STATIC - EXCITERS

Dissertation submitted in partialfulfilment
of the requirements for the Degree
of Master of Engineering
(Electrical Machine Design)

By

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July, 1962

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ACKNOWLEDGEMENTS

The author's most sincere gratitude is to Dr. T. S. Madhava Rao, Reader in Electrical Engineering, University of Roorkee, Roorkee for his invaluable help and guidance, without which the preparing and presentation of this work would not have been possible.

The author also gratefully wishes to acknowledge the help given by Dr. L. M. Ray, Reader in Electrical Engineering, University of Roorkee, Roorkee in giving an insight of the subject and guiding the experimental work. The author's gratitude is also to Dr. G. C. Jain, now on the staff of the Purdue University, U.S.A., for suggesting and introducing the subject.

The author is also indebted to Prof. C. S. Ghosh, Head of Electrical Engineering Department, University of Roorkee for the facilities and help rendered by him in completing this work.

July 1962
ROORKEE

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List of Symbols

E_t	=	Terminal voltage of the alternator per phase
E_i	=	Internal E. M. F. per phase.
X_d	=	Synchronous reactance of the alternator.
I	=	Line current.
E	=	Line to neutral voltage drop of alternators.
i_F	=	Field current of the alternator.
N_f	=	Number of the field turns per pole
X_L	=	Reactance of Linear Reactor.
R	=	Per Phase resistance representing the field loading on the exciter.
N_p	=	Number of turns on primary of the current transformer.
N_s	=	Number of turns on secondary of the current transformer.
a	=	$\frac{N_p}{N_s}$ = ratio of primary to secondary turns of the current transformer.
I'	=	Line current referred to the secondary of the current transformer.
I_R	=	R.M.S. value of current in R.
$I_{R,E}$	=	Component of I_R derived solely from E_t.
$I_{R,I}$	=	Component of I_R derived solely from I.

ϕ = Power factor angle of load.

θ_1 = Angle between E_t and $I_{R,E}$.

θ_2 = Angle between I and $I_{R,I}$.

α = Angle between E_t and X_d I.

θ_2' = Angle between E_t and $I_{R,I}$.

β = Angle between $I_{R,I}$ and $I_{R,E}$.

N_1 = Number of turns on potential winding of SCPT.

N_2 = Number of turns on current coil of SCPT.

N_3 = Number of turns on output winding of SCPT.

N_c = Number of turns on control winding on SCPT.

X_m = Magnetizing reactance of saturable core transformer.

e_T = $E_t \frac{N_3}{N_1}$ is the voltage source referred to N_3 winding.

i_L = $I \frac{N_2}{N_3}$ is the current source referred to N_3 winding.

x_L = $X_L \left(\frac{N_3}{N_1}\right)^2$ is the reactance referred to the N_3 winding.

R_o = Value of R at 25°c or some other rated temperature.

X_{mo} = Specific value of X_m.

K_f = A factor involving a number of machine constants.

K = $\frac{\text{Ampere}}{\text{Volt}}$, constant of proportionality.

K_{ir} = Constant of proportionality.

INTRODUCTION

The static exciter extracts a portion of the voltage and current output of the a.c. generator to be excited, and utilizes this power to supply controlled excitation back into the field of the generator.

In the present text, it is intended to make a review of the existing literature on the static exciters and thereafter to design and set up a static excitation system for an alternator in the Electrical Engineering Department of the University of Roorkee and then to obtain its steady state and transient performance.

The concept of static excitation system for a.c. generators is relatively new. In 1951 a static excitation system was developed utilizing a. c. machine terminals through current and potential transformers, to provide excitation power. The first applications of this system were confined to small generators rated upto approximately 15 KVA at 420 cycles. Since then, similar systems have been extensively[1] applied to generators on commercial and military air-craft, as well as to many 60 cycles generators with ratings upto approximately 100 KVA. In addition, this system has been applied to generators rated upto 2,500 KVA, at 60 cycles for marine service. All these applications have been to generators with armature voltage ratings of less than 1,000 volts. Wide experience with this system has established design procedure which permits consideration of the system for application to the larger generators.

Recent technological advances have made large ratings of static excitation systems attractive. These advances include improved semi-conductor rectifiers, better steels for use in magnetic amplifiers, saturable reactors, and the introduction of the silicon zener diode references for voltage regulators. In 1958, it was decided that the technology and economics of a machine-terminal-excited static exciter had reached the point where manufacture of an equipment for large generators should be undertaken.

In the fall of 1960, a completely static excitation system rated 90 KW, 250 volts, which obtained excitation power exclusively from the a.c. machine terminals was installed on a 25,600 KVA, 13,800 Volts steam turbine generator for the International Paper Company. The development work in the field of static exciters is still being continued at present.

CHAPTER I

STATIC EXCITERS FOR SYNCHRONOUS MACHINES

[Definitions, Difficulties met with commutator exciters and directly mounted main and pilot exciters, Reasons for the increased application of static - exciters]

1.1 **Definitions:-** The following definitions are proposed by the American Standards Association.[1]

1.1.1 **Excitation System:-** An excitation system is the source of field current for the excitation of a principal electric machine, including means of its control.

Thus an excitation system includes all the equipment required to supply field current to excite a principal electric machine which may be an a.c or d.c machine and any equipment provided to regulate or control the amount of field current delivered.

