_f = flux in each field core, in webers

R = field-circuit resistance, in ohms

i = field current, in amperes

E = pilot-exciter armature voltage

e = main-exciter armature e.m.f, in volts

The equation applies to separate excitation if E is used, and to self-excitation if e is used.

For a flat compounded pilot exciter E may be taken as constant whereas for a shunt wound or under-compounded pilot exciter E may again be considered as constant equal to the no-load voltage of the pilot exciter and increasing R by the proper amount to account for the linear decrease of voltage.

If the exciter is running at constant speed, then the armature voltage e is proportional to the flux ϕ_a which crosses the air gap and links the armature conductors, i.e.

$$e = k\,\phi_a \quad \ldots\ldots \quad \ldots\ldots \quad \ldots \quad (2.2.)$$

where k is a constant depending upon the total no. of conductors on armature, speed of rotation of exciter, no. of poles and no. of parallel paths through the armature.

Now $$\phi_f = \phi_a + \phi_l \quad \ldots\ldots \quad \ldots\ldots \quad (2.3.)$$

where ϕ_l is the leakage flux.

Assuming that leakage flux is proportional to armature flux we may write

$$\phi_f = \phi_a + \phi_l = (1 + C_1)\,\phi_a = \sigma\,\phi_a \quad \ldots\ldots \quad (2.4)$$

where σ is a constant known as the coefficient of dispersion; usual values of σ being 1.1 to 1.2

Substituting the relationship (2.4) in equation (2.1)

$$\frac{N\sigma}{k}\,\frac{de}{dt} + Ri = E \text{ or } e \quad \ldots\ldots \qquad \ldots\ldots (2.5)$$

In this equation e is a non-linear function of i as given by the magnetisation curve.

2.5. Voltage-time curves of unloaded separately excited exciter.

Method of graphical integration is used.

2.5.1. Build up :

Let subscripts 1 and 2 be used to denote the initial and final conditions respectively.

Equation (2.5) can be written for this case as

$$\frac{\sigma N}{k}\,\frac{de}{dt} = E - Ri \quad \ldots \quad \ldots \quad \ldots (2.6)$$

Multiplying by e_2/E

$$\frac{\sigma N e_2}{k E}\,\frac{de}{dt} = e_2 - \frac{Re_2}{E}\,i \quad \ldots \quad \ldots\ldots \qquad (2.7)$$

$$\text{or} \quad T.\,\frac{de}{dt} = \Delta e \quad \ldots\ldots \quad \ldots\ldots \qquad (2.8)$$

$$\text{where} \quad T = \frac{\sigma N e_2}{k E} \quad \ldots\ldots\ldots \quad \ldots\ldots\ldots \qquad (2.9)$$

$$\text{and} \quad \Delta e = e_2 - \frac{R\,e_2}{E}\,i = e_2 - \frac{e_2}{i_2}\,i \quad \ldots\ldots \qquad (2.10)$$

T is a constant having the dimension of time though it cannot be given the same interpretation as the time constant of a linear circuit since the build-up of neither e nor i is exponential.

The geometric interpretation of Δe is seen by reference to fig. 2.10 (a). The slope of the line drawn through the origin and the final operating point (i_2, e_2) is $\frac{e_2}{i_2} = \frac{Re_2}{E}$. For any given abscissa i the ordinate of the line is $\frac{e_2}{i_2} i = \frac{e_2}{E} Ri$ ..(2.11)

Δe is then the vertical distance from this line upto the horizontal line drawn through the intersection of this line and the magnetisation curve.

Solving equation (2.8) for t,

$$t = T \int_{e_1}^{e} \frac{de}{\Delta e} \qquad \ldots\ldots \qquad \ldots \qquad (2.12)$$

The whole process of graphical solution is illustrated in Fig. 2.10. The shaded area is measured for various values of e. This area multiplied by T, gives the value of t corresponding to e, and is plotted against t in Fig. 2.10 (c)

2.5.2 Build-down:

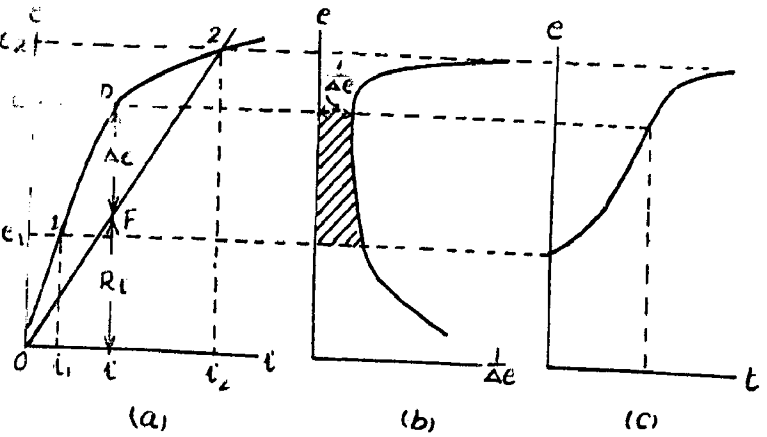
Proceeding exactly in the same manner as build up the process is illustrated in Fig. 2.11. Δe is now a negative quantity. The time constant T is smaller than it was for build up because e_2 is smaller.

2.6. VOLTAGE- TIME CURVES OF UNLOADED SELF-EXCITED EXCITER

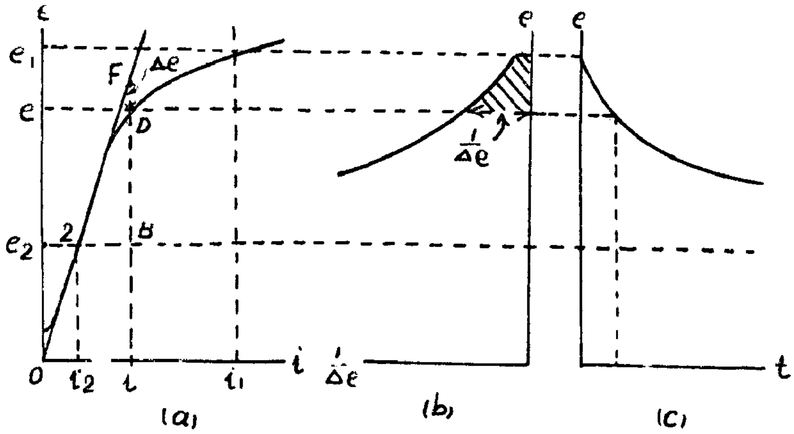
Equation (2.5) can be written for this case as

$$\frac{\sigma N}{k} \frac{de}{dt} = e - Ri \qquad \ldots\ldots \qquad \ldots\ldots \qquad (2.13)$$

$$\text{or} \quad T \frac{de}{dt} = \Delta e \qquad \ldots\ldots \qquad \ldots\ldots \qquad (2.14)$$


e
e_2
2
D
Δe
F
e_1
1
Ri
0
i_1
i
i_2
i
e
$\frac{1}{\Delta e}$
$\frac{1}{\Delta e}$
e
t
(a)
(b)
(c)

[illegible]


e
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D
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B
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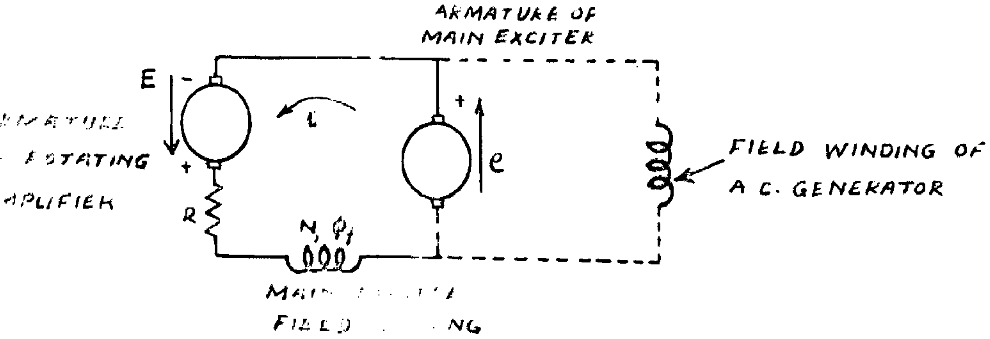
$\frac{1}{\Delta e}$
e
t
(a)
(b)
(c)

[illegible]


ARMATURE OF MAIN EXCITER
E
-
+
i
+
e
R
N, ϕ_f
FIELD WINDING OF A.C. GENERATOR
RMATURE
ROTATING
MPLIFIER
MAIN
FIELD NG

$$\text{or} \quad t = T\int_{e_1}^{e} \frac{de}{\Delta e} \qquad \ldots \qquad \ldots \qquad (2.15)$$

where

$$T = \frac{\sigma N}{k} \qquad \ldots \qquad \ldots \qquad (2.16)$$

$$\Delta e = e - Ri \qquad \ldots \qquad \ldots \qquad (2.17)$$

Time constant T for the self-excited machine is different from those for separately excited machine in that it is independant of the final value of armature voltage. Hence the same value of T applies both to build-up and to build down.

Fig. 2.12 and 2.13 show the build up and build down of voltage for self-excited exciter.

2.7. VOLTAGE-TIME CURVE OF UNLOADED EXCITER HAVING ROTATING AMPLIFIER E.M.F. IN SERIES WITH ITS SHUNT FIELD CIRCUIT.

The circuit diagram for this type of excitation is shown in fig. 2.14. The equation of voltages around the closed path is

$$N\frac{d\phi_f}{dt} + Ri = e + E \qquad \ldots. \qquad (2.18)$$

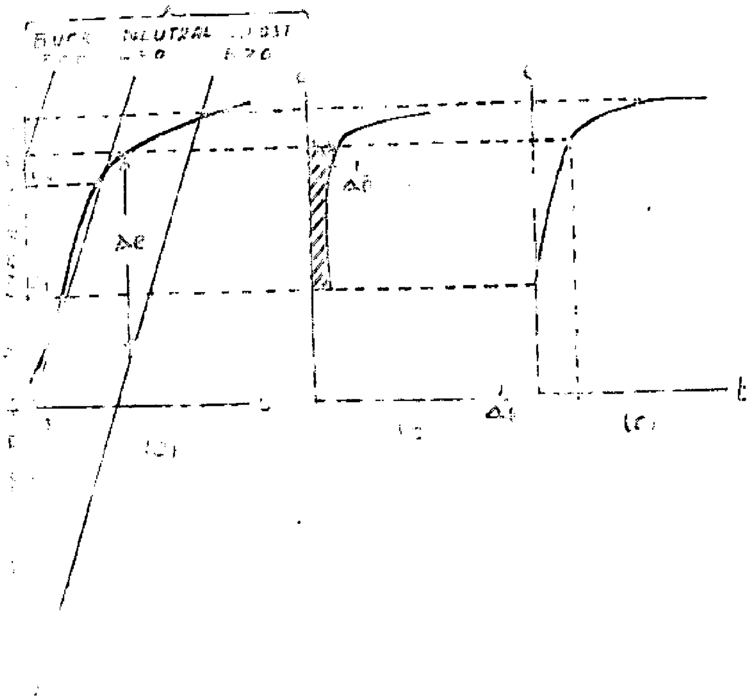
E, the armature e.m.f of the rotating amplifier is positive when boosting e, the armature e.m.f. of the main exciter.

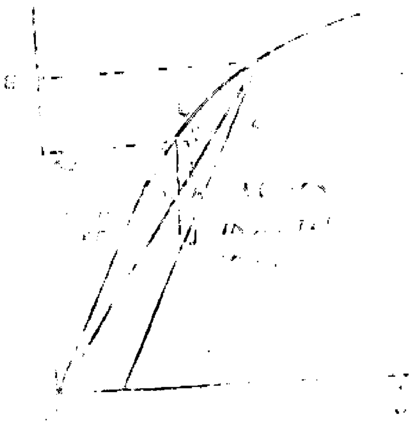
With the assumption of constant coefficient of dispersion equation (2.18) becomes

$$\frac{\sigma N}{k}\frac{de}{dt} = e - (Ri - E) \qquad \ldots. \qquad (2.19)$$

$$\text{or} \quad T\frac{de}{dt} = \Delta e \qquad \ldots.. \qquad \ldots. \qquad (2.20)$$

$$\text{where} \quad T = \frac{\sigma N}{k} \qquad \ldots. \qquad \ldots. \qquad (2.21)$$





Right

Δe

ΔL

and $\Delta e = e - (Ri - E)$ ..... (2.22)

Build up of voltage for this type of exciter is illustrated in Fig. 2.15

2.8.

Fig. 2.16 compares Δe for the excitation system considered in 2.7 with Δe for a system in which build up was caused by reduction of the resistance of the shunt field circuit of a self excited exciter, the ceiling voltage being the same in both cases.

It is seen that Δe is greater for insertion of series boosting voltage from the rotating amplifier than it is for reduction of the field resistance. Since the time constant is the same in both cases, the build up is more rapid with the rotating amplifier.

Rapid build down can also be obtained with the rotating amplifier, the line $Ri - E$ of Fig 2.15 (a) being elevated initially to maximum buck. However, the bucking voltage decreases as the alternating voltage comes near the correct value. A similar decrease of boost voltage occurs during build ups in which correct alternating voltage is approached.

2.9. EXCITER WITH TWO OR MORE FIELD WINDINGS:

When an exciter has two or more field windings, one of which is self excited while one or more others are separately excited, the time constant is the sum of the time constants of the two field circuits separately (including external resistance but with external inductance assumed negligible). The time constant of each field winding is approximately proportional to the volume of that winding;

hence the sum of the time constants of two windings will be almost equal to the time constant of a single field winding occupying the same space. The two applied voltages are additive, very much as if they were connected in series. Thus it makes little difference in the response of the machine whether the two voltages are applied to separate windings or in series, to the same winding.

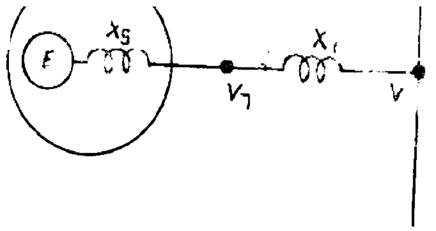
2.10 RESPONSE OF LOADED EXCITER[4]

The terminal voltage of a loaded exciter differs from the unloaded exciter with the same field current because of the effects of armature resistance (including bush drop), armature inductance and armature reaction. Of these, resistance and reaction are the most important.

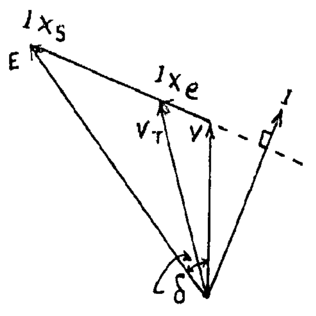
With either kind of excitation, the exciter response is decreased by load. The effect is much greater in the self-excited exciter than in the separately excited one. In addition to reducing the response, load also reduces the ceiling voltage.

2.11. DYNAMIC STABILITY[5]

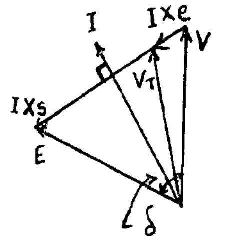
The generator is usually tied to a large system through a certain amount of external reactance provided by transformers, transmission lines etc. and the system voltage is very little influenced by a change of terminal voltage on the generator. If the generator terminal voltage changes then the change is accommodated across the external reactance by a corresponding change of reactive load current. Thus although a dead band of , say 1% in a regulator does not seem very great it may represent a considerable change of reactive load. Hence an accurate regulator leads to a more tightly controlled system.


F
x_S
X_l
V_T
V

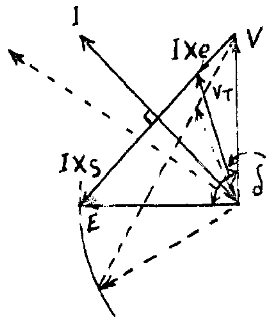
(a)


IX_S
E
IX_e
V_T
V
I
δ

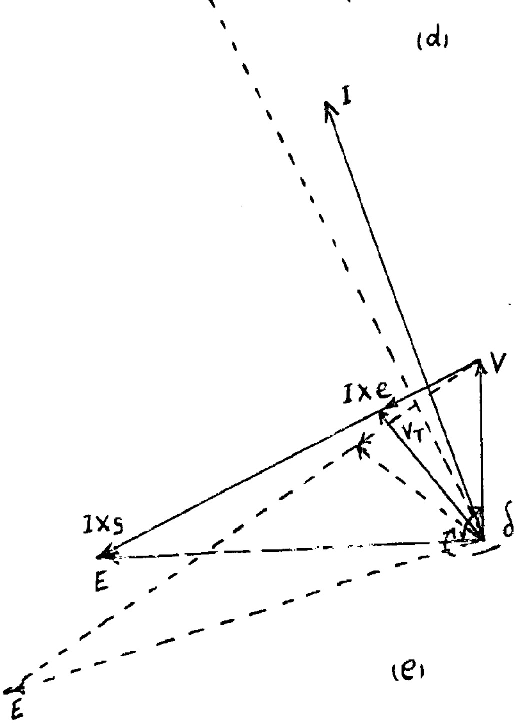
(b)


I
IX_e
V
V_T
IX_S
E
δ

(c)


I
IX_e
V
V_T
IX_S
E
δ

(d)


I
V
IX_e
V_T
IX_S
E
δ
E

(e)

If a fault or other disturbance occurs on the power system it is usually cleared quickly but the sudden shock to the system can cause a generator to lose synchronism. The performance of the regulator has a considerable influence on the system stability, but to be effective it must act very rapidly and powerfully, for it is the performance during the first half-second after the start of the disturbance that matters most.