1.1.2 **Exciter Ceiling Voltage:-** Exciter ceiling voltage is the maximum voltage that may be attained by an exciter with specified conditions of load. For rotating exciters ceiling should be determined at rated speed and specified field temperature.

1.1.3 Nominal Exciter Ceiling Voltage:- Nominal Exciter ceiling voltage is the ceiling voltage of an exciter loaded with a resistor having an ohmic value equal to the resistance of the field winding to be excited. The resistance shall be determined at a temperature of:-

(a) 75°c for field winding designed to operate at rating with a temperature rise of 60°c or less.

(b) 100°c for field windings designed to operate at rating with a temperature rise of greater than 60°c.

For rotating exciters the temperature of the exciter field winding should be considered to be 75°c.

1.1.4 Rated Load Field Voltage:- Rated load field voltage is the voltage required across the terminals of the field winding of an electric machine under rated continuous load conditions with the field windings at:-

(a) 75°c for field windings designed to operate at rating with a temperature rise of 60°c or less.

(b) 100°c for field windings designed to operate at rating with a temperature rise greater than 60°c.

1.1.5 No Load Field Voltage:- No load field voltage is the voltage required across the terminals of the field winding of an electric machine under conditions of no load, rated speed and terminal voltage and the field winding at 25°c.

1.1.6 Excitation System Stability:- Excitation system stability is the ability of the excitation system to control the field voltage of the principal machine so that transient changes in the regulated voltage are effectively suppressed and sustained oscillations in the regulated voltage are not produced by the excitation system during steady-load conditions or following a change to a new steady-load condition.

1.1.7 Exciter Response:- Exciter response is the rate of increase or decrease of the exciter voltage when a change in this voltage is demanded.

1.1.8 Main Exciter Response Ratio:- The main exciter response ratio is the numerical value obtained when the response, in volts per second, is divided by the rated-load field voltage, which response, if maintained constant would develop, in one - half-second the same excitation voltage - time area as attained by the actual exciter. The response is determined with no load on the exciter, with the exciter voltage, initially equal to the rated load, field voltage, and then suddenly establishing circuit conditions which would be used to obtain nominal exciter ceiling voltage.

The half second interval is chosen because it corresponds approximately to one half period of the natural electromechanical oscillation of the average power system. It is the time during which the exciter must become active if it is to be effective in assisting to maintain system stability.

The construction of the response line in accordance with the definition for determining response ratio for a typical main exciter response ratio is shown in Fig. 1.1. The curve aed is the actual voltage time curve of the exciter as determined under the specified conditions. Beginning at the rated -

- load field voltage, point a , the straight line a c is drawn so that the area under it, a b c, during the one-half second interval from zero time is equal to the area under the actual - voltage - time curve a b d e, during the same interval.

The response used in determining response ratio is the slope of the line a c in volts per second.

$$\frac{100 \text{ volts}}{0.5 \text{ second}} = 200 \text{ volts per second.}$$

The rated - load field voltage is 200 volts, and the response ratio, obtained by dividing the response by the rated - load field voltage is 1.0.

1.2. <u>Difficulties met with Commutator Exciters[2] and and directly mounted main and pilot exciters</u>:-

1.2.1 Atmosphere contaiminated by such gases as SO_2, SO_3 and Cl_2 which are detrimental to commutator films. These contribute to the excessive sparking, short brush life, heavy carbon deposits in the exciter and brush rigging and excessive or uneven wear of the commutator.

1.2.2 In many cases a shut down of the turbine - generator has been necessary to correct these difficulties.

1.2.3 For vertical shaft generators, the constructional height of the shaft is more and therefore the costs for the construction of the power house are appreciably increased.

1.2.4 For low speed generators, the size of the directly coupled exciter has to be larger and this results in their being more expensive.

1.2.5 Also the exciters of low speed generators, have large magnetic inertia, resulting in lower response ratio. This is particularly disadvantageous especially in the case of generators feeding into long distance transmission lines in which case high exciter response is an essential requirement.

1.3. Reasons For Increased Application Of Static-Exciters:-

1.3.1 This excitation system is potentially more reliable than a rotating system.

1.3.2 Less maintenance is expected than on a rotating excitation system.

1.3.3 Maintenance under load can be accomplished for all components except for the power magnetic components (P P T's, S C T's and linear reactors). This may permit elimination of the usual spare rotating exciters.

1.3.4 Generator - rotor removal is simpler without a shaft driven exciter.

1.3.5 The excitation system components can be arranged in various combinations to provide flexibility of power house arrangement.

1.3.6 The basic circuit of the static exciter makes the alternator as much self regulating as possible.

1.3.7 The transient response is rapid and yet well damped.

1.3.8 A short circuit of the alternator will not cause loss of excitation, but during a short circuit the excitation becomes several times normal, a feature desirable for selective tripping of protective devices.

1.3.9 Since the exciter is not attached with the generator, so it results in reduced overhung moment on the pad of the engine or prime mover on which the generator is mounted.

1.3.10 The length of the generator can be appreciably reduced compared with generators with integral exciters.

CHAPTER II

Theoretical concept of Design of Static Magnetic Exciter for Synchronous Machines:

2.1 In this chapter the theory of a static magnetic exciter for synchronous machine is discussed. The basic exciter circuit is of such nature as to make the alternator as much self regulating as possible.

Assuming the alternator with:-

i) Cylindrical rotor

ii) no saturation

iii) negligible resistance of the armature winding

For an alternator line to neutral voltage drop is given by,

$$\triangle E = j X_d I \quad .. \ 2.1$$

where X_d = Synchronous reactance of the alternator.

I = Line current.

At zero power factor and in vicinity of rated terminal voltage when loaded with rated line current this voltage drop ΔE is very large in comparison with that in a d.c generator. It therefore follows that the excitation of an alternator has to cover a relatively wide range. As a result alternators usually require high gain regulators which often pose stability problems.

This excitation system under description, however, avoids the need of a high gain regulator by attempting inherent compensation for the voltage drop ΔE. In order to compensate for the voltage drop ΔE, the excitation is required to provide an internal voltage E_i,

$$E_i = E_t + j X_d . I \qquad .. 2.2$$

This internal voltage is proportional to the field (excitation) ampere turns $i_F . N_f$.

$$E_i = K_f (i_F N_f) \qquad .. 2.3$$

where i_F = Field current of the alternator

N_f = Number of field turns per pole

K_f = a factor involving a number of machine constants, such as:-

i) number of turns on a.c. winding

ii) size of air gap

iii) saturation of magnetic circuit.

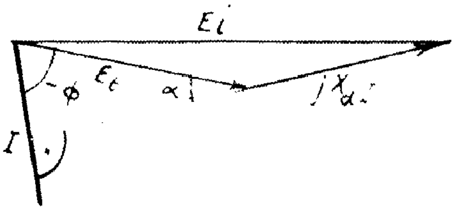


FIG.21 VOLTAGE VECTOR DIAGRAM OF IDEALIZED ALTERNATOR WITH CYLINDRICAL ROTOR

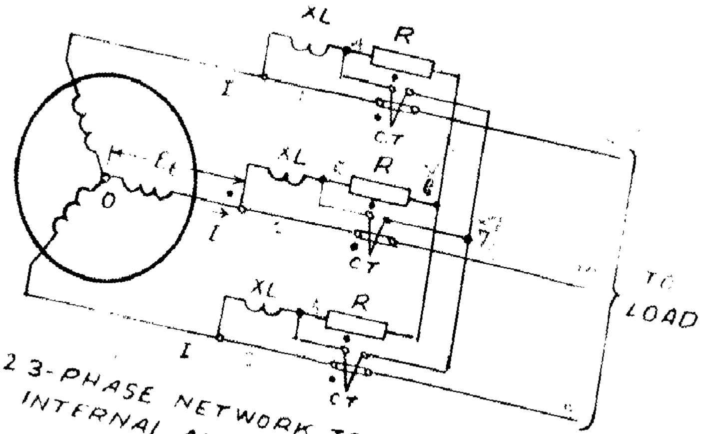


FIG.22 3-PHASE NETWORK TO RECONSTRUCT THE INTERNAL ALTERNATOR VOLTAGE Ei

2.2 Voltage Drop Compensation:[3] - Voltage drop compensation is obtained by a field current i_F which is proportional to the magnitude of internal voltage, E_1 as shown in Fig. 2.1.

In Fig. 2.2. is shown a 3-phase alternator connected through three identical current transformers to the load. There are also three identical, linear reactors X_L which are interconnected with the secondaries of the current transformers to three identical resistors R. These resistors symbolize the resistance of the alternator field and it will be shown that the current through the resistors R is proportional to E_1.

Assuming a symmetrical three phase load, points 7 and 8 of Fig. 2.2. will be at the same potential as the neutral 0 of the alternator. By connecting 7 and 8 to the neutral 0, no change in the system currents shall occur, the system, however, degenerates into three single phase systems Fig. 2.3. which are simpler to analyze.

The current transformer CT of Fig. 2.3 is shown by its equivalent circuit in Fig. 2.4 when winding resistances and leakage reactances are neglected.[4]

Resistor R is the same as shown in Fig. 2.3 and X_m the magnetizing reactance of the secondary of the transformer CT.

Denoting the turns ratio of primary to secondary turns,

$$\frac{N_p}{N_s} = a \qquad .. 2.4$$

the alternator current I when referred to the secondary of the current transformer becomes I',

$$I' = a\,I \qquad .. 2.5.$$

The equivalent circuit of Fig. 2.3 now is shown in Fig. 2.5. The quantity to be determined is the current I_R which will finally appear to be proportional to the field current i_F.

Acting in the circuit are the terminal voltage E_t and the referred alternator currant I.a. Accordingly, the current I_R can be seen to consist of the two components of $I_{R,E}$ derived solely from E_t and $I_{R,I}$ derived solely from I.

$$\bar{I}_R = \bar{I}_{R,E} + \bar{I}_{R,I} \qquad .. 2.6.$$

2.2.1 Determination of $I_{R,E}$:- Assume I = 0, Applying Thevenin's theorem, to circuit of Fig. 2.5, with R disconnected, the terminal voltage E_{2-0} between 2 and 0 is

$$\bar{E}_{2-0} = \bar{E}_t \frac{X_m}{X_L + X_m} \qquad .. 2.7.$$

The source impedance X, as seen from terminals 2 - 0 is equal to X_L and

$$X = \frac{X_L X_m}{X_L + X_m} \qquad .. 2.8.$$

Current $I_{R,E}$ becomes,

$$\bar{I}_{R,E} = \frac{\bar{E}_{2,0}}{R + jX}$$

$$= \frac{\bar{E}_{2,0}}{R(1+j\frac{X}{R})} \qquad .. 2.9.$$

Substituting from equation (2.7)

$$\bar{I}_{R,E} = \bar{E}_t \frac{X_m}{X_L + X_m} \frac{1}{\sqrt{R^2 + X^2}} \quad .. \ 2.10.$$

$$\theta_1 = -\tan^{-1} \frac{X}{R} \quad .. \ 2.11.$$

The angle θ_1 is the angle between E_t and $I_{R,E}$ Fig. 2.6.