Under certain conditions the generator may be called upon to supply leading current and so the performance of the generators in the leading region is of some concern. Under manual controls of the excitation the leading current that a generator can supply is limited, it being determined mainly by the generator short circuit ratio and partly by the power-system parameters. If this limit (the manual stability limit) is exceeded the generator loses synchronism with the system.

The use of a fast-response regulator allows stable operation of a generator well beyond the manual stability limit.

Fig. 2.17 (a) shows a generator tied to a large system via an external reactance X_e. The fictitious generator internal e.m.f E due to rotor excitation feeds the machine terminals through the synchronous reactance X_s.

Fig. 2.17(b) is a vector diagram showing conditions when the generator is supplying lagging current. The ratio between the two voltage drops IX_e and IX_s is constant.

Fig. 2.17(c) is a vector diagram showing conditions when operating well into the leading region.

Under manual excitation control or under control of a comparatively slow regulator it is assumed that the generator excitation and hence the internal e.m.f., E is constant. Maximum possible power (for any fixed value of E) is generated when the angle δ between E and V is 90° (refer Fig. 2.17 d). With $\delta > 90^{\circ}$ although the current I increases it swings round more out of phase with V so that the in-phase current and therefore the generated power, is less than for the 90° condition. (Dotted lines in Fig. 2.17 (d) indicate this condition). The rotor is still being supplied with the same mechanical power by the turbine and so there is a surplus of power which accelrates the rotor still further and synchronism is lost.

With a fast response regulator the rotor excitation is so adjusted that V_T (instead of becoming progressively smaller with increase of δ) is always held constant. In other words E is increased as δ increases. Fig. 2.17 (e) is similar to Fig. 2.17(d) except for the fact that V_T is held at the correct value. For such a case when $\delta > 90^{\circ}$ the in-phase component of current increases with increase in δ showing that the maximum power is no longer limited to that generated when δ is 90°. It is therefore possible to operate the generator with $\delta > 90^{\circ}$ without loss of synchronism.

As δ increases it becomes more and more difficult for the regulator to boost the excitation fast enough to prevent the rotor pulling out of synchronism. The limit of stability reached when the generator is under control of a fast response regulator is known as the dynamic stability limit.

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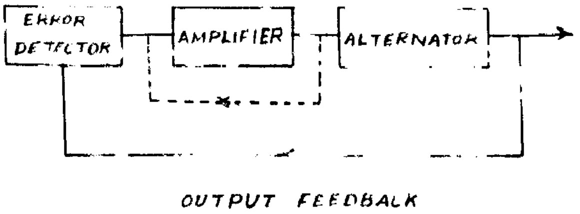


Fig. [illegible] control [illegible]

CHAPTER - 3

VOLTAGE REGULATION SYSTEMS FOR SYNCHRONOUS MACHINES.

3.1. CLOSED-LOOP CONTROL SYSTEMS:[6]

In this type of system, the alternator output voltage is fed back and continuously compared with a reference quantity ; any difference between the two quantities results in an error signal that acts on the system to reduce this difference.

Fig. 3.1 indicates the essential elements of a closed-loop alternator voltage-control system. As the name implies the error detector compares the fed-back quantity with a reference quantity, and provides the corrective-error signal. Normally this signal is at such a low power level that it requires further amplification, as indicated, before it may be employed to produce a corrective action. The reference quantity in this case is a constant quantity and may take the form of a voltage, flux, spring tension or other suitable quantity. In every case, the feed back voltage from the alternator has to be converted into the appropriate quantity depending on the nature of the reference.

This type of system thus endeavours to keep the output voltage at a constant value, irrespective of the characteristic of the machine itself, and to counter-act the fall of speed of an alternator set on load as well as the fall of terminal voltage due to increased resistance when they get hot, but special arrangements may be necessary to avoid hunting, or periodic variation about the steady value, due to the time-factors in the control system.

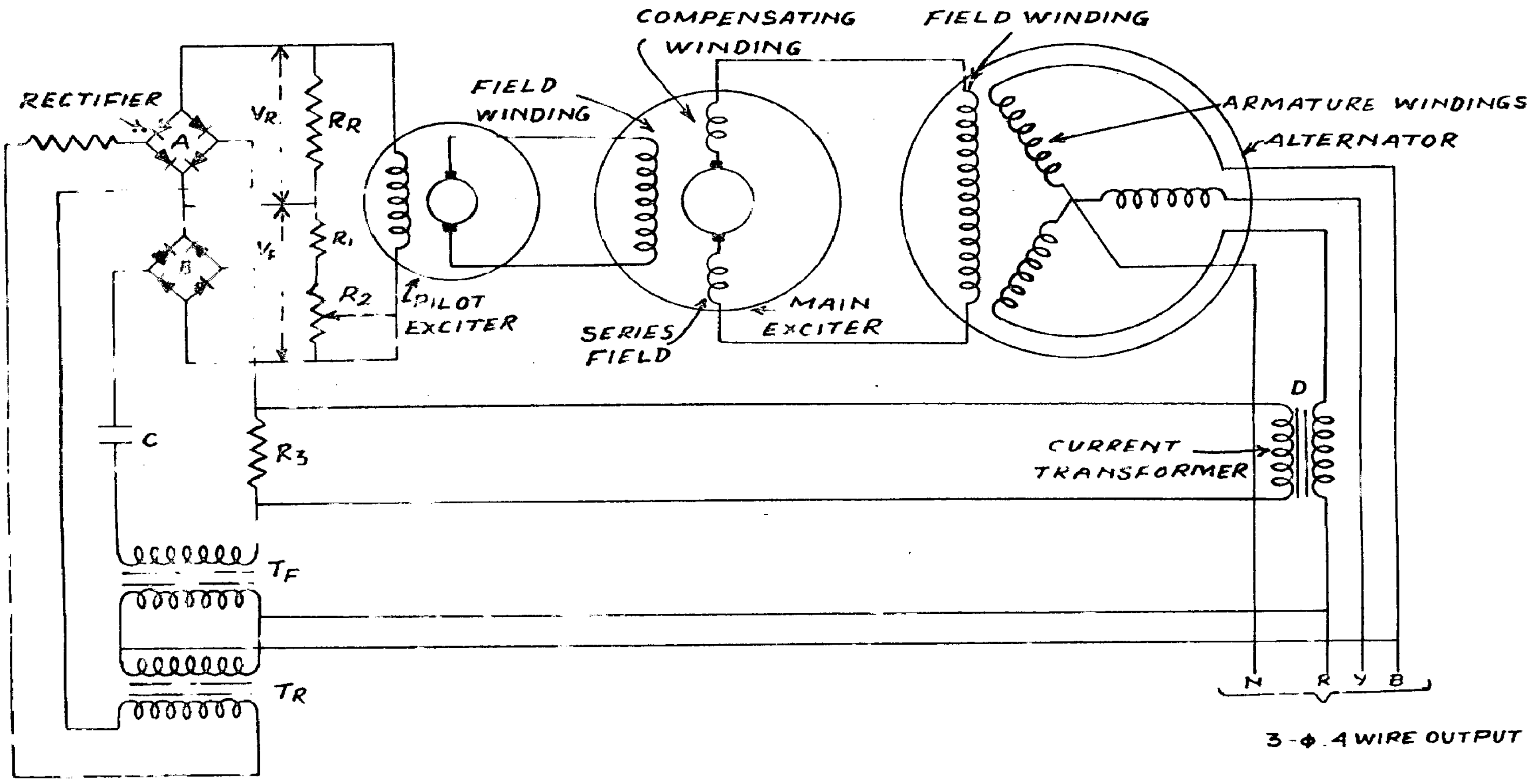


Fig. 6.5 [illegible] regulator [illegible]

3.2. THE "AMPLIDEX" CONTROL SYSTEM[7]

This system may be used with an alternator of normal design. The field windings of the alternator are fed from a main exciter which has its own field winding supplied from a pilot exciter, the two exciters being mounted in tandem in a single frame. In order to ensure rapid response, a laminated-iron field system is used in the main exciter, this being provided with a distributed compensating winding for the neutralization of armature reaction; this enables the exciter to operate with good commutation at high loadings. The field system of the pilot exciter is similarly laminated. The arrangement is indicated in Fig.3.2. The output of the alternator is applied to two full-wave bridge-connected rectifiers A and B, through the transformers T_R and T_F.

The core of the reference transformer T_R is saturated and that of the feed back transformer T_F is unsaturated at the normal voltage of the alternator.

Thus, by limiting the change of flux, the virtual value of the secondary voltage of the saturated transformer can be kept sufficiently constant to act as a reference voltage. This voltage is applied to rectifier A, the d.c. voltage V_R of which is practically constant for all nromal variations of alternator terminal voltage. The output voltage of the feed-back transformer T_F is however, practically proportional to the alternator voltage, and is applied to the rectifier B through the series capacitor C (the purpose of C is to avoid variations of alternator voltage due to normal changes of engine speed).

The output voltages of the two rectifiers are applied to the resistances R_R , R_1 and R_2 in such a way that the volt-drop across the series resistors is equal to $V_R - V_F$(or to $V_F - V_R$), this

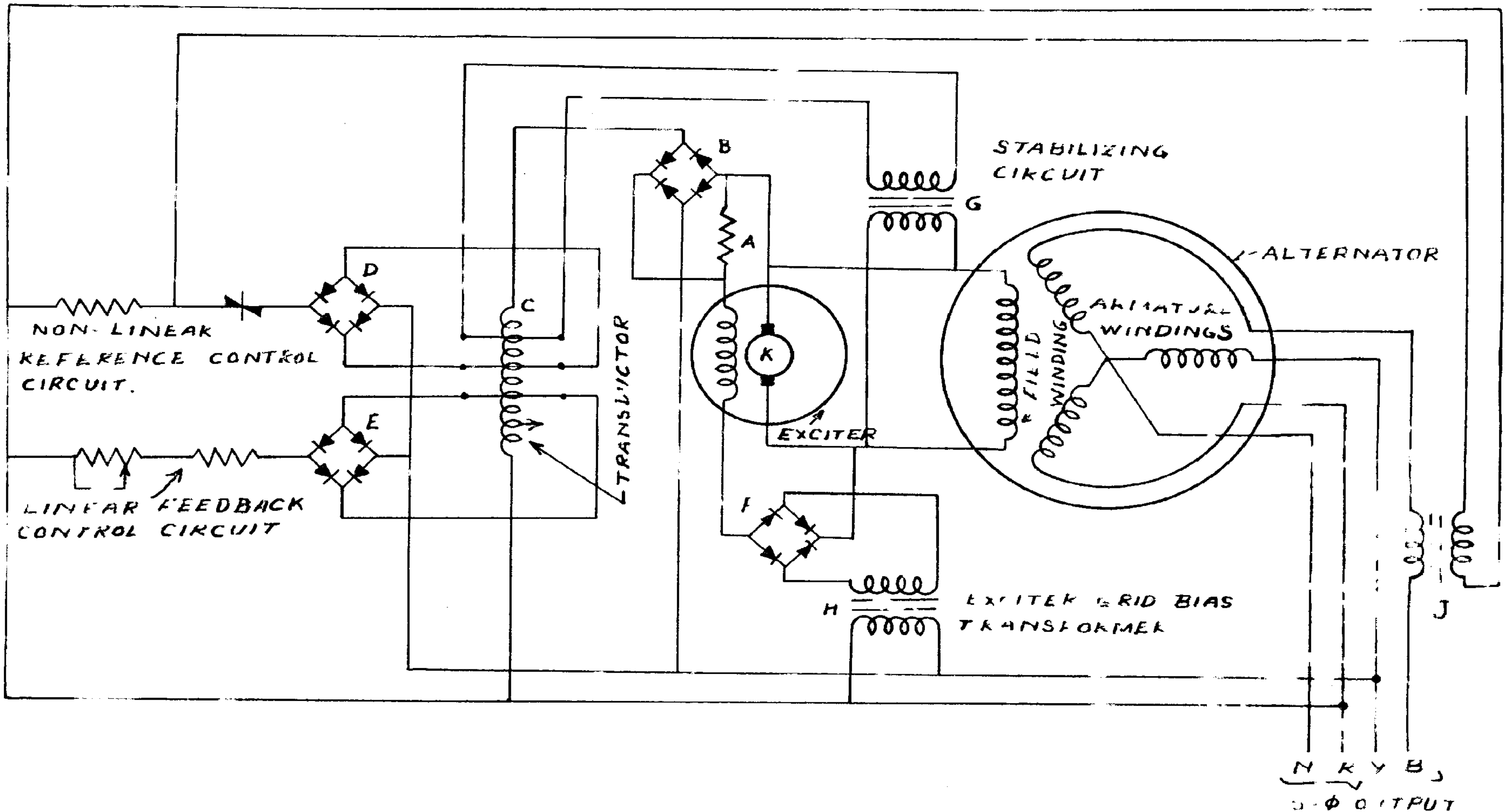


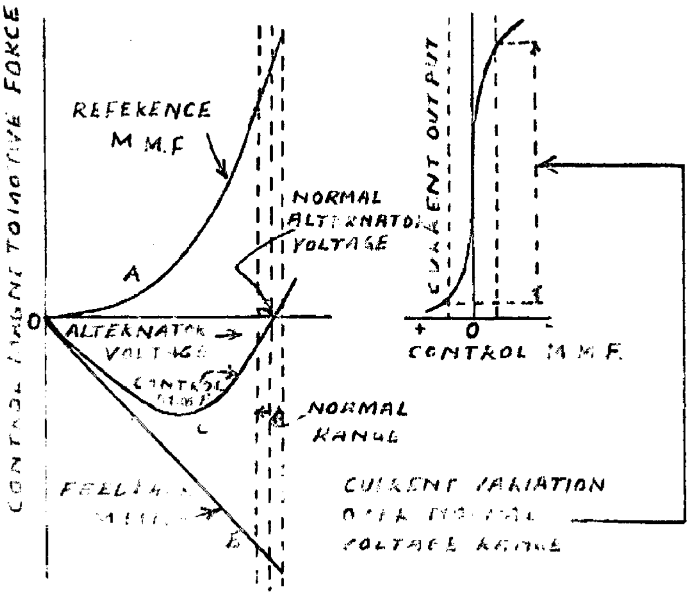
Fig. [illegible] of transductor alternator regulator connections.

The resistors thus act as an "error detector", the field windings of the pilot exciter then receiving a current which depends on the difference between the actual voltage of the alternator and the required voltage. The pilot exciter amplifies any such error or difference and applies this to the field winding of the main exciter, so that the field current of the alternator is altered to correct its voltage. An additional stabilizing circuit, (omitted for simplicity from Fig. 3.2) is used to inject into the field circuit of the pilot exciter a negative feed back in order to avoid hunting.

The current transformer D and the resistor R_3 can be used to inject into the control circuit a component of voltage which depends on the magnitude and phase of the load current to ensure correct load sharing between the sets in parallel operation.

3.3."TRANSDUCTOR" CONTROL SYSTEM[7]

A transductor can be used as a magnetic amplifier. Fig.3.3 shows a simplified circuit in which a transductor is used for voltage control of a conventional alternator. The field windings of the alternator are fed from a shunt-wound exciter which has a resistor A in series with its own field windings. A single-phase full wave rectifier B is connected in parallel with this resistor, the rectifier being fed from the alternator through the a.c. windings of the transductor C. The transductor has two main d.c. windings, which are fed through the rectifiers D and E from the alternator, the corrections being such that the two d.c. windings have opposition magnetic effects. The circuit with rectifier D is non-linear and acts as the reference circuit. The rectifier E forms part of the feed back circuit, in which the current is proportional to the alternator voltage. For one particular value of


CONTROL MAGNETOMOTIVE FORCE
REFERENCE
M.M.F
A
NORMAL
ALTERNATOR
VOLTAGE
0
ALTERNATOR
VOLTAGE
CONTROL
M.M.F
C
NORMAL
RANGE
FEEDBACK
M.M.F
B
CURRENT OUT PUT
+
0
-
CONTROL M.M.F.
CURRENT VARIATION
OVER NORMAL
VOLTAGE RANGE

(a) (b)

the alternator voltage, therefore, the ampere turns of the reference and the feed back control windings on the transductor are equal and opposite, with zero resultant.

The curves A and B in Fig. 3.4 (a) show the manner in which the M.M.F. or amp-turns in the reference and feed back windings of the transductor change with the alternator voltage. The curve C shows the total or resultant control MMF due to both the windings. The resultant control M.M.F. changes considerably if the alternator voltage departs from the required value, at which the amp-turns of the two windings are equal. Fig. 3.4 (b) illustrates the saturation effect in the transductor and shows the considerable variation of the virtual value of the a.c. output -current which results from a small change of the resultant control ampturns. In this way the transductor acts as an amplifier. If the alternator voltage rises above the preset value, an increased a.c. voltage is applied to the rectifier B. This causes an increased volt-drop across the resistor A in opposition to that supplied by the armature K (Fig. 3.3.) thus reducing the field current of the exciter which in turn reduces the field current of the alternator to lower the alternator voltage.

In order to avoid hunting, due to the transductor causing a momentary change of alternator flux in excess of that required to restore the alternator voltage, a stabilizing circuit is included. This consists of a transformer G which is connected across the exciter to supply an additional control winding on the transductor. When the exciter voltage changes in response to change of its field current, voltage is induced in the secondary windings of this transformer, the secondary voltage being proportional to the rate of change of the alternator field current. This secondary voltage creates in the transductor a magnetomotive force in opposition to th net control M.M.F., thus providing a negative feed-back signal.