2.2.2 Determination of $I_{R,I}$

Next assume $E_t = 0$,

$$\bar{I}_{R,I} = a \bar{I} \frac{jX}{R + jX}$$

$$= a \bar{I} \frac{1}{1 - j \frac{R}{X}} \quad .. \ 2.12.$$

or,

$$\bar{I}_{R,I} = a \bar{I} \frac{X}{\sqrt{R^2 + X^2}} \angle \theta_2 \quad .. \ 2.13.$$

Here,

$$\theta_2 = \tan^{-1} \frac{R}{X} \quad .. \ 2.14.$$

The angle θ_2 is from I to $I_{R,I}$

It follows from equation (2.11) and (2.14)

$$\theta_2 = \theta_1 + \frac{\pi}{2}. \quad .. \ 2.15.$$

If the current I is lagging the terminal voltage E_t by an angle ϕ, Fig. 2.1 the angle between $j X_d I$ and E_t equals

$$\alpha = \frac{\pi}{2} - \phi \qquad .. 2.16.$$

Now the corresponding angle β between $I_{R,I}$ and $I_{R,E}$ is to be determined. If the line current I lags ϕ radians behind E_t, $I_{R,I}$ lags behind E_t by an angle θ_2',

$$\theta_2' = \theta_2 - \phi$$

$$= \theta_1 + \frac{\pi}{2} - \phi \qquad .. 2.17.$$

The angle β between $I_{R,I}$ and $I_{R,E}$ from Fig. 2.6 becomes,

$$\beta = \theta_2' - \theta_1 = \frac{\pi}{2} - \phi \qquad .. 2.18.$$

So from (2.16) and (2.18)

$$\alpha = \beta \qquad .. 2.19.$$

which is a necessary condition for the similarity of the triangles OAB and OCD, Fig. 2.6.

By proper selection of X_L, X_m and a the ratio of $\frac{\dot{I}_{R,I}}{\dot{I}_{R,E}}$ can be made identical to the ratio $X_d I / E_t$. Hence the vector diagram OAB becomes similar to OCD. The resultant current I_R, equation (2.6) will therefore be proportional to the required excitation at any terminal voltage and at any load. By rectifying the current I_R, the alternator field current i_F is obtained.

2.2.3 Correction Circuit:- The above field current i_F will compensate for most of the inherent alternator voltage drop, equation (2.1), but does not produce a perfectly constant alternator voltage, because conditions in an alternator deviates to some extent from the assumptions previously made. Furthermore, the alternator field resistance is subject to variation due to temperature changes, which also will affect the alternator terminal voltage.

In order to obtain the desirable high degree of alternator voltage constancy, a correction consisting of a voltage sensitive circuit is superimposed on the excitation system. This correction circuit modifies the magnitude of the current I_R and hence, the field current i_F. Because the excitation system without correction makes the alternator nearly self-regulating, only a small amount of gain now is necessary for the superposed correction circuit. As a result of this low gain, antihunt means are not necessary.

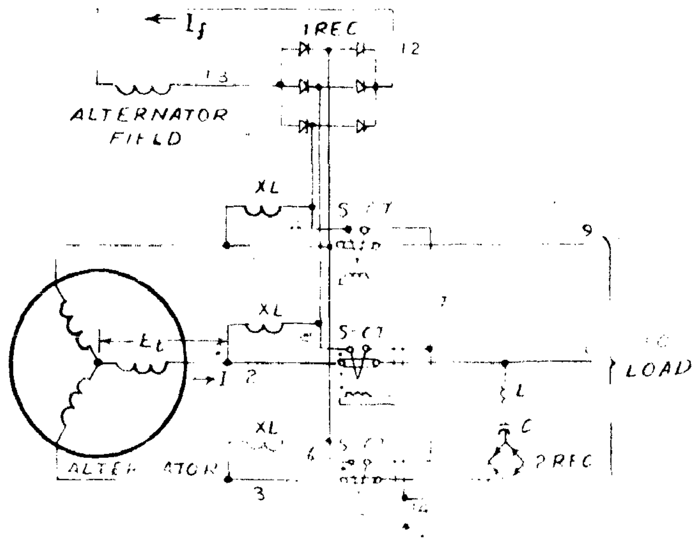
2.3. The Static Exciter Circuit:

From Fig. 2.6, the magnitude of I_R is given by,

$$I_R^2 = I_{R,E}^2 + I_{R,I}^2 + 2\, I_{R,E} \cdot I_{R,I} \cos\left(\frac{\pi}{2} - \phi\right)$$

Substituting the values of $I_{R,E}$ and $I_{R,I}$ from equations (2.10) and (2.13) I_R is determined,

$$I_R^2 = \frac{X_m^2}{R^2(X_L + X_m)^2 + X_L^2\, X_m^2} \cdot (E_t^2 + a^2 I^2\, X_L^2 + 2E_t a I X_L \sin\phi) \qquad \ldots\ldots 2.20.$$



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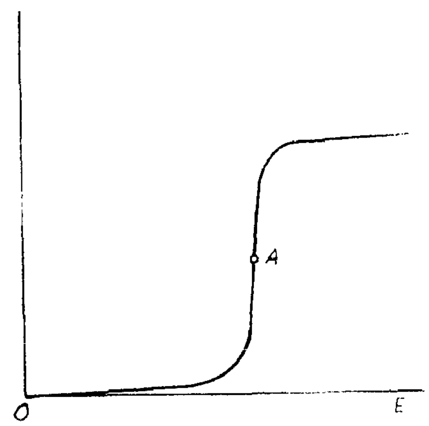


FIG.2.9 CURRENT I_c OF CORRECTION CIRCUIT AS FUNCTION OF ALTERNATOR TERM. VOLTAGE E

From equation (2.20) it is observed that I_R varies with X_m By applying d.c ampere turns to the current transformer C.T. of Figures 2.2 and 2.3 saturation can be affected in the cores, resulting in a change of X_m and subsequently a change of I_R.

A schematic diagram of such a transformer, called a saturable current transformer and designated by S.C.T, is shown in Fig. 2.7. A three legged core structure is used. The primary a.c windings are between terminals X_1, and X_2 and the secondary a.c. windings are between terminals H_1 and H_2. The d.c control winding and its terminals F_1, F_2 is wound around the centre leg. Because of the polarities of the windings, the a.c. fluxes of fundamental frequency and higher, odd harmonics circulate between the outer legs, and no voltage of fundamental or odd frequency is induced in the control winding.[5] A group of three such saturable current transformers is shown in Fig. 2.8.

The excitation circuit including the saturable current transformers is shown in Fig. 2.8. Instead of having points 4,5,6 connected to the resistors R, Fig. 2.2, they are now connected to a 3-phase bridge rectifier I REC which energizes the field of alternator. The control windings of the saturable current transformers are connected in series and terminate at 14 and 15.

In order to superpose corrective action on the excitation system, the control windings of the saturable current transformers are energized from a non-linear resonant circuit.[6] The single phase voltage for the energization of this circuit may be taken directly from one phase of the alternator, or it may be obtained from a circuit which produces the average voltage of the three phases of the alternator.

The nonlinear circuit consists essentially of a capacitor C, an iron core reactor L, a rectifier 2 REC which energizes the control windings of the saturable current transformers. The current flowing in this nonlinear circuit is shown in Fig. 2.9 as a function of the applied voltage. In the vicinity of A, which is the operating region, a small change in the alternator voltage E causes a very large variation in the current I_c. If for instance, the alternator voltage E increases, the current I_c in the non linear circuit rises sharply. This produces additional saturation in the saturable current transformers, resulting in a reduction of field current i_F equation (2.20). In cases where the power output of this nonlinear circuit is not sufficient for its direct application to the saturable current transformers, a magnetic amplifier may be interposed.

CHAPTER III

CALCULATION OF THE PERFORMANCE OF STATIC MAGNETIC EXCITER BY MATCHING THE GENERATOR AND EXCITER TRANSFER FUNCTIONS.

3.1. Basic Theory of Operation:

The three phase static exciter is shown symbolically in Fig. 3.1. It consists of :-

1. Three saturable current potential transformers (SCPT)
2. Three linear reactors x_L.
3. A three phase full wave rectifier.

3.2. SCPT[7]:- The saturable current potential transformers have three a.c windings and a d.c control winding. The a.c windings are designated N_1, N_2 and N_3 and are respectively the voltage, current and output windings.

The output windings are connected in delta.

The SCPT's combine voltage and current quantities from the generator output in the correct proportion and control the magnitude of the resultant field current in the generator by means of d.c. saturation.

The SCPT's also act as an impedance matching member between the generator output and the generator field. The reactors shift the phase of the current derived from the generator voltage with respect to that derived from load current such that the field current, which is proportional to the vector sum of these currents, has self corrective action with respect to changes in load and power factor as shown in Fig.3.2.

'R' is the main field rectifier and converts the 3-phase output of the exciter to d.c. field excitation.

3.3. Single Phase Equivalent Circuit:

The single phase equivalent circuit of Fig.3.3 can be derived from the circuit of Fig. 3.1, by making the following simplifying assumptions:-

3.3.1 The generator is symmetrically loaded.

3.3.2 The reactors have negligible winding resistance and core loss.

3.3.3 The leakage reactance, winding resistance core loss of the SCPT are negligible.

3.3.4 The field of the generator can be represented in the steady state by a linear resistance in the single phase equivalent circuit.

3.3.5 The direct current in the field is proportional to the alternating current flowing through the linear resistance in the single phase equivalent circuit.

The equivalent circuit can be referred to any of the three a.c windings of the SCPT. In the circuit of Fig.3.3,(a), voltages, currents and impedances are referred to the output winding N_3.

R → is the per phase resistance representing the field loading on the exciter.

X_m → is the exciting reactance of the SCPT referred to the N_3 winding and is a function of the d.c control current.

e_T = $E_t(\frac{N_3}{N_1})$ is the voltage source in the equivalent circuit referred to the N_3 winding and is proportional to the generator voltage E_t.

i_L = $I(\frac{N_2}{N_3})$ is the current source in the equivalent circuit referred to the N_3 winding and is proportional to the generator load current.

x_L = $X_L(\frac{N_3}{N_1})^2$ is the reactance referred to the N_3 winding.