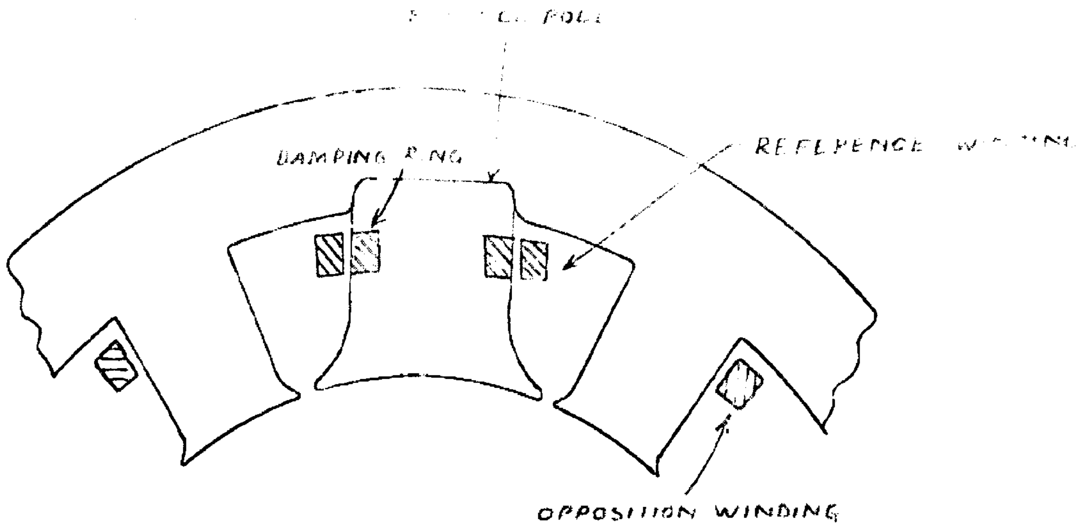
In the event of a sudden change of alternator load current there may be a tendency for the polarity of the exciter to be reversed. Exciter reverssal is, however, prevented by means of a small transformer H fed from the alternator output, which feeds the exciter field to assist self-excitation. By means of a change-over switch the field current may be controlled, either by the transductor circuit or by a simple hand-operated variable resistor in the exciter field circuit, if required. This is a convenience in the event of failure of the regulator and during synchronizing.

The alternator may be operated in parallel with other alternators by using a current transformer J, to inject into the reference circuit a voltage which depends on the load current. This is dealt in greater detail in Chapter -4.

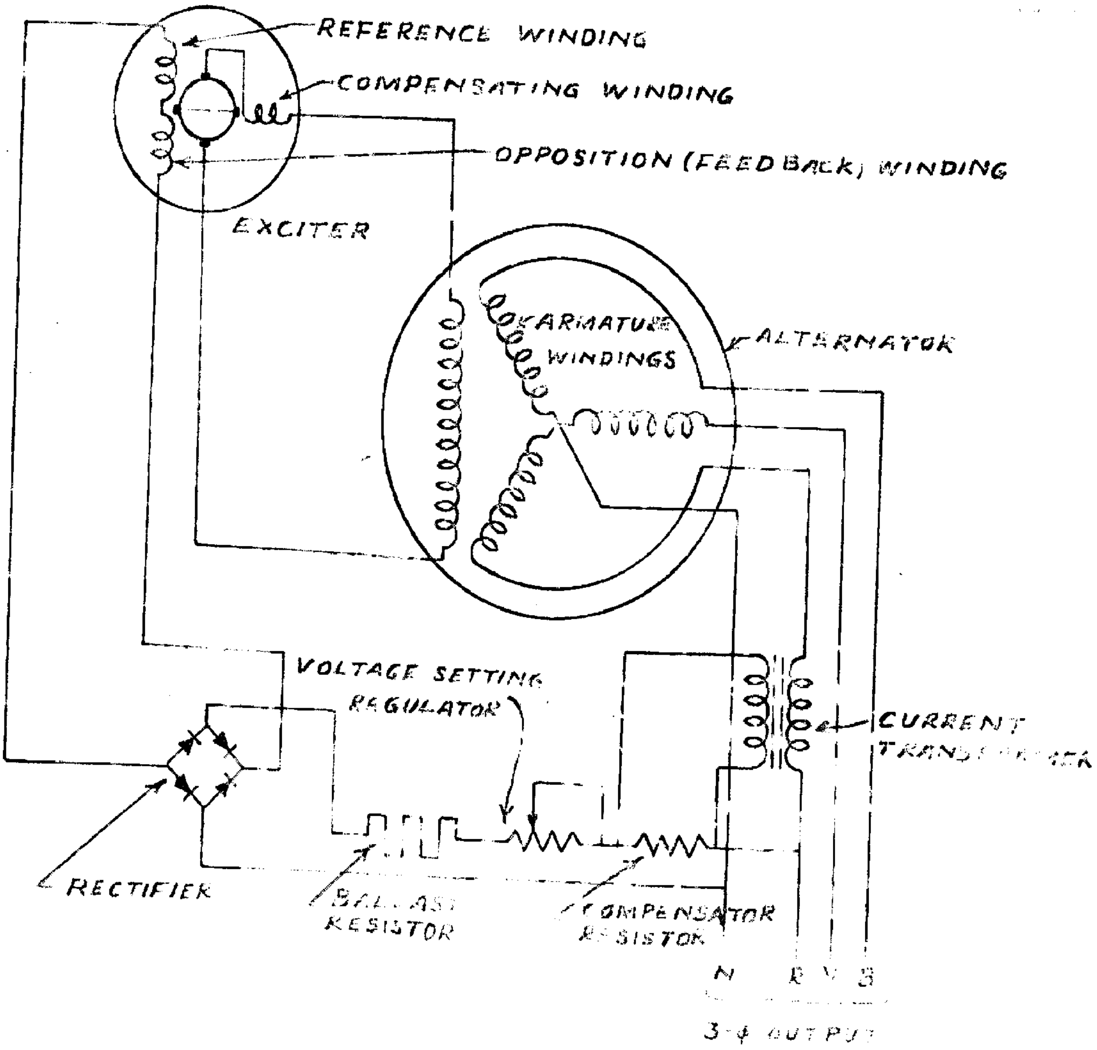
3.4. THE " MAGNICON"[7]

The "Magnicon" has been used as a quick-response exciter for alternators requiring a low voltage regulation. "Magnicon" acts as a two-stage amplifier of the control-field current. The two stage amplification of the "Magnicon" depends on the square of the speed at which it is driven; thus the "Magnicon" is driven at a higher speed than the controlled alternator as a rule. Variation of control-field power may be reflected in a 20,000 times greater variation of power output.

The "Magnicon" is used for voltage regulation of an alternator in conjunction with a circuit in which the M.M.F. of the control field is dependent on the difference between a reference M.M.F. and a M.M.F. which is proportional to the actual voltage of the controlled alternator. The reference M.M.F. is provided in the "Magnicon" exciter by means of a special control pole.


POLE
DAMPING RING
REFERENCE WINDING
OPPOSITION WINDING

[illegible]


REFERENCE WINDING
COMPENSATING WINDING
OPPOSITION (FEED BACK) WINDING
EXCITER
ARMATURE WINDINGS
ALTERNATOR
VOLTAGE SETTING REGULATOR
CURRENT TRANSFORMER
RECTIFIER
BALLAST RESISTOR
COMPENSATOR RESISTOR
N
R
Y
B
3-φ OUTPUT

[illegible]

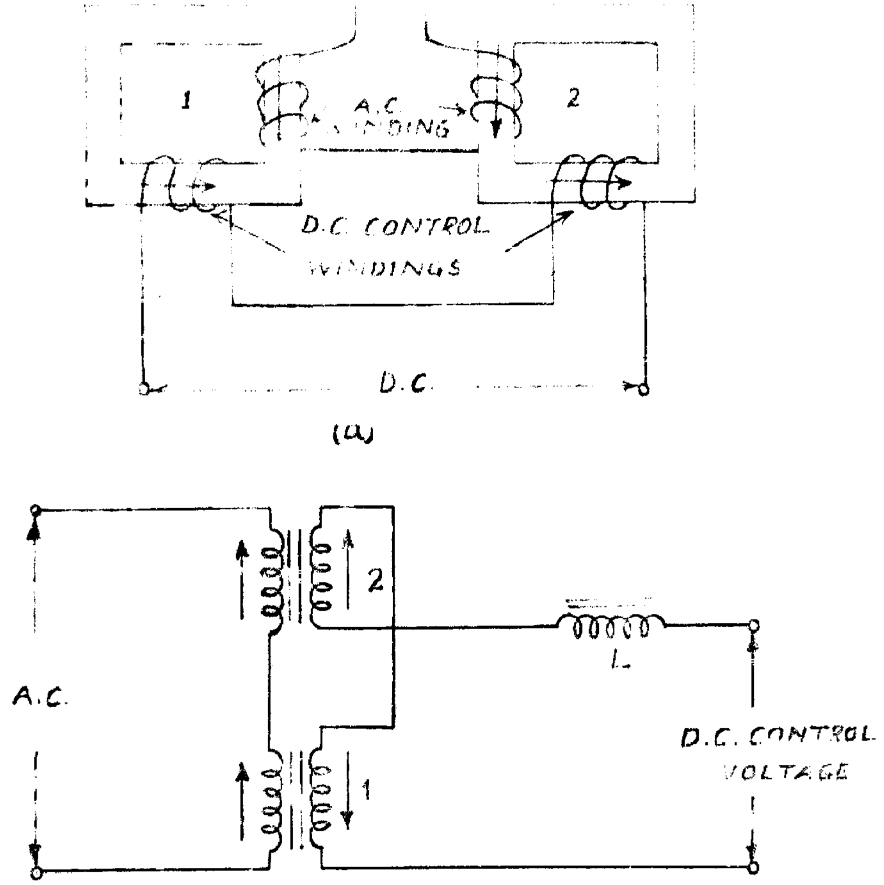
fitted in place of the central tooth of each control pole, the insert having a magnetic portion which is surrounded by a copper damping ring as shown in Fig. 3.5. In this insert is created the reference M.M.F., the purpose of the damping ring is to delay changes in the reference flux should there be a sudden large change of alternator voltage. The insert is wound with a 'reference' coil and with a small opposition'feed back' coil which embraces the whole of the teeth on the control pole. These two windings are connected in series and supplied from a rectifier which is fed from the alternator as shown in Fig. 3.6

Due to small cross-sectional area of the neck of the insert this portion is magnetically saturated with a current much below the value which flows on normal alternator voltage. Since the remainder of the control pole is unsaturated and is excited by an opposition winding, the control-pole flux is dependent on the difference between the reference voltage and the actual alternator voltage. The 'Magnicon' amplifies any difference, and the output is used to excite the alternator to correct the voltage. At normal alternator voltage, excitation is provided by slight over-compensation of the 'Magnicon'.

This system has been applied to give a voltage regulation on a single phase alternator as low at ± 1% under all conditions of load from no load to full load, cold to hot, and with varying p.f. in spite of a speed variation of ± 1-1/2% ; although the normal voltage regulation of a 3-phase set is plus or minus 2-1/2 %.

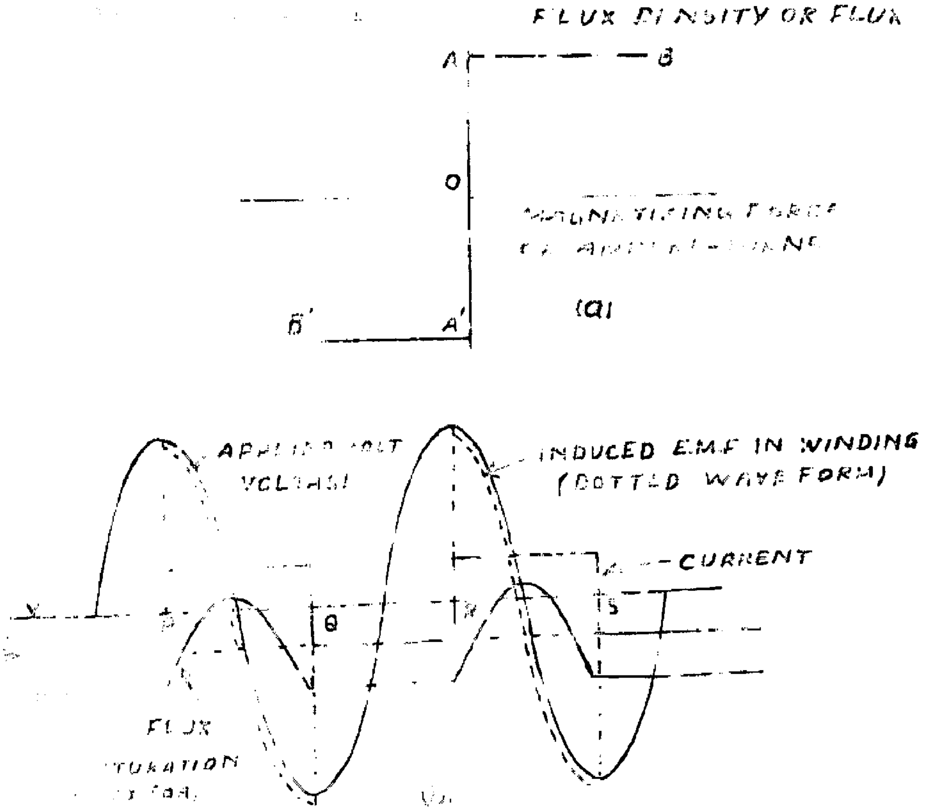
"Magnicon" controlled alternators can be operated in parallel with similar machines by connecting the compensating windings of the "Magnicons" in parallel through a ballast resistor. If the

"Magnicon" controlled alternator is required to run in parallel with an alternator having an electromechanical automatic voltage regulator, this can be accomplished by injecting into the control-circuit a voltage which depends on the magnitude and phase of the alternator load-current. This voltage can be applied by means of a current transformer and compensating resistor as shown in Fig. 3.6.


1
2
A.C. WINDING
D.C. CONTROL WINDINGS
D.C.
2
1
L
A.C.
D.C. CONTROL VOLTAGE

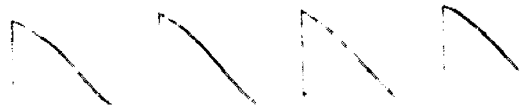
(a)

(b)


FLUX DENSITY OR FLUX
A
B
O
MAGNETISING FORCE OR AMPERE-TURNS
B'
A'
APPLIED VOLTAGE
INDUCED E.M.F IN WINDING (DOTTED WAVE FORM)
CURRENT
P
Q
R
S
FLUX SATURATION

(a)

(b)



CHAPTER - 4

STATIC VOLTAGE REGULATORS - TRANSDUCTOR TYPE

4.1. TRANSDUCTOR (MAGNETIC AMPLIFIER) THEORY[8,9]

By transductor is meant a reactance whose value can be varied by varying the direct current flowing in a winding on the same core. The effect of the direct current is to saturate the core and, therefore, reduce its permeability and hence the reactance of the alternating current winding. This type of regulating unit is some times known as a magnetic amplifier since a small input can be made to produce a much larger change of output.

One type of transductor construction is shown in Fig. 4.1.(a), where two iron cores are used, each having two windings, one carrying an alternating current and the other a direct current. The direct-current windings must always be connected in series but the alternating -current windings may be connected in series or parallel. The characteristics of the transductor depend on whether the alternating-current windings are in series or parallel and also whether an alternating current is allowed to flow in the direct-current control circuit. If an alternating current is allowed to flow the effect is similar to connecting the alternating-current windings in parallel.

The series arrangement of the alternating current windings together with the prevention of alternating current flowing in the direct-current windings by the use of inductor L appears most common and is shown in Fig. 4.1 (b).

To simplify the explanation the following assumptions are made :-

(i) The magnetization curve is an ideal curve, as shown in Fig. 4.2 (a) being composed of a portion OA and OA' of infinite permeability and a portion AB and A'B' of zero permeability.

(ii) The resistance of the circuit is negligible.

(iii) There is no external load.

(iv) There are equal turns on the alternating- and direct-current windings.

Since the voltage induced in any winding is proportional to the rate of change of flux, there can be no induced voltage in the windings when the core is in a saturated condition i.e. over the portion AB or A'B'. Considering the half-cycle where the direction of current flow is as shown in Fig. 4.1(b) i.e. from P to Q on Fig. 4.2 (b), since the alternating and direct currents in core (2) are in the same direction the core will be saturated and no e.m.f. can be induced in its windings. Since the applied voltage must be balanced by an equal and opposite e.m.f induced in core (1) a change of flux must occur and hence the core must operate along the portion A'A. This means that the alternating current flowing must equal the direct current so that the ampere turns cancel, otherwise the core would be saturated and would not be operating along portion A'A. Thus, from P to Q a constant current flows in the alternating current winding, the flux changing as shown, so that an e.m.f equal to the supply voltage is induced in the winding. Exactly the same thing happens to core (2) during the other half-cycle from Q to R. Hence the alternating current through the transudctor is of square shape and equal in magnitude to the direct current in the control windings. It may be considered that the apparatus behaves as a d.c. current transformer, since the alternating and direct currents must always be equal. The voltage induced in the direct-current coil is the same as the alternating-current coil, but since the direct-current coils are connected in series and in the opposite direction to the alternating current coils, a voltage of double the supply frequency, having the wave form shown in Fig. 4.2.(c) is produced. The reactor L in Fig. 4.1.(b) is used to prevent the flow of a corresponding current which would upset the operation. The effect of a series load (of limited value) in the alternating current circuit is to modify the current slightly but not to alter the general principle.

In order to reduce the direct control current the transductor is commonly self-excited. In other words part of the output current is rectified and fed back to provide part of the saturating ampere-turns. This self-excitation may be obtained by a third winding or by auto self- excitation.

4.2. TRANSDUCTOR DESIGN PRINCIPLES:[8,10,11]

Principal Symbols:

A = Cross-section of core
B_o = Amplitude of sinusoidal flux density.
B_m = Steady component of flux density
l = Magnetic length
m = Core constant
μ = Permeability
T_{AC} = Turns in a.c. winding of transductor element
T_{SE} = Turns for self-excitation
T_C = Turns in control winding

R = Resistance of transductor load resistor

r = Internal resistance of transductor

R_C = Resistance of control winding

g = Constant relating r and T_{AC}

s = Constant relating R_C and T_C

n = Ratio R/r

V = Supply voltage

V_C = Signal voltage

f = Supply frequency, c/s

ω = Angular frequency of supply, radians/sec.

I_{av} = Mean output current

I = R.M.S. output current

I_o = Initial transductor current

I_c = Signal current in control winding

P = Maximum useful transductor output power

P_i = Initial transductor output power

p = Power amplification

K, k = Output constants

t_1 = Time lag

Z = Constant in time-lag equation

4.2.1 Power- Output :

The maximum output current of a transductor is $\frac{kV}{R + r}$ where R is the transductor load resistance , r is the internal resistance and k (output constant) is between 0.8 and 1.1. The power output is, therefore

$$\frac{k^2V^2R}{(R + r)^2}$$

It can be shown that for a given supply voltage the output power is a maximum when $R = r$. Circuit efficiency is then only 50 %; the output power, therefore, cannot be greater then the power that the transductor will dissipate without excessive temperature rise. Normal transductor designs have $R = nr$ where n is usually greater than 5 and may be as high as 20. In such designs the circuit efficiency is much higher than 50%, and if the supply voltage is high enough, the output power of the transductor may be serveral times its power dissipation rating. A further advantage of choosing a value of R that makes n greater than (say)5 is that variation of rectifier resistance does not have an important effect on total circuit resistance.

The characteristic of a transductor is found to depart seriously from linearity at a value of about half the maximum output current. For convenience we will write the maximum useful output current as $\frac{KV}{R + r}$ where K is termed an output factor. It follows that the useful output power of the transductor is

$$\left.\begin{aligned} P &= \frac{K^2V^2R}{(R + r)^2} \\ &= \frac{k^2V^2}{(1 + \frac{1}{n})^2 R} \end{aligned}\right\} \qquad \ldots \quad (4.1.)$$

For a given winding space allowed to the a.c. winding, relation between resistance and turns (assuming a constant insulation space factor) is

$$r = g\,T_{AC}^2 \qquad \ldots \quad (4.2)$$

As $r = \frac{R}{n}$ we can combine equs. (4.1) and(4.2) to give

$$\left(\frac{V}{T_{AC}}\right)^2 = \frac{(n+1)^2}{n} g \frac{P}{K^2} \qquad (4.3.)$$

This expression fixes a possible value of the ratio V/T_{AC}.

The intial power dissipation in the transductor load should not be large or it will restrict the range of control of the transductor. Normally a transductor is disigned so that at zero d.c. excitation the a.c. flux is limited to the linear part of the magnetization curve below the knee. Therefore we can write equations for the voltage and current of a simple choke, and then combine them to give

$$I_0 T_{AC} = \frac{ul}{\mu A f} \frac{V}{T_{AC}} \quad \ldots . \; (4.4)$$

where u is a numerical constant, f the supply frequency A the core area, l the magnetic length, μ the permeability, and I_0 the initial transductor magnetizing current The power dissipation in the transductor load by the initial current is

$$P_i = I_0^2 R = ng (I_0 T_{AC})^2 \quad \ldots .. \qquad (4.5)$$

From equations (4.3), (4.4) and (4.5) we can obtain an expression for the control range.

$$\frac{P}{P_i} = \left[\frac{K \mu A f}{(n+1)\, g\, ul}\right]^2 \qquad (4.6)$$

This expression though somewhat artificial and not of direct use in design work demonstrates the influence of certain factors on the control range. If this range is too small then design can be modified by increasing the a.c. turns and the space allocated to the a.c. winding, since the effect of this in the equation is a decrease in g.

Alternatively the core area or supply frequency must be increased. The expression shows that, if two materials have about the same saturation flux the one with the higher permeability before the knee has the greater control range.

4.2.2 Power Amplification :

Transducter amplification is a rather difficult quantity to define unless the load is a heating circuit when obviously, the power amplification is the ratio of the output power I^2R to the input power, $I_c^2 R_c$. However, if the load is an electromagnetic apparatus the significant quantity is the excitation produced in the load for a given input power in the magnetic amplifier. This is not a particularly convenient ratio to use, and in transductor work it is common practice to use instead the apparent or mean power amplification. This is given by

$$p = I_{av}^2 R / I_c^2 R_c \ .$$

In this expression I_{av} is the mean output current which is given by $\dfrac{I_{av}}{I_c} = N \dfrac{T_c}{T_{AC}}$ where $N = \dfrac{1}{\left(1 - \dfrac{T_{SE}}{T_{AC}}\right)}$

Hence

$$\left.\begin{aligned} p &= N^2 \frac{R}{T_{AC}^2} \, \frac{T_c^2}{R_c} \\ &= N^2 \frac{R}{T_{AC}^2} \, s \end{aligned}\right\} \qquad (4.7)$$

where s is proportional to the control winding cross-section.

Equation (4.7) shows that to obtain a large amplification the positive feed back should be large and the ratio $\dfrac{R}{T_{AC}^2}$ also large. The effect of increasing this ratio, however, is a reduction in the power handling capabilties of the transductor

This can be shown by assuming that the transductor is operated at a constant value of B_0 just below the knee of the magnetisation curve, so that the useful mean power output

$$P = \frac{K^2 V^2}{(1 + 1/n)^2 R}$$

can be rewritten as

$$P = \frac{K^2}{\left(1 + \frac{1}{n}\right)^2 R} \cdot (mAf\ T_{AC})^2 \qquad (4.8)$$

where m is a constant dependent on B_0. It will be seen from this equation that the mean output power is inversely proportional also to the amplification. From eqns. (4.7) and (4.8) the product of amplification and out-put is

$$pP = \frac{N^2 s K^2 m^2 A^2 f^2}{\left(1 + \frac{1}{n}\right)^2} \qquad (4.9)$$

In any particular application of a magnetic amplifier, the operating conditions determine the values of p and P, and the design proceeds from the separate equations for these quantities - usually by assuming a trial cross sectional area of core for a certain supply frequency. Equation (4.9) demonstrates clearly that for a given application (i.e. a given value of pP) the area of the core stack required is inversely proportional to supply frequency and to the positive feedback used.

4.2.3. Time lag:

A transductor is a resistive-inductive apparatus and there is thus a time lag between the application of the signal voltage and the attainment of the full output current. The minimum time delay will be of the order of one cycle of the a.c. supply frequency. Any closed circuit linking the two cores is inductively coupled to the control circuit, and increases the time lag by an amount equal to the L/R value of the damping circuit. If the a.c. windings are connected in parallel, a change of signal causes a current to circulate, and this increases the time lag.

Consider a voltage V_c applied to the control circuit of a transductor; the rise of current in the circuit is opposed by the voltage produced by the change of the mean flux in the cores. We have

$$\left.\begin{aligned} V_c &= i_c R_c + 2 T_c A \frac{d(B_m)}{dt} \\ &= i_c R_c + 2 T_c^2 A \frac{d(B_m)}{d(i_c T_c)} \cdot \frac{di_c}{dt} \end{aligned}\right\} \qquad (4.10)$$

If we neglect the effect of the voltage induced in the self-exciting winding, which is small compared with the supply voltage, we can apply the relation $\frac{I_{av}}{I_c} = \frac{NT_c}{T_{AC}}$ which gives

$$V_c = \frac{i_{av} T_{AC}}{N T_c} R_c + 2 T_c^2 A \frac{T_{AC}}{T_c} \frac{d(B_m)}{d(i_{av} T_{AC})} \frac{di_{av}}{dt} \qquad (4.11)$$

where N is the ratio in which the current amplification is increased by positive feed back or by self-excitation.

Now for a limited range except at low values of d.c. excitation, the term $d(B_m)/d(i_{av} T_{AC})$ can be taken as approximately constant. Hence the growth of output current is exponential and has a time constant.

$$t_1 = N \frac{T_c^2}{R_c} 2A \frac{d(B_m)}{d(i_{av} T_{AC})} \qquad \ldots \qquad (4.12)$$

For Mumetal or Radiometal the calculated value of

$d(B_m) / d(i_{av} T_{AC})$ is proportional to the non-dimensional transductor load, $R/Af\,T^2_{AC}$. It follows that equation (4.12) can be rewritten.

$$t_1 = Z \frac{NR}{f\,T^2_{AC}} \frac{T^2_c}{R_c} \quad \ldots\ldots \quad (4.13)$$

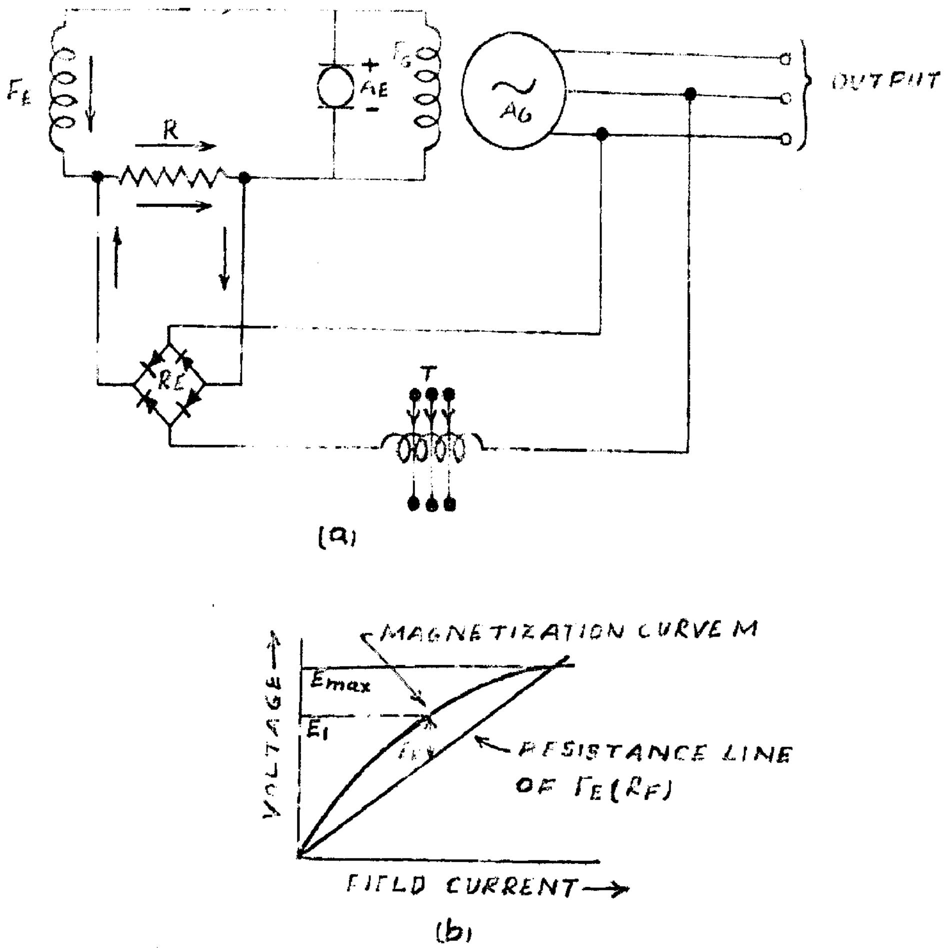
where Z is a constant for a given core material.

This equation shows the linear variation of time constant with transductor circuit resistance and inversely as the supply frequency. Also the normal effect of positive feed back is to increase the circuit time constant. However if we combine equations (4.7) and (4.13) we see that

$$t_1 \propto \frac{p}{Nf} \quad \ldots\ldots \quad (4.14)$$

This shows that the time-constant and power amplification are directly related, and that the ratio p/t_1 is increased by the application of positive feed back or self-excitation, the core area does not enter into this expression.

When a number of stages of amplification are connected in cascade, the overall power amplification is the product of the stage amplifications, whereas the total time-constant is roughly the sum of the individual time constants. Since the time constant is proportional to amplification, it follows that as the number of stages is increased there is an increase of the ratio of amplification to time-constant. Therefore, magnetic amplifier designs tend to take the form of a number of stages connected in cascade, each stage having a low power amplification and yet using the maximum positive feed back that is consistent with

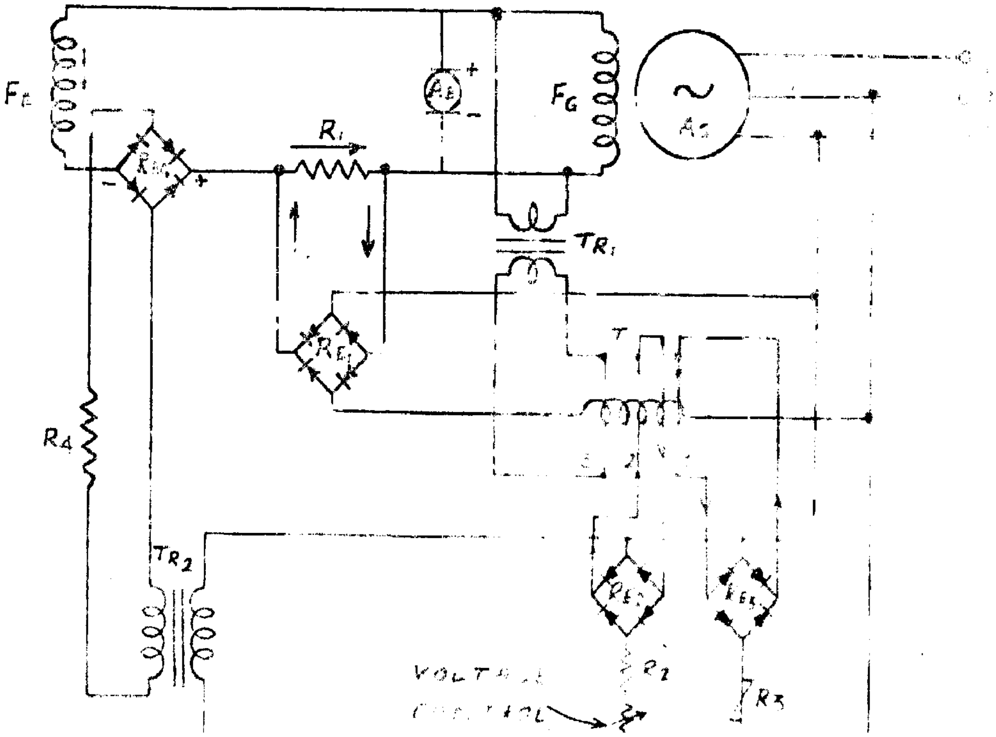


F_E
R
A_E
F_G
A_G
OUTPUT
R_E
T
(a)
MAGNETIZATION CURVE M
VOLTAGE
Emax
E_1
RESISTANCE LINE
OF $F_E(R_F)$
FIELD CURRENT
(b)

[illegible]

[illegible]

[illegible]