3.4. Transfer Function:- Transfer function of a system or of elements is the relationship between the output and input under the specified conditions. Hence it is the ratio of the output and input and it is a function of input signal frequency.

3.5. Steady State Exciter Transfer Function:

In using the equivalent circuit, it is also assumed that X_m is a linear reactance that can be varied. With this additional assumption all voltages and current become sinusoidal and simple steady state analysis can be made.

By Thevenin's theorem, transferring the single phase equivalent circuit of Fig. 3.3(a) to the circuit of Fig.3.3(b). One usual equation for describing the exciter performance in terms of generator output quantities and exciter parameters can be obtained.

Let the equivalent impedance be Z, then

$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{jX_m} + \frac{1}{jx_L}$$

Since $\left(\frac{\bar{e}_T}{jx_L} + \bar{i}_L \right) \cdot Z = \bar{I}_R R$

$$\therefore \quad \bar{I}_R = \left(\frac{\bar{e}_T}{jx_L} + \bar{i}_L \right) \frac{Z}{R}$$

$$= \frac{\bar{e}_T + j x_L \bar{i}_L}{R\left(1 + \frac{x_L}{X_m}\right) + j x_L} \qquad .. \; 3.1.$$

Equation 3.1 can also be written as

$$|I_R| = \frac{1}{\sqrt{R^2\left(1 + \frac{x_L}{X_m}\right)^2 + x_L^2}} \left| \bar{e}_T + j x_L \bar{i}_L \right| \qquad .. \; .. \; 3.2.$$

As mentioned previously, it has been assumed that the d.c. field current will be proportional to the absolute value of r.m.s current in R. Equation 3.3, expresses this,

$$i_F = K_{ir} \left| I_R \right| \qquad .. \; 3.3.$$

Where i_F = d.c field current

K_{ir} = constant of proportionality

We obtain the steady state exciter transfer function combining equations 3.2 and 3.3

$$i_F = \frac{K_{ir}}{\sqrt{R^2\left(1 + \frac{x_L}{X_m}\right)^2 + x_L^2}} \cdot \left| \bar{e}_T + j x_L \bar{i}_L \right| \qquad .. \; 3.4.$$

3.6. Steady State Generator Transfer Function:

The field current requirements of a synchronous generator can be expressed in terms of its terminal voltage, load current, direct and quadrature axis synchronous reactance and armature resistance.

Great simplification results by assuming a round rotor machine with negligible armature resistance and no saturation. Using these assumptions, it can be shown that the field current requirements of the generator are expressed as

$$i_F = K\left[\bar{E}_t + j X_d \bar{I}\right] \qquad .. \; 3.5.$$

where i_F = field current

$\bar{E}_t$ = output voltage

$\bar{I}$ = Load current

K = $\frac{\text{Amp.}}{\text{Volt}}$ constant of proportionality

X_d = Synchronous reactance.

3.7. Matching Exciter and Generator Transfer Functions:

From the equivalent circuit of Fig. 3.3, the voltage and current in equation 3.4 can be written in terms of generator voltage and load current as shown in equation 3.6.

$$i_F = \frac{K_{ir}}{\sqrt{R^2\left(1 + \frac{x_L}{X_m}\right)^2 + x_L^2}} \left| \frac{N_3}{N_1} \cdot \bar{E}_t + j\, x_L \frac{N_2}{N_3} \bar{i}_L \right| \qquad .. \quad .. \; 3.6.$$

Since in equation 3.6 there are available two independent choices of turns ratio, it is possible to match the coefficients of equations 3.6 to 3.4. When these coefficients have been matched, the output of the exciter (equation 3.6) as a function of generator voltage and load parameters equals the field current requirements of the generator for the same voltage and load conditions.

The idealized exciter, therefore, at a fixed field temperature can supply correct excitation to the idealized generator for all symmetrical load conditions without any steady state change from the voltage regulator.

Equation 3.6 also shows that a change in the resistance of the field will cause a mismatch of the exciter and generator changing the value of X_m slightly by action of the voltage regulator will restore the matching.

In matching the coefficients of equations 3.5 to 3.6, the impedance levels of X_m, x_L and R should be specified before the turns ratio are chosen. It is convenient to refer x_L and X_m to R since this is a function of generator field resistance.

X_m and x_L can be referred to R at a field temperature of 25 ^{o}c or some other rated temperature as follows:-

$$X_{mo} = K_m . R_o \qquad .. 3.7.$$

$$x_L = K_L \; R_o \qquad .. 3.8.$$

where R_o is the value of R at 25^{o}c.

X_{mo} is the specific value of the variable X_m which will match the coefficients of equations 5 and 6, with $R = R_o$.

x_L is the fixed reactance chosen according to equation 3.8.

To match the exciter to the generator with the field resistance at $25^{\circ}c$ equations 3.5. and 3.6. are used with the values defined in equations 3.7. and 3.8.

$$i_F = \frac{K_{ir}}{\sqrt{R_o^2\left(1 + \frac{K_L}{K_m}\right)^2 + K_L^2 R_o^2}} \cdot \left| \frac{N_3}{N_1} \bar{E}_t + j\, K_L\, R_o \frac{N_2}{N_3} \bar{I}_t \right|$$

$$= K \left| \bar{E}_t + j\, X_d\, \bar{I}_t \right|$$

Comparing the real terms

$$\frac{N_3}{N_1} = \frac{K\ R_o}{K_{ir}} \cdot \sqrt{\left(1 + \frac{K_L}{K_m}\right)^2 + K_L^2} \quad .. \ 3.9.$$

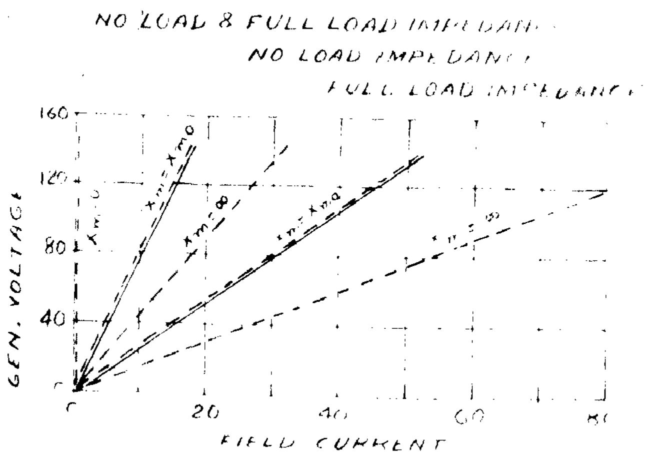
Compaging the imaginary terms

$$\frac{N_2}{N_3} = \frac{K\ X_d}{K_{ir}\ K_L} \cdot \sqrt{\left(1 + \frac{K_L}{K_m}\right)^2 + K_L^2} \quad .. \ 3.10.$$

3.8. <u>Self-Excitation Lines:</u>

In the a.c. exciter, the field excitation lines (generator voltage against field current) are varied statically by means of the variable X_m.

In d.c. compound machines the excitation is a function of generated voltage and load current. The static exciter is a method of self excitation for a.c. machines that closely parallels the series compounded d.c. machines in that excitation is a function of voltage and load currmnt. In addition the output of a.c. exciter is a function of power factor.



3.3 (a) LINEARIZED GENERATOR & EXCITER TRANSFER CHARACTERISTIC..

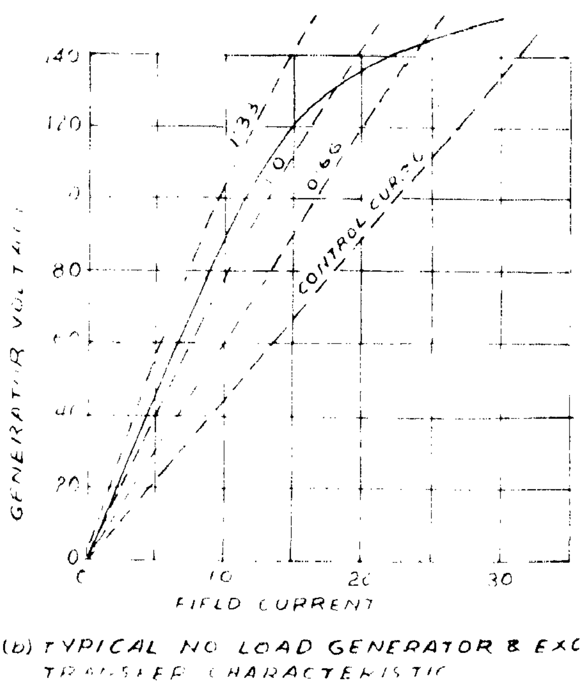


FIG 3.4 (b) TYPICAL NO LOAD GENERATOR & EXCITER TRANSFER CHARACTERISTIC

——— GENERATOR CHARACTERISTIC
– – – EXCITER CHARACTERISTIC

The output current of the exciter can be plotted as a function of generated voltage alone for any specified fixed load impedance on the generator. A series of field lines can be plotted for the a.c. exciter as a function of the variable X_m.

In figure 3.4 the characteristics of an idealized machine at no load and full load impedance rated power factor are shown as solid lines.

The constants of the machine are:-

$K = 0.125$ ampere/volt

$X_d = 2.43$ ohms

$R_o = 0.70$ ohms

Rated current = 167 amps.

Rated voltage = 120 volts

Rated p.f. = 0.75

Rated K.V.A. = 60.

The output of an idealized exciter for three different values of X_m and for a constant R_o are also shown as dashed lines of Fig. 3.4. Maximum exciter output occurs when $X_m = \infty$. The exciter characteristics are coincident with those of the generator when $X_m = X_{mo}$. The exciter characteristics are coincident with the ordinate when $X_m = 0$.

The constants of this exciter are:-

$K_m = 0.8$

$K_L = 3$

$K_{1r} = 2.08$

$\frac{N_2}{N_3} = 0.274$

$\frac{N_3}{N_-} = 0.236$

3.9. Design Considerations:

While discussing the theory of operation certain assumptions were made concerning the generator and exciter in order to clearly illustrate the principle involved in the static exciter. Design equations developed under more rigorous assumptions make it possible to predict to within 5 percent of the actual steady state operating point of an exciter.

In an idealized generator - exciter combination, the exciter is capable of supplying correct excitation to the generator for any load condition without any steady state correction required from the voltage regulator. In practice if an exciter is matched to a generator for normal loading some reserve capacity is usually required for overload conditions due to generator saturation. Reserve capacity also allows faster recovery from load transients.