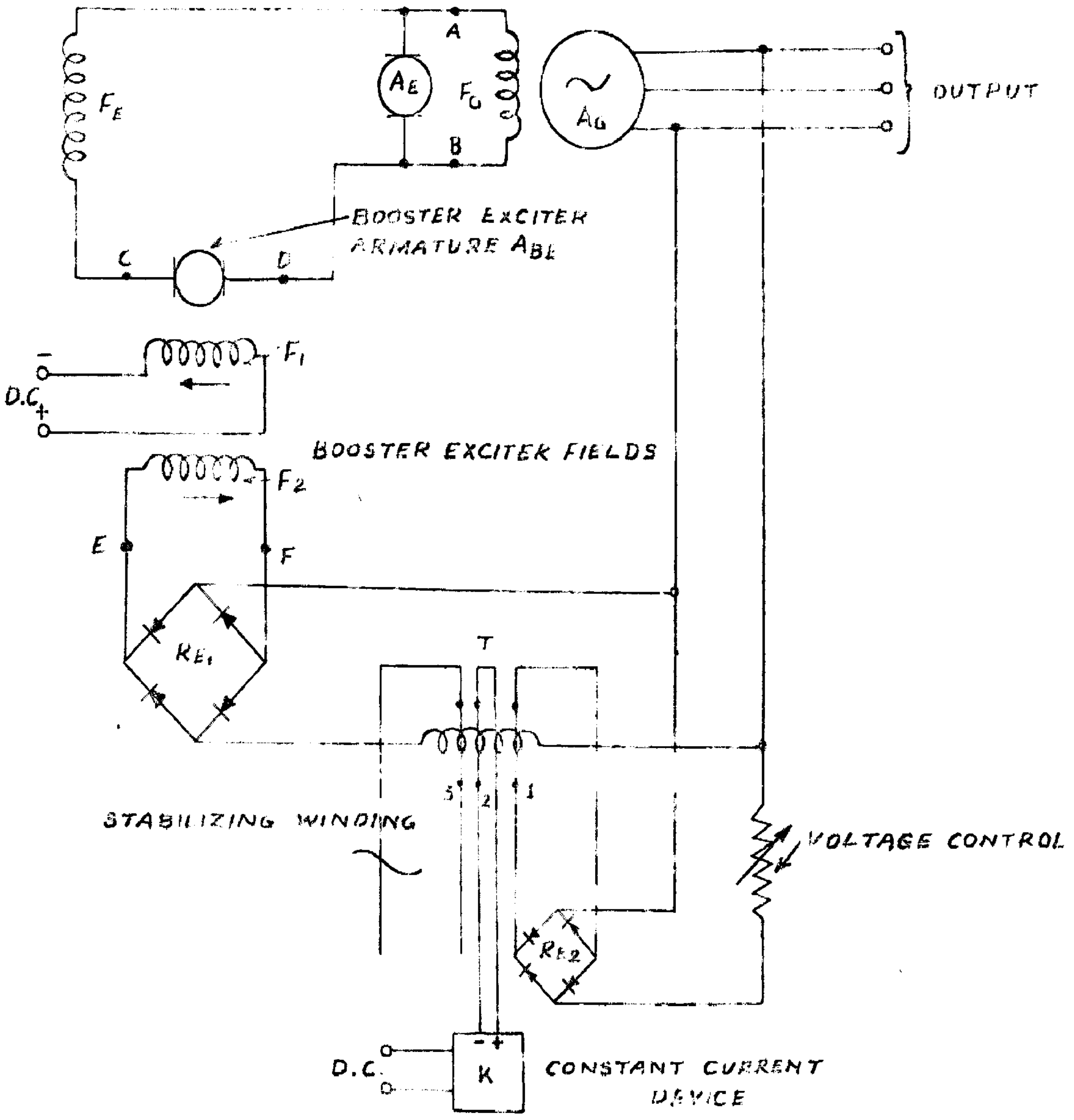
F_E
R_{E2}
R_1
A_E
F_G
A_G
TR_1
R_{E1}
T
R_4
TR_2
R_{E3}
R_{E4}
R_2
R_3
VOLTAGE
CONTROL

4.3. A TRANSDUCTOR VOLTAGE REGULATOR FOR SMALL ALTERNATORS[9,12]

The basic circuit for a voltage regulator using transductors and having no moving parts and no valves (as developed by ASEA) is shown in Fig. 4.3.(a). The exciter field is shunt connected through a resistor R, the current normally flowing in the direction shown. The output voltage is fed through a transductor T to a rectifier R_E arranged so that the output from the rectifier flows in the same direction as that from the exciter i.e. it increases the drop in R so reducing the exciter voltage. The magnetization curve M and the total field resistance R_F are arranged (Fig. 4.3 (b)) so that the exciter voltage corresponding to E_{max} is produced when no current flows from the rectifier R, and E_{max} is made larger than normally required. The arrangement has the advantage that, should the generator voltage be reduced to a very low value due to a fault, there is no chance of the generator becoming demagnetised.

In operation the reactance of the transductor is controlled so that the additional voltage drop across R due to the rectifier current is E_R (Fig.4.3(b), just sufficient to maintain the output voltage at some value E_1. The method used to control the transductor is shown in Fig. 4.4. The two windings 1 and 2 on the transductor T are connected in opposition and fed from rectifiers RE_2 and RE_3. R_{E_2} is fed through a linear resistor R_2 and R_{E_3} is fed through a non-linear resistor R_3.

The current through winding 1 is in such a direction that when it increases it decreases the reactance of transductor T and hence decreases the exciter voltage. At normal voltage the currents in windings 1 and 2 are approximately equal. If the voltage increases, the current in winding 1 increases more



A
B
F_E
A_E
F_G
A_G
OUTPUT
BOOSTER EXCITER ARMATURE A_BE
C
D
F_1
D.C.
−
+
BOOSTER EXCITER FIELDS
F_2
E
F
RE_1
T
5
2
1
STABILIZING WINDING
VOLTAGE CONTROL
RE_2
− +
K
D.C.
CONSTANT CURRENT DEVICE

than in winding 2 and so reduces the exciter and generator voltages. Transformer T_{R1} and winding 3 form the antihunting circuit, the current through winding 3 being dependent on the rate of change of exciter voltage. Transformer T_{R2} and rectifier R_{E4} are used to prevent reversal of the exciter potential on heavy load- variations and to improve the performance when the generator is running on light load. The voltage from the rectifier assists the exciter voltage as shown in Fig. 4.4.

Application: This type of voltage regulator is made for high-speed generators upto about 500 kVA.

4.4. A TRANSDUCTOR VOLTAGE REGULATOR FOR LARGE ALTERNATORS:[9,13]

For larger sizes of synchronous machines the speed of response is important. Fig. 4.5 shows a simplified circuit used for this purpose. The field F_G of the generator is fed from the exciter armature A_E which is shunt excited by the field F_E. The shunt field is controlled by the armature voltage of a booster exciter A_{BE}. A constant m.m.f. is produced in the booster exciter by the field winding F_1 and an opposing control m.m.f. by the field winding F_2 which is fed from the rectifier R_{E1}, through the transductor T from the output of the generator. By the use of a booster exciter, the speed of response may be made rapid, due to the forcing action of the booster exciter when the voltage deviates from its normal value. The purpose of the constant m.m.f. due to field winding F_1 is so that the voltage of the booster exciter may be reversed. This would be impossible without this winding, since the direction of current flow in winding F_2 cannot be reversed due to the rectifier R_{E1}. The measuring unit consists of two windings on the transductor T, winding 1 being fed from a current proportional to the output voltage and winding 2 being fed with a constant current in opposition to that in winding 1, the constant current being obtained from the device marked K. By operating the exciter so that its field resistance line is a tangent to the magnetization curve i.e. the normally unstable operating point the regulator may be made astatic. This is due to the fact that an infinitely small change of booster voltage will cause a large change of exciter voltage . An increase in output voltage increases the current in winding 1 of transductor T which causes the current in F_2 to change so as to produce a decrease in exciter and therefore generator voltage. For stable operation it is necessary to add a number of antihunting circuits. Voltages are taken from the points AB, CD and EF and after suitable modification are fed to the winding 3 on the transductor T through an impulse transformer (not shown).

These regulators have the advantage of being very robust and constructed from devices which have a practically unlimited life. The speed of response may be made very high. Oscillograph records taken on a 72000 kVA showed a speed of response of 1400 V/sec, the control cycle being completed in 0.7 to 0.8 second.

CHAPTER - 5

STATIC VOLTAGE REGULATORS- ELECTRONIC TYPE

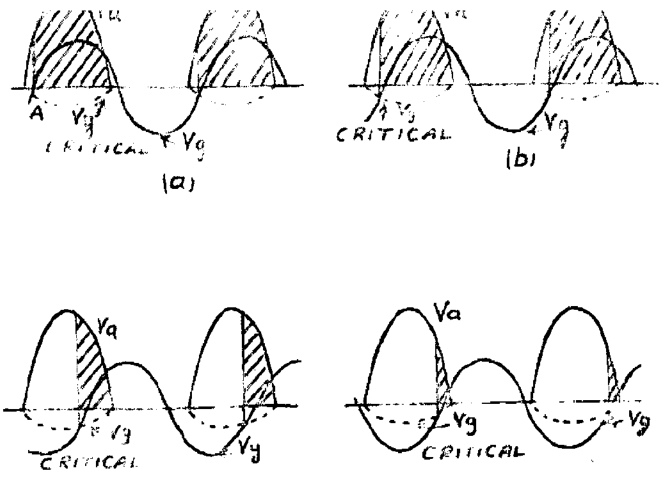
5.1. PRINCIPLES OF ANODE CURRENT CONTROL FOR THYRATRONS[9].

In general characteristic of the grid control of a gas filled valve is quite different to that of a high-vacuum valve. With the gas filled valve the grid is only able to determine the instant when anode current flows and has no control over this current once it has started to flow. The grid voltage just required to prevent the flow of anode current depends on the anode voltage and is known as the critical grid voltage. The relationship between the critical grid voltage and the anode voltage varies between different types, but is approximately a linear relationship (except at low anode voltages where the critical grid voltage becomes approximately constant). When the anode is fed with direct voltage it is impossible once current is flowing to control it by means of the grid. With an alternating anode voltage, since the anode is negative for half a cycle (when no anode current can flow) the grid is able to regain control and the average anode current may be varied from the maximum value to zero.

The principle of the method of control is to prevent anode current flowing (by a suitable voltage on the grid) until a certain instant in the cycle. By varying this instant, the average anode current may be varied. Two principal methods of varying the grid voltage for this purpose are:-

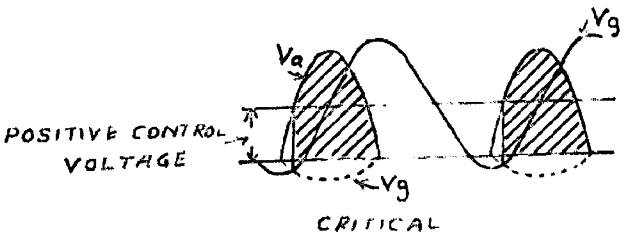
5.1.1. Phase - shift control

The grid is fed with an alternating voltage which is varied in phase to vary the anode current. In Fig. 5.1.

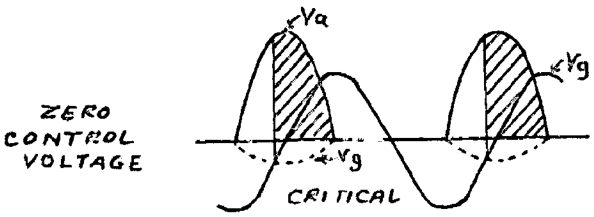

A
Vg
CRITICAL
Vg
Vg
CRITICAL
Vg
Va
Vg
CRITICAL
Vg
Va
Vg
CRITICAL
Vg

(a) (b)

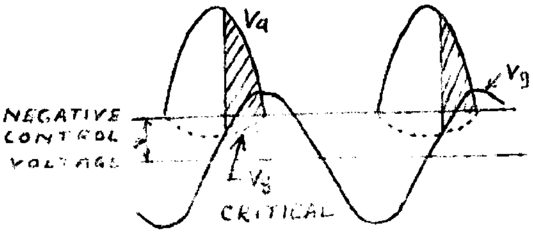
(c) (d)


Vg
Va
POSITIVE CONTROL VOLTAGE
Vg
CRITICAL

(a)


Va
Vg
ZERO CONTROL VOLTAGE
Vg
CRITICAL

(b)

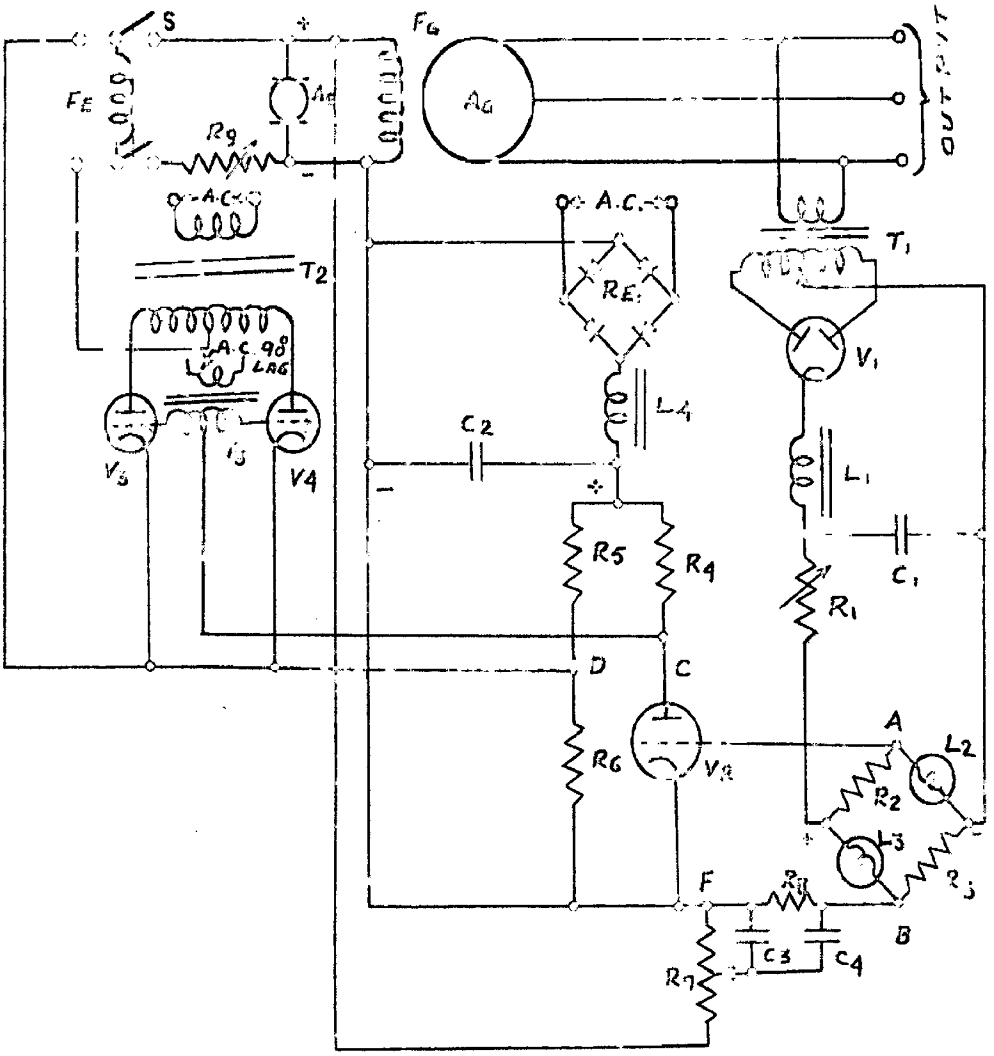

Va
Vg
NEGATIVE CONTROL VOLTAGE
Vg
CRITICAL

one half-cycle of the anode voltage is shown together with a critical grid-voltage curve. If the actual grid voltage at any instant is below this line the valve is prevented from conducting, and at the point where the grid-voltage curve cuts it the valve "fires" and anode current flows for the remainder of the half-cycle. In case (a) the valve will 'fire' at point A and the anode current will flow as indicated by the shaded portion for practically the whole cycle. In cases (b),(c) and (d) the grid-voltage wave has been progressively retarded in phase and as can be seen, the mean anode current is gradually reduced to zero. The method gives control over the whole range and the relationship between phase angle and mean anode current can be made approximately a straight line.

5.1.2. Alternating and Direct Grid-voltage Control:

The grid is supplied with an alternating voltage of constant magnitude lagging the anode voltage by approximately 90° together with the direct control voltage which is made to vary from a positive to a negative value. The effect of verying this direct control voltage on the firing angle, and therefore the mean anode current is shown in Fig. 5.2. Varying the direct voltage from a positive to a negative value varies the anode current from a maximum to zero value. This method gives good control and the relationship between the control voltage and the mean anode current may be made reasonably linear. This has an advantage over the first method in that the control signal to the regulating unit is more often in the form of a voltage of varying magnitude and not varying phase.

In both the cases the valves may be operated single


S
+
FG
FE
AE
Rg
-
AG
OUTPUT
A.C.
A.C.
T2
RE
T1
A.C. 90° LAG
V1
L4
V3
T3
V4
C2
+
-
L1
C1
R5
R4
R1
D
C
A
L2
R6
V2
R2
+
L3
R3
F
R8
B
C3
C4
R7

[illegible]

phase (half-wave and full-wave), three phase, six phase etc.. The output current of the thyratron is unidirectional and the arrangement is really a controlled rectifier.

5.2. AN ELECTRONIC VOLTAGE REGULATOR USING THYRATRON CONTROL[9]

An electronic voltage regulator for control of generators, the schematic diagram of which is shown in fig. 5.3, consists of a lamp-bridge with thyratron valves. The valves control the field current of an exciter which feeds the alternator. The operation is as given below:

The output voltage of the machine is transformed into a suitable voltage by transformer T_1 and then rectified by valve V_1. The output from the rectifier is smoothed by inductance L_1 and capacitance C_1, and then fed through the voltage adjusting resistor R_1 to the voltage-sensitive bridge, composed of L_2 and L_3, R_2 and R_3. L_2 and L_3 are tungsten-filament lamps, which increase in resistance with increasing voltage, and R_2 and R_3 are linear resistors.

The output of the bridge is fed to the grid and cathode of valve V_2 which is connected to form a bridge circuit with resistors R_4, R_5 and R_6. A slight change in grid voltage of V_2 unbalances this bridge and supplies a voltage between grid and cathode of the main thyratrons V_3 and V_4. The thyratrons are fed in a full-wave circuit from the transformer T_2 connected to the alternating current supply. The output of the thyratrons is fed through the change-over switch S to the field of the exciter F_E which controls the voltage output of the exciter armature A_E and hence the current of the alternator field F_G. In order to obtain complete and continuous control of the thyratrons the grids are also fed with an alternating voltage lagging the anode voltage by 90°.

To prevent hunting an antihunting circuit is used between the exciter and amplifier valve V_2. This circuit is composed of R_7 and C_3, C_4 and R_8 and feeds back a voltage to V_2 which is proportional to the rate of change of exciter voltage i.e. C_4 and R_8 form a differentiating circuit. Rectifier RE1, inductor L_4 and capacitor C_2 form a rectifier and smoothing circuit to feed the bridge formed by R_4 and R_5, R_6 and V_2. The change-over switch S is used so that the machine may be operated with manual control, voltage control being by means of resistor R_9.

Suppose that the output voltage decreases due to say an increase of load. This causes the voltage across the lamp bridge to decrease and hence point A to become more negative then B, due to the decreasing resistance of lamps L_2 and L_3. This increases the bias on the valve V_2 and unbalances the bridge formed by R_4 and R_5, R_6 and V_2 so that C goes in a positive direction, tending to become more positive than D. Thus the negative voltage on the thyratron decreases and (as explained above) causes the anode current, and therefore exciter field current, to increase. This causes the output voltage of the alternator to increase until equilibrium conditions are reached. As the voltage of the exciter increases, point E becomes more positive than F, opposing the action of the lamp bridge, so preventing hunting (i.e. the action is similar to a dashpot).

In actual practice the circuit is rather more complicated than that of Fig. 5.3 and the following additional features may be included:

(i) The valves may be duplicated so that if one fails the regulator will still operate.

(ii) Over-voltage and under-voltage relays may be fitted so that the machine reverts to manual operation if a fault occurs in the regulator.

(iii) To prevent an excessive current being fed to the exciter on faults a current limit circuit may be incorporated.

(iv) To allow time for the thyratron cathodes to reach their correct operating temperature a time-delay circuit is usually fitted.

(v) For parallel operation a current transformer may be fitted.

In some regulators the lamp-bridge circuit is replaced by a saturated diode-valve bridge circuit; the principle of operation, however, remains the same. On large machines a 3-phase thyratron circuit may be used. By suitable modifications the circuit may also be used with a d.c. generator.

Application:

This type of regulator has been used on machines upto 10,000 kVA but may be used upto 20,000 kVA.

Accuracy:

The accuracy is nromally 0.5% but by the addition of compensating features to overcome the effects of temperature variations, it can be improved to 0.1%.

CHAPTER - 6

STATIC VOLTAGE REGULATORS - TRANSISTOR TYPE

6.1. SYMBOLS :

A_1, A_2, A_3 = Numerical gain factors

I, i = Input current of transistor A

I_1, i_1 = Exciter shunt field current

I_2, i_2 = Control current

k = dV/dI_{γ}

L = Exciter shunt field inductance

R_0 = Output resistance of transistor A

R_1 = Resistance of exciter shunt field winding

R_2 = Potentiometer arm, positive end.

R_3 = Potentiometer arm, negative end

R_4 = Internal resistance of control source

$$\left.\begin{array}{l} a, r_b, r_c, \\ r_e, r_m \end{array}\right\} = \text{Parameters of transistor equivalent circuit}$$

T_1, T_2, T_3 = Time constants

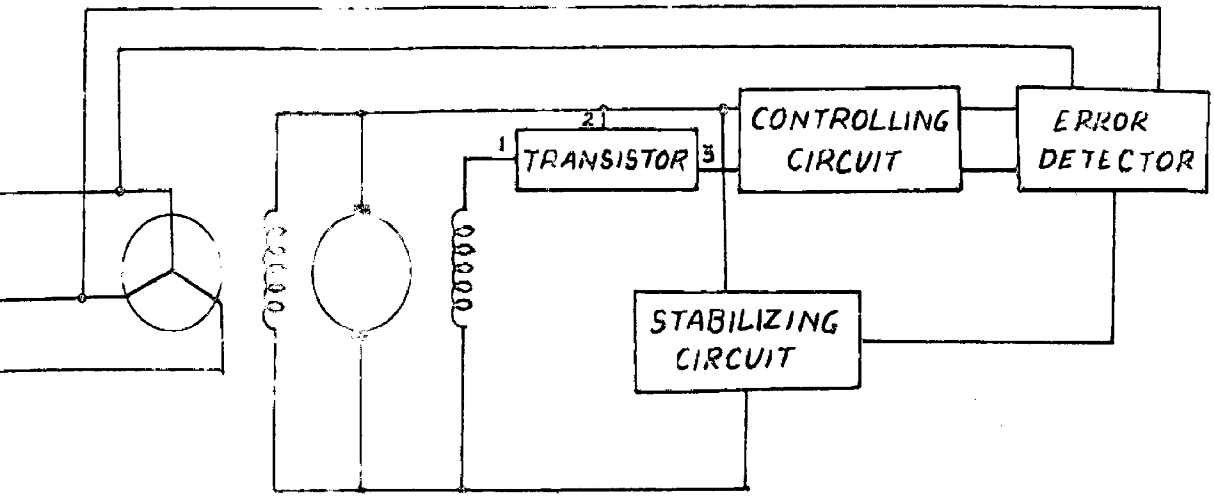
V, v = Exciter terminal voltage

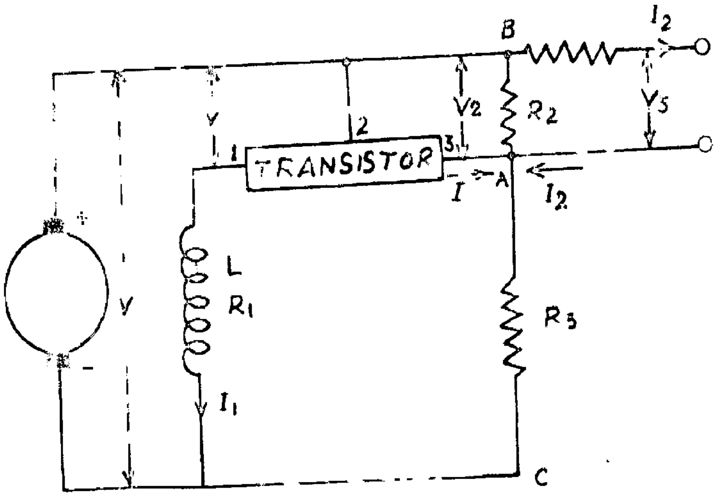
V_1, v_1 = Output voltage of transistor A

V_2, v_2 = Input voltage of transistor A

V_{2A} = Voltage across R_2 when transistor is disconnected from point A

V_3 = Control source e.m.f.


2
1
TRANSISTOR
3
CONTROLLING CIRCUIT
ERROR DETECTOR
STABILIZING CIRCUIT


B
I_2
V_2
R_2
V_S
V
2
1
TRANSISTOR
3
A
I
I_2
+
V
-
L
R_1
I_1
R_3
C

6.2. INTRODUCTION :

It is possible to build an automatic voltage regulator utilising junction transistors. This Chapter discusses the topic in detail.

Fig. 6.1 gives the block diagram of a voltage regulator, where the transistor is connected in series with the field winding of the exciter. The exciter field circuit and its series transistor is called the "regulating circuit" and the network conveying the signal from the error detector to the regulating transistor is called the "control circuit".

Referring to fig. 6.1, transistor terminal 1 may be any one of the three electrodes; in each case there are two ways of connecting terminals 2 and 3. There are therefore six ways of connecting the transistor; they are known by the electrode connected to terminals 2 which is the terminal common to both input and output circuits. Of these six circuits the two wherein terminal 3 is the collector and the third where-in 2 is the collector and 3 the emitter have little practical application.

For a regulator designed on the general plan shown in Fig. 6.1. the common-base connection suffers the serious disadvantage of giving no current amplification. The common- collector circuit gives large current amplification, but its input characteristic shows that it must be supplied from a high - resistance source to preserve d.c. stability. It is therefore attractive as a means of mannual control from a low power rheostat, but for automatic regulation its low output impedance leads to poor dynamic performance. The common-emitter circuit is, therefore, best for automatic regulation; its output impedance is high enough within the linear range for useful practical application. though not as high as in the its input voltage and current are small and are related by a simple monotonic function; finally the circuit lends itself to the addition of negative feed back, by which its output impedance may be increased.

6.3. CONTROL CIRCUITS :

The functions of the control circuit are :

(a) To transmit the error signal from the error detector to the regulating transistor and to provide any amplification which may be needed to keep the finite voltage error within the acceptable limits.

(b) To provide such input conditions for the regulating circuit as will ensure d.c. stability when the control loop is open.

(c) To provide such dynamic properties in the closed control loop as will ensure dynamic stability and give fast operation; a further stabilizing circuit may be added to improve these properties.

(d) To provide, if required, some protection against the reversal of polarity of the exciter.

(e) To provide full exciter output if the sampling signal vanishes owing to a short circuit on the alternator. This may be done in three ways;

(i) A supplementary control signal may be derived from current transformers in the alternator output leads.

(ii) Special elements may be added to the control circuit which function only on alternator short circuit to increase the excitation to its maximum.

(iii) The control circuit may be designed so that it inherently takes up the condition of maximum excitation when the sampling signal vanishes.

To perform these functions any of the two circuits described below may be used.

(A) Potentiometer control circuit

(B) Resistance control circuit

The Potentiometer circuit inherently gives full excitation in the absence of the sampling signal; the Resistance circuit which is a special instance of the first arrangement needs additional elements to provide full excitation on short-circuit, but has certain inportant advantages.

6.4. POTENTIOMETER CONTROL CIRCUIT :

This circuit is shown in Fig. 6.2 for a p-n-p transistor whose terminal 1 is the collector, 2 is the emitter and 3 the base; the error detector produces a direct voltage V_3 in a circuit of internal resistance R_4 resulting in a control current I_2 which flows into the tapped point of the potentiometer.

6.4.1. Analysis of Control Circuit :

General Relations:

Referring to Fig. 6.2, in the steady state the conditions in the regulating circuit may be written as :

$$V = f_1 (I_1) \quad \ldots \quad (6.1.)$$

$$V = V_1 + I_1R_1 \quad \ldots \quad (6.2.)$$

$$V_1 = f_2 (I ,I_1) \quad \ldots \quad (6.3.)$$

$$V_2 = f_3 (I, I_1) \quad \ldots \quad (6.4)$$

The regulating characteristic is the relation

$$V = f_4 (I) \quad \ldots \quad (6.5)$$

and the input characteristic of electrode 3 of the transistor is the relation

$$V_2 = f_5 (I) \quad \ldots \quad (6.6)$$

6.4.2. Criterian for D.C. Stability :-

The electrode 3 of the transistor is normally controlled from point A of the potentiometer R_2, R_3 but in order to explore the working of this arrangement it is convenient to disconnect terminal 3 from point A and to imagine a current I flowing into the point A from an external source, and at the same time an equal current I flowing out at terminal 3. If, under these conditions, the potential across R_2 is V_{2A} , then by Superposition theorem,

$$V_{2A} = V \frac{R_2}{R_2 + R_3} - (I + I_2) \left(\frac{R_2 R_3}{R_2 + R_3} \right) \quad \ldots \quad (6.7)$$

and for the source of signal

$$V_{2A} = V_3 + I_2 R_4 \quad \ldots \quad (6.8)$$

giving

$$V_{2A} = \frac{V - IR_3 + \frac{V_3 R_3}{R_4}}{\frac{R_3}{R_4} + \frac{R_2 + R_3}{R_2}} \quad \ldots \quad (6.9)$$

If the currents entering at A and leaving at terminal 3 are now increased by δI while V_3 remains constant, the condition for stability is that

$$\delta V_2 > \delta V_{2A} \quad \ldots \quad \ldots \quad (6.10)$$

These increments are

$$\delta V_2 = \delta I \frac{dV_2}{dI} \quad \ldots \quad (6.11)$$

$$\delta V_{2A} = \delta I \frac{dV_{2A}}{dI}$$

$$= \delta I \frac{dV/dI - R_3}{\frac{R_3}{R_4} + \frac{R_2 + R_3}{R_2}} \quad \ldots \quad (6.12)$$

and therefore d.c. stability will be obtained if

$$\frac{dV_2}{dI} > \frac{(dV/dI) - R_3}{\frac{R_3}{R_4} + \frac{R_2 + R_3}{R_2}} \quad \ldots\ldots \qquad (6.13)$$

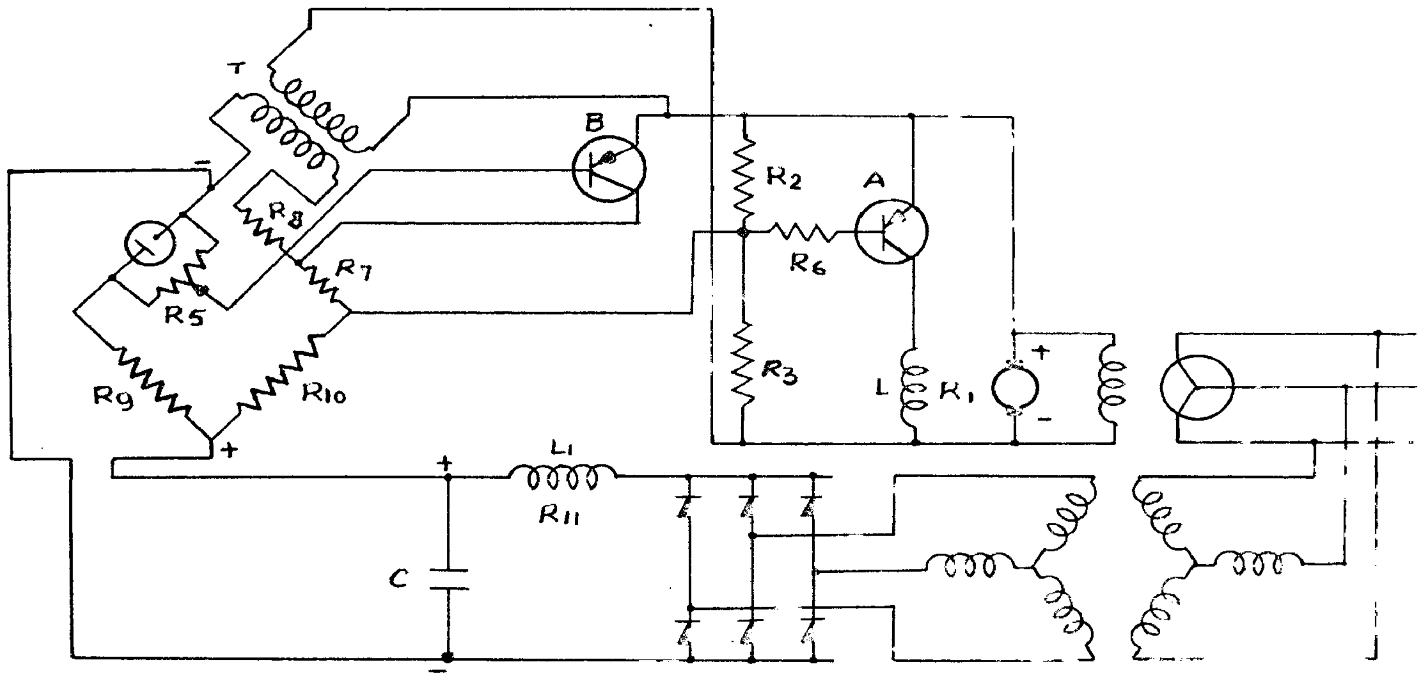
i.e. $$\frac{dV_2}{dI}\left[1 + \frac{R_2 R_3}{R_4\ (R_2 + R_3)}\right] > \frac{R_2}{R_2 + R_3}\left(\frac{dV}{dI} - R_3\right) \qquad (6.14)$$

The above criterion of stability means in practical terms that the control circuit may be designed in one of the three ways:

(a) R_3 may be made larger than the maximum value of dV/dI and in this case the source resistance R_4 may have any positive value. The result is that at zero error when $I_2 = 0$ the operating point is well down the control curve and the machine delivers only a fraction of its full output voltage. The upper portion of the control curve can only be reached if the error detector can provide a current I_2 of reverssible polarity; the requirement leads to a complicated circuit since the error detector output must in general be passed through a transistor amplifier in order to provide acceptable sensitivity. This arrangement has therefore not been used.

(b) R_3 may again be given a large value as above, and a source of direct potential may be connected in series with it so that when $I_2 = 0$ the operating point is at the top of the control curve giving full excitation. R_4 may still have any value. Stable operation will result and I_2 need not now reverse in sign, but the circuit does not provide full excitation on short circuit unless the direct potential is provided by some source such as a battery which is unaffected by the bus bar voltage.

(c) R_2 and R_3 may be chosen so that when I_2 vanishes full excitation occurs. The resulting value of R_3 is now too low for stability unless R_4 is made small. If R_2, R_3 and R


T
B
R2
A
R8
R7
R6
R5
R9
R10
R3
L
R1
L1
R11
C
+
-

are chosen in this way the circuit meets all the above requirements.

Circuit (b) in which a source of potential is added in series with R_3 has not been used in practice; however, if in this circuit R_2 is made infinite, valuable properties appear (the arrangement is discussed in more detail under the heading "Resistance Control Circuit").

Circuit (c) is preferred as the basis of a regulator. It leads to a simple design and the low source resistance which it requires is favourable to the use of series feed back to increase the transistor output resistance. (In the actual circuit employed this low resistance has been obtained by using a small amplifying transistor in common-collector connection having an output resistance of a few ohms; the base of the transistor is fed directly from the error detector.)

6.5. REGULATOR CIRCUIT USING POTENTIOMETER CONTROL:

Fig. 6.3. shows a complete regulator circuit employing potentiometer control, as used for a 10 kVA alternator[14]. The regulating transistor is labelled A and the amplifier B; a 3-phase rectifier has been used to feed the error detector in order to reduce the time-constant of the smoothing circuit. The potentiometers R_5 are used for setting the no-load alternator voltage, and the resistances R_6 vary the sensitivity of the regulator.

It will be seen that the regulating transistor A is in common-emitter connection and controlled from a low-resistance source, its output resistance is, therefore, high resulting in a small time-constant of the exciter field circuit.(This is shown under the heading "Exciter Field Time-Constant"). Since transistor B in common-collector connection has no voltage amplification, considerable ripple voltages may be tolerated at the output of the error detector, and the time-constant of the smoothing circuit may be small. This circuit is therefore better adopted to applications calling for fast transient response

6.6. RESISTANCE CONTROL CIRCUIT :

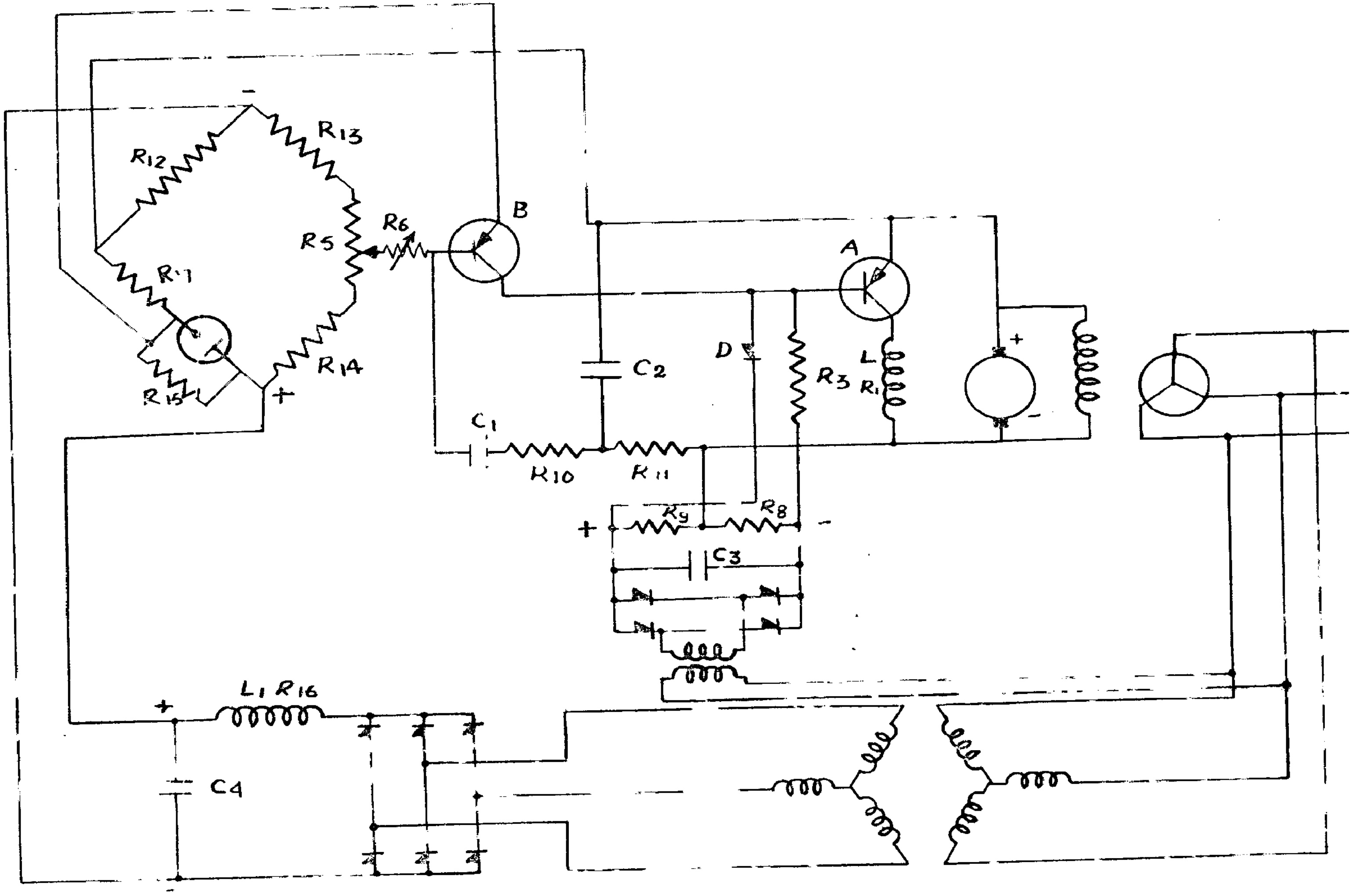
This circuit is also a common-emitter connection and may be represented by Fig. 6.2 if transistor terminal 3 again represents the base, resistor R_2 is infinite, and a source of constant e.m.f. is connected in series with R_3. The circuit may be regarded as a positive-feed back arrangement in which resistor R_3 has the effect of increasing both the control sensitivity and the input resistance. It may alternatively be thought of as a special case of the potentiometer circuit.

6.6.1 Criterian for D.C. Stability:

The criterian for d.c. stability is given by making R_2 infinite in relation (6.14) and is therefore

$$\frac{dV_2}{dI}\left(1 + \frac{R_3}{R_4}\right) > \left(\frac{dV}{dI} - R_3 \right) \qquad \ldots \qquad (6.15)$$

The resulting requirements are the same as those placed on the potentiometer circuit, namely either that R_4 must be small or that R_3 must exceed the greatest value of dV/dI. It is this second arrangement which is of particular interest; since it may be controlled from a high-resistance source, an amplifying transistor in common-emitter connection may be used to supply the control signal. Also if R_3 does not greatly exceed the maxi-



Res

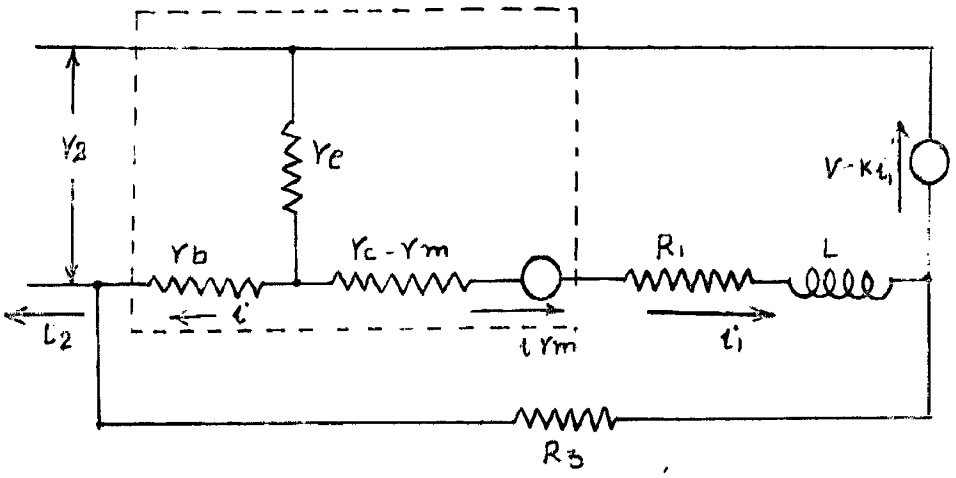
mum value of dV/dI the full range of excitation may be controlled by only a small change in I_2 ; these factors lead to a high control sensitivity.

6.7. REGULATOR CIRCUIT USING RESISTANCE CONTROL:

Fig. 6.4 shows a complete regulator circuit employing resistance control as used for a 10 kVA alternator.[14] As before the regulating transistor is labelled A and the amplifier B.

The constant e.m.f. in series with resistor R_3 is provided by the single-phase bridge rectifier which feeds the potentiometer R_8, R_9 ; the required constant e.m.f. appears across resistor R_8 and will be proportional to the regulated alternator output voltage, so that its variation over the range of load is small, However, this arrangement by itself cannot provide full excitation on short-circuit, since the output of the rectifier vanishes under these conditions. The difficulty is overcome by a diode-clamp circuit consisting of the diode D polarized by the potential across resistor R_9 ; the diode is a small metal-plate rectifier which is unable to conduct so long as the busbar voltage is near to its normal regulated value; on short-circuit, however, the polarizing potential of the diode clamp vanishes and connects the base of transistor A to the negative line through resistor R_9 which is chosen so that in conjunction with R_3 and R_8 it affords full exciter output.

As discussed earlier the amplification available in the resistance control regulator is considerably greater than that with potential control method so that the voltage regulation is much better.


v_2
r_e
r_b
$r_c - r_m$
R_1
L
$V - Ki_1$
i
$i r_m$
i_1
i_2
R_3

6.8. TRANSFER FUNCTION OF CONTROL CIRCUIT :

An equivalent circuit for the regulating transistor in common-emitter connection and the control circuit is given in Fig. 6.5. The elements within the dotted rectangle represent the transistor. For simplicity of treatment small displacements will be assumed and the system will be considered linear for such displacements. The resistance R_2 has been omitted from the equivalent circuit, since it is not used in the resistance control circuit and in the potentiometer control circuit its effect in shunt with the low resistance control is very small; the internal impedance of the exciter armature will be assumed to be negligible.

The following transfer functions may be derived from the equivalent circuit :

$$\frac{v}{v_2} = \frac{A_1}{1 + pT_1} \qquad (6.16)$$

where
$$A_1 = \frac{k\,(r_m - r_e\ )}{(R_1 - k + r_c)(r_e + r_b) - r_b(r_m - r_e\ )}$$

$$\simeq \frac{k\alpha}{r_e + r_b(1-a)}$$

$$a = r_m/\,r_c$$

$$T_1 = \frac{L}{R_1 - k + r_c(1-a) + ar_c\left(\frac{r_e}{r_e + r_b}\right) + \frac{r_e\,r_b}{r_e + r_b}}$$

$$\frac{v}{i} = \frac{k\,A_2}{1 + p\,T_2} \qquad \ldots \qquad (6.17)$$

where
$$A_2 = \frac{r_m - r_e}{R_1 - k + r_c - r_m + r_e}$$

$$\simeq \frac{a}{1 - a}$$

$$T_2 = \frac{L}{R_1 - k + r_c(1 - a) + r_e}$$

$$\frac{v}{i_2} = \frac{k\,A_3}{1 + p\,T_3} \quad \ldots\ldots \qquad (6.18)$$

where $$A_3 = \frac{A_2}{1 - \frac{k\,A_2}{R_3}\left(1 - \frac{1}{A_1}\right)}$$

$$\simeq \frac{A_2 R_3}{R_3 - kA_2} \qquad A_1 \gg 1$$

$$T_3 = A_3\left(\frac{T_2}{A_2} + \frac{T_1}{A_1} \quad \frac{k}{R_3}\right)$$

For the potentiometer control circuit the source of control signal must be of low internal resistance and of constant voltage; the relevant transfer function is, therefore, given by equation (6.16).

The converse holds for the resistance control circuit, which is fed from a source of high internal resistance and therefore constant current, so that the transfer function is given by equation (6.18)

6.9. EXCITER FIELD TIME- CONSTANT :

If in Fig. 6.2 a generator of small sinusoidal voltage δV is connected in series with terminal 1 of the transistor, thereby causing an alternating current δI_1 to flow in the field circuit and a variation $k\,\delta I_1$ in the armature induced e.m.f., then

$$\delta V + k\,\delta I_1 = \delta I_1 (R_1 + R_o + pL) \quad \ldots \qquad (6.19)$$

where R_o is the output resistance of the transistor and $k = dV/dI_1$.

From this relationship

$$\delta I_1 = \frac{\delta V}{pL + R_1 - k + R_o} \qquad (6.20)$$

showing that the effective time constant of the field circuit is

$$\frac{pL}{R_1 + R_o - k} \qquad (6.21)$$

If R_o is very small, this time constant may rise to large values if dV/dI_1 at the operating point is only slightly less than R_1. The time-constant is reduced in the familiar manner for large values of R_o. The common-collector, common-emitter and common-base transistor configurations have output impedances in assending order. However, if in the common-emitter connection, a feed back resistor is inserted in the emitter lead and the base is fed from a low-resistance source, the circuit has an output impedance which may approach that of the common-base configuration.

CHAPTER - 7

DESIGN AND PERFORMANCE OF A TRANSISTOR VOLTAGE REGULATOR.

7.1. INTRODUCTION:

This chapter deals with actual design and performance of a transistor type voltage regulator built in the Electrical Engineering Laboratories of the University of Roorkee and gives the test results of the regulator on a 4.4 kVA alternator for steady state and transient performance.

7.2. SPECIFICATION OF EQUIPMENT :

(i) Alternator : 4.4 kVA 400 V 3phase 6.4 A 50 c/s P.F 0.8
B.S 2613 Field Sep. Exc 250 V Lancashire Dynamo & Crypto Ltd,
Manchaster & Willesden
coupled to

(ii) D.C. Motor (Prime Mover) 5 H.P. 250 V 21.6A 1300/1750 R.P.M.

(iii) Exciter (mounted on a separate shaft) 5 H.P. 220 V D.C.
20A 1450 R.P.M.

7.3. PRELIMINARY TESTS AND DATA OBTAINED:

(1) (i) Resistance of Field winding of Alternator: 163 ohms (cold); 196 ohms (hot)

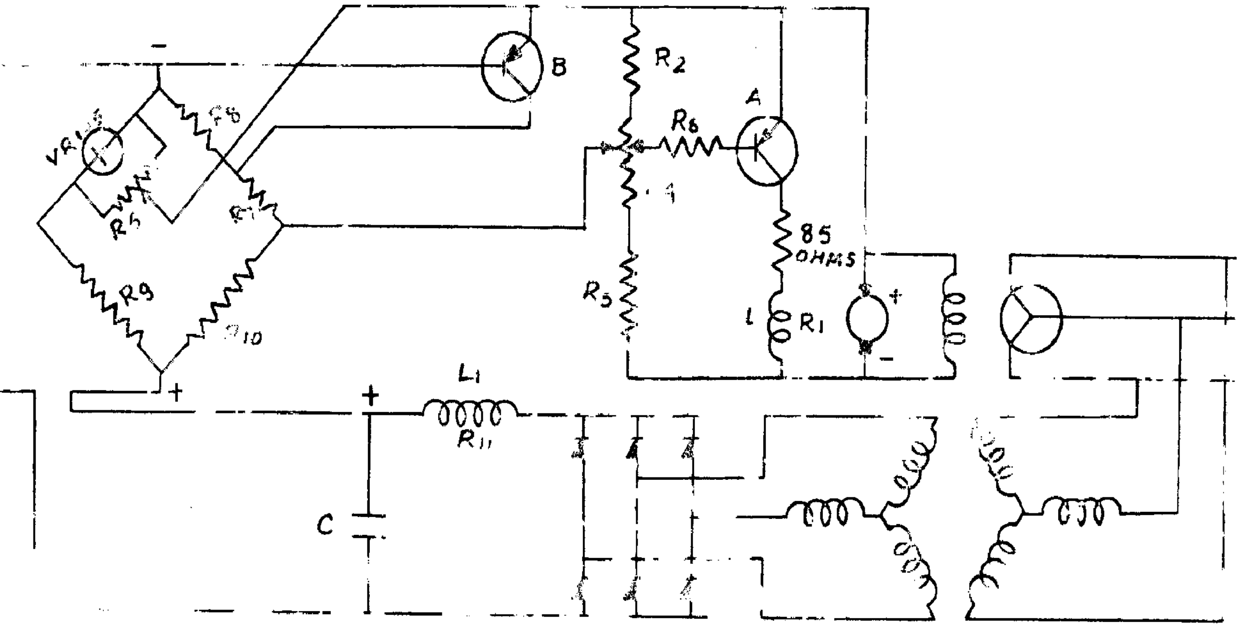
(ii) Resistance of Field winding of Exciter: 380 ohms (cold); 456 ohms (hot)

(2) To determine the range of exciter voltage variations required:

(i) Full load at rated p.f. (0.8 lagging) was applied to the alternator terminals. Excitation was adjusted so as to obtain rated voltage (400 V) across alternator terminals. Under these conditions

Exciter volts 195

Exciter Field current 0.40 A



	[illegible]	R6	1000 OHMS	R10	400 OHMS
5	[illegible]	R7	50 OHMS	R11	4·25 OHMS
	1000 OHMS	R8	1100 OHMS	L1	1 25 HENRIES
	[illegible] OHMS	R9	2200 OHMS	C	16 MF

'A' REGULATING TRANSISTOR
OC 26

'B' AMPLIFYING TRANSISTOR
OC 72

Act

4. A

C

External resistance in Exciter Field Circuit 95 ohms.

(ii) Full load at rated p.f. was then thrown off and excitation for alternator reduced so as to get the rated voltage across its terminals. Under these conditions

Exciter volts 95

Exciter Field Current 0.14 A

External resistance in Exciter Field Circuit 250 ohms.

(3) Critical resistance for the exciter (as a d.c. shunt machine) at the rated speed was found to be 657 ohms.

7.4. CIRCUIT DESIGN :

Based on theoretical analysis in Chapter 6, Potentiometer control circuit was adopted for the regulator. The actual values of various resistances, inductance and capacitance etc. as used are given along with Fig. 7.1. Ratings for V.R. tube and transistors are :

VR tube 105 10 - 30 m.a.

Transistor 'A' (Regulating) OC 26

Collector volts	32
Collector current	3.5 A
Dissipation	7.5 W

Transistor 'B' (Amplifying) OC 72

Collector volts	32
Collector current	50 mA
Dissipation	75 mW

In the choice of resistances care was taken to ensure that these had the required heat dissipation while carrying normal currents.

D.C. output voltage across capacitor C was of the order of 130 V and the d.c. output current was 120 mA. The d.c. output voltage wave when observed on the C.R.O. was found to contain 1/2% ripple.

From data obtained in 7.3 it is clear that highest voltages appearing across transistor 'A' corresponding to full load and no load on the alternator will be

$$\frac{95}{380 + 95} . 195 = 39 \text{ V}$$

and $\frac{250}{380 + 250} . 195 = 38$ V respectively.

A reference to data for transistor OC 26 indicates that these figures are higher than its maximum Emitter - Collector volts (32V). To keep Emitter - Collector voltages for this power type transistor within rated value it was decided to insert permanently a resistance of 85 ohms in series with exciter shunt field (making its total resistance 465 ohms). This would limit the voltages across the transistor for the two conditions to 4 V and 25 V respectively. This arrangement proved satisfactory .

7.5. PERFORMANCE - STEADY STATE :

(A) Alternator terminal voltage rises from 400 V on full load at rated p.f. to 490 V on no load, excitation remaining unchanged (i.e. without voltage regulator) so that

$$\% \text{ regulation} = \frac{490 - 400}{400} . 100 \%$$

$$= 22. 50\%$$

(B) With static voltage regulator no load terminal voltage (400V) falls to 390 volts on full load at rated p.f. This gives an accuracy of voltage regulator within 2.5%. It may, of course, be mentioned that upto about 80% full load output there was no appreciable change in terminal voltage. It is important to note that d.c. supply voltage in the laboratory was not steady, the variations being as much as 15%.

7.6 PERFORMANCE - TRANSIENT STATE

For transient response of this voltage regulator oscillograms of

(A) Generator Voltage

(B) Exciter Voltage and

(C) Exciter Field current

were taken for conditions of

(i) Generator carrying Full load at rated p.f.

(ii) Switching off Full load at rated p.f. from generator terminals.

(iii) Switching-in capacitor load across generator terminals, the generator initially unloaded.

Last test was carried out to simulate the behaviour of generator when connected to an open circuited long line. (3 capacitors of 5 μF capacity each were connected in star for this test). The oscillograms are shown in Figs. 7.2(i),(ii) and (iii),respectively.

The following information is obtained from these oscillograms:

Switching off Full load at rated p.f.

Initially the generator voltage rises from 390 V to 433 V, the regulator bringing down this voltage to a steady state value of 406 V in 16 cycles (0.32 secs).

There is no marked change in exciter terminal voltage during the transient, while exciter field current gradually reduces to that corresponding to no load conditions.

Switching in Capacitor load :

The wave shape of generator terminal voltage is no longer sinusoidal. Due to presence of both inductance (due to generator windings) and capacitance in the circuit there is a doubling effect.

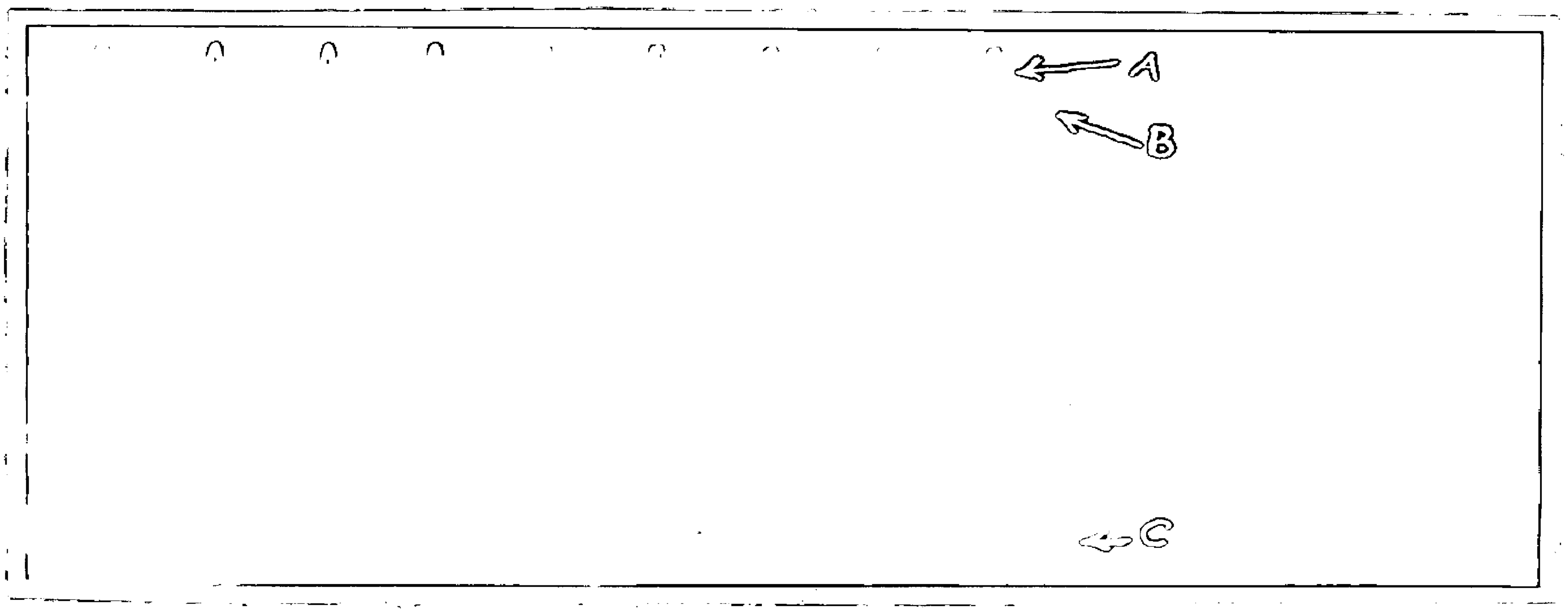


Fig.7.2 (i) Oscillograms of A. Generator Voltage B. Exciter Voltage C. Exciter Field Current.
Generator carrying Full load at rated p.f.

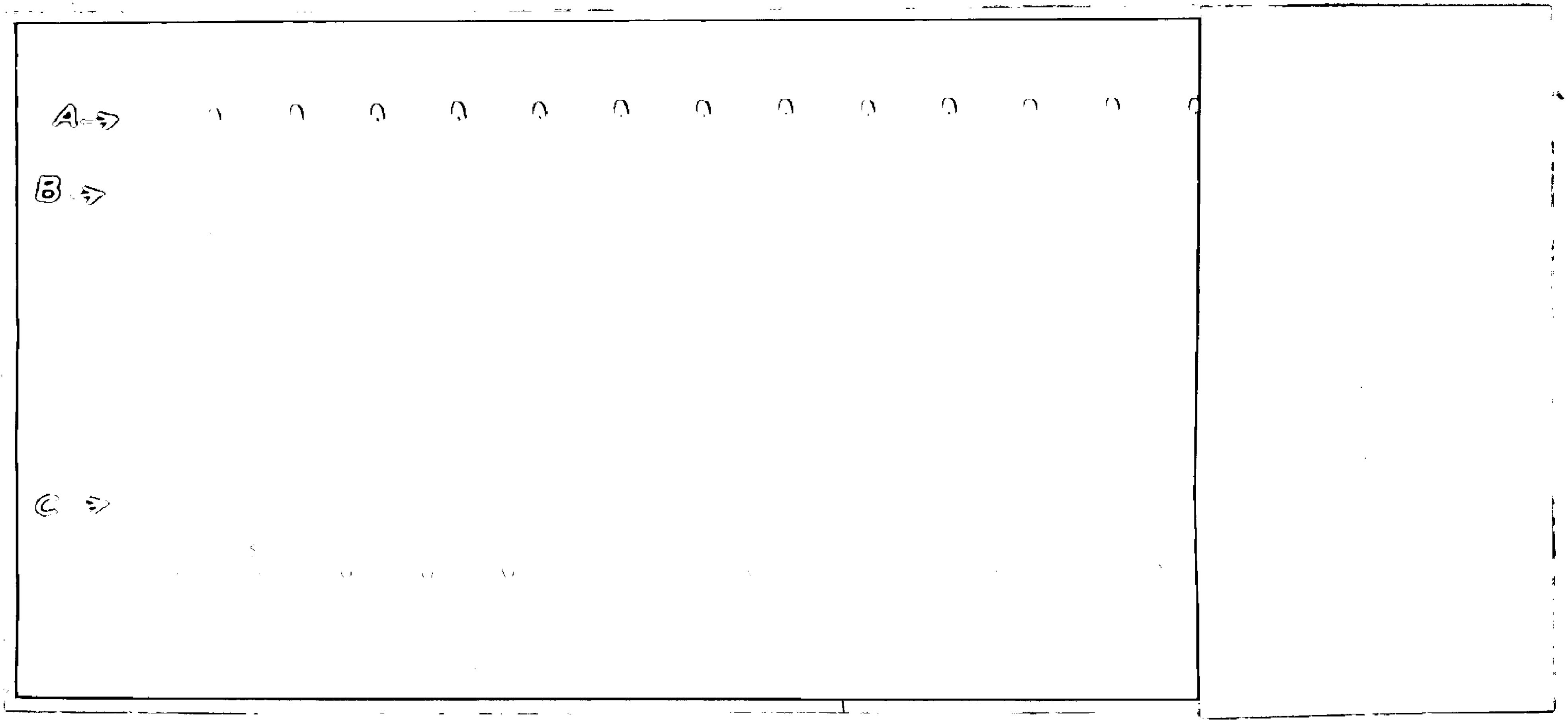


Fig.7.2 (ii) Oscillograms of A. Generator Voltage B. Exciter Voltage C. Exciter Field Current.
Switching off Full load at rated p.f. from the generator terminals.

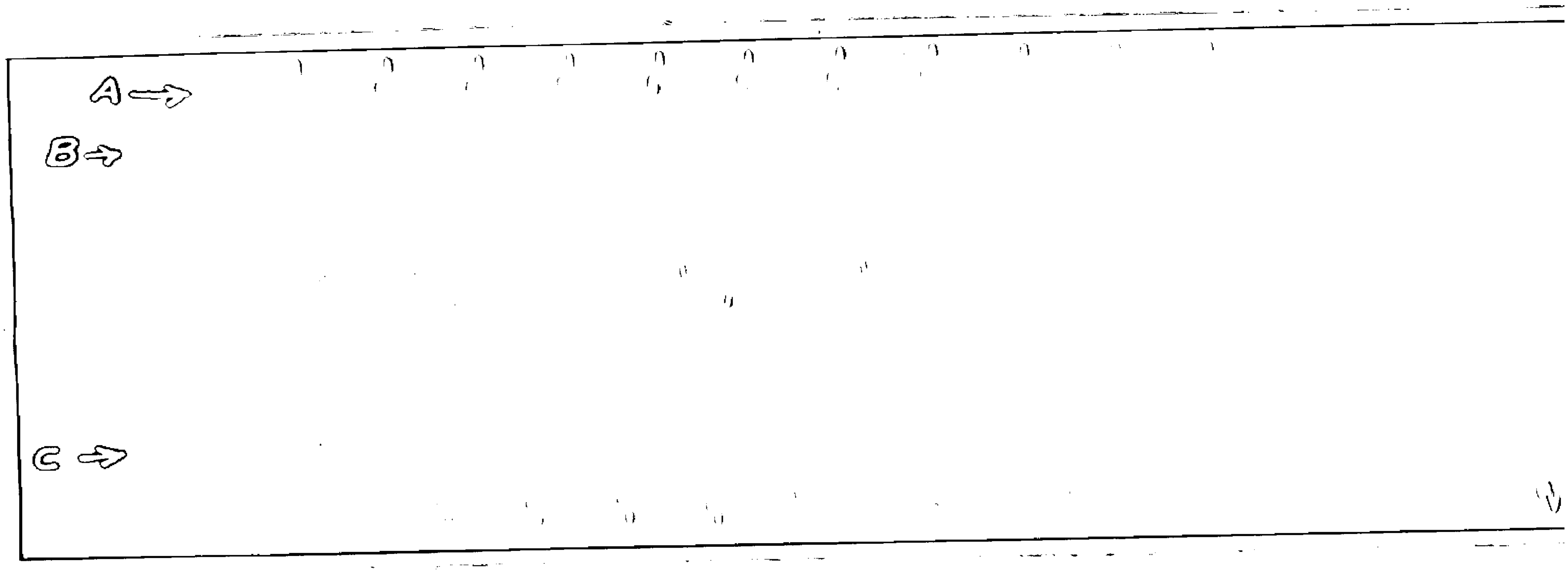


Fig.7.2 (iii) Oscillograms of A. Generator Voltage B. Exciter Voltage C. Exciter Field Current Switching - in Capacitor load across generator terminals, the generator initially unloaded.

The voltage, however, cannot actually rise beyond a certain value on account of saturation in the magnetic circuit of the machine. The voltage across the generator during the entire interval of time continues to be 455 V. This shows that the performance is not satisfactory in controlling generator voltage at zero p.f. leading, but with a more careful design of the circuit the performance could be improved.

There is no marked change in either exciter terminal voltage or exciter field current.

7.7. CONCLUSIONS :

1. The fast response of this type of regulator is brought out from the fact that on suddenly throwing off the full load at rated p.f. the control cycle is completed in 16 cycles (0.32 seconds)
2. The voltage regulator could be made more accurate by increasing its sensitivity. This would necessitate more careful choice of the various components used. Also, in the laboratory model, no damping arrangement has been used to reduce the amplitude of the swings in the exciter voltage under transient conditions. This could be done by introducing a damping transformer in the bridge circuit fed from the exciter voltage .

CONCLUSIONS

The tests on static (transistor) voltage regulator assembled in the laboratory for experimental purposes (Chapter 7) have demonstrated the fast response of this type of regulator.

In conclusion it may be stated that the static voltage regulators are superior in respect of accuracy of control, response, reliability and maintenance to conventional voltage regulators employing electromechanical principles.

The choice among static voltage regulator of a particular type depends upon the features considered most essential for a particular system.

Summarizing, ,the important points with regard to their performance are as follows :

TRANSDUCTOR REGULATORS :[8,15]

✓ These have the advantages of low power- input requirements (in the order of a few milliwatts) and are able to operate continuously for indefinite periods of time, requiring no maintenance, as these consist of components which do no wear out or lose their efficiency.

Their main disadvantage is that speed of response is not high (Where this factor is extremely important it is possible to use magnetic amplifiers designed for use with special high frequency supplies, such as 400 cycles in order to reduce the response time).

ELECTRONIC REGULATORS:[9,15]

Their main advantages are : They are capable of high system gains; their power input requirements are extremely low in the order of micro-watts; they offer rapid response to change of load and have the ability to bring about a high rate of change of exciter voltage.

Disadvantages with this type of regulator are : They are not simple in either circuitery or operation. They however provide a fair degree of reliability if tubes are occasionally checked and replaced if the emission from the cathode is no longer satisfactory or they may fail in operation.

TRANSISTOR REGULATORS: 14

Their advantages are : They can offer high amplification and therefore small error; the high output resistance which may be realized with a transistor can improve the exciter response and will allow the exciter voltage to be regulated down to its remanent magnetism value.

The chief difficulty with this type of regulator is doubtful life of transistors, their high costs and effects of temperature, but with the present trend in the development of transistors with higher reliability and less susceptibility to temperature changes, there is bound to be a swing in favour of transistorised voltage regulators.

REFERENCES

1. Brown J.Guthrie " Hydro Electric Engineering Practice" (Blackie & Sons, London) 1958

2. Young H.P. "Power System Control" (Chapman & Hall)1950

3. McClure J.B, Whittlesey S.I., and Hartman M.E. "Modern Excitation Systems for Large Synchronous Machines" Transactions of the American I.E.E. 1946 Vol.65 p 939.

4. Kimbark E.W. " Power System Stability" Vol. III Synchronous Machines (Wiley) 1956

5. Evans D.C. " Fast Response Static Automatic Voltage Regulators for Hydro Electric Stations " Water Power Vol. 11 No. 9 September 1959 p 338

6. Thompson D.C. "The Problem of Alternator Voltage Control " Journal I.E.E. 1963 p 110.

7. Watts J.L. " Voltage-Regulation Systems for Alternators' Power and Works Engineering Vol 51 May 1956 p 175

8. Frost - Smith E.H " The Theory and Design of Magnetic Amplifiers " (Chapman & Hall, London) 1958

9. Patchett G.N. " Automatic Voltage Regulators and Stabilizers " (Pitman) 1954

10. Milnes A.G. " Magnetic amplifiers" Proceedings I.E.E. 1949 Vol 96 Part I p 89

11. Feinberg R. " A review of transductor principles and applications " Proceedings I.E.E. 1950 vol. 97 Part II p 628.

12. Krabbe U. " Transductor type Voltage Regulators for for Small a.c. generators " ASEA Journal Vol. 20 Feb. March 1947 pp 39 - 44

13. Hedstrom S.E. " The use of transductor regulators with booster exciters " ASEA Journal Vol. 23, Feb. 1950 pp 23 - 31

14. Ward E.E., and Sabah " Transistor Voltage Regulators for Alternators " Proceedings I.E.E., June 1957 Vol 104 Part A p 194

15. Montgomery J.P. " A Comparison of Rotating ,Electronic and Magnetic Amplifier Regulators " Transactions of the American A.I.E.E. 1956 Vol 75 p 359.