3.10. System Considerations:

Voltage Drop Across SCPT Current Winding:-

Since field power is derived from the generator output, the generator should be designed taking this view into consideration. Field power is derived from both:

1) Potential

and 2) Current sources

however, nearly all this power, under full load and overloads, is obtained from the current source. At no load, all power is obtained from the potential source, which results in a small current being drawn from the generator. Since this current is further decreased as load is added to the generator, its effect can be neglected in considering the design of the generator. The voltage drop across the SCPT current winding is appreciable and must be considered.

It is evident from the equivalent circuit of Fig. 3.3(a) that the voltage drop across R is the voltage drop across SCPT secondary. The voltage drop across the primary of the SCPT is therefore merely the turns ratio times this voltage.

$$\bar{I}_R = \frac{\bar{e}_T + j\, x_L\, \bar{i}_L}{R\left(1 + \frac{x_L}{X_m}\right) + j\, x_L} = \frac{\frac{N_3}{N_1} \cdot \bar{E}_t + j\, x_L \cdot \frac{N_2}{N_3}\, \bar{I}}{R\left(1 + \frac{x_L}{X_m}\right) + j\, x_L}$$

and $$V_p = \bar{I}_R \cdot R\, \frac{N_2}{N_3}$$

Substituting the value of I_R,

$$\bar{V}_p = \frac{\left(\frac{N_3}{N_1}\, \bar{E}_t + j\, x_L\, \frac{N_2}{N_3}\, \bar{I}\right) \cdot R\, \frac{N_2}{N_3}}{R\left(1 + \frac{x_L}{X_m}\right) + j\, x_L} \qquad .. 3.11.$$

$$\bar{V}_p = \frac{\frac{N_2}{N_1} \cdot E_t + j\, x_L \left(\frac{N_2}{N_3}\right)^2 \dot{I}}{\left(1 + \frac{x_L}{X_m}\right) + j\, \frac{x_L}{R}} \qquad .. 3.12.$$

Inspection of equation 3.12, reveals that even at no load there is a voltage drop across the SCPT primary. This voltage lags the generated voltage by an angle determined by the x_L, X_m and R parameters. As full load rated p.f. is approached the drop increases and approaches more nearly the phase of the generated voltage.

On a typical 60 KVA machine at full load and hot field conditions, the series drop across the SCPT primary would be approximately 2 percent.

3.11. Regulator Requirements:

Increasing the value of X_m will increase the output of the exciter at any given load and the converse is also true. X_m increases as the control current in the SCPT decreases. Hence the sense of the voltage regulator should be such that the regulator output current will increase with increasing generator voltage and be zero at zero voltage.

Thus during a transient caused by load application the voltage will dip and cause the regulator output to decrease. The exciter output will increase due to load application and still greater forcing will be obtained as the regulator output decreases. The result will be rapid voltage recovery. A typical steady state regulator transfer characteristic is shown in Fig. 3.5.

3.12. Effect of a Short Circuit between the Generator and Exciter:

In the event that a short circuit is applied between the generator terminals and the current winding on the SCPT, there will be tendency for the exciter output to collapse to zero. This tendency is caused by the fact that the short circuit requires additional excitation in the generator field. Since the current flowing into the fault does not flow through the current winding, the exciter does not inherently supply the required excitation to the generator. Provided the fault is of higher impedance, the regulator action may have sufficient effect in raising the value of X_m to prevent the system voltage from collapsing. On a low impedance fault, the field excitation and the voltages and currents on all phases will collapse to zero. The exact fault impedance at which the excitation will collapse is a function of the generator reactances, the number of phases faulted, the normal load on the system and the constants of the exciter.

The following are data taken from a typical 60 KVA system at 25^{o}c.

1. Steady state voltage regulation of ± 5 percent from no load to full load, 0.75 p.f.
2. Most of harmonics changed less than 0.1 percent due to the contribution of the exciter. Two harmonics were increased by as much as 0.4 percent and one harmonic was decreased by 0.5 percent.

3.13. Performance During a 3-Phase Fault:

During a three phase fault, the generator transfer function of fault current as a function of field current approaches the idealized generator since it is linear within range of practical fault currents.

In the exciter the potential source becomes zero and X_m increases to its maximum value due to regulator action. Thus neglecting X_m, the exciter equivalent circuit is a current shunted by a reactance and the field.

CHAPTER IV

APPLICATION OF STATIC EXCITERS TO SYNCHRONOUS MACHINES

4.1. In this chapter a complete schematic diagram of static excitation equipment for 13,800 volts, 25,600 KVA steam turbine generator is discussed. The theory has already been discussed in chapters II and III.

The essential elements of the excitation system are shown in Fig. 4.1. The major components are:-

4.1.1 The static magnetic power components consisting of three single phase power potential transformers (PPT's), three linear reactors ($x_{L's}$) and three single phase saturable-current transformers (SCT's)

4.1.2 The power rectifier consisting of two individual 3-phase full wave bridge water cooled rectifiers utilizing silicon diodes. Each rectifier section can be isolated for maintenance under load.

4.1.3 An a.c. (automatic) voltage regulator controlling the a.c. generator voltage consisting of two stages of magnetic amplifiers, a zener diode reference circuit and a rectifier comparison circuit.

4.1.4 A d.c. manual voltage regulator con-sisting of a rheostat which permits an adjustment of the d.c. voltage of the exciter when the a.c. regulator is out of service.

4.1.5 Other components of the excitation system consisting of a field circuit breaker for the static exciter (and a field breaker for a spare exciter if desired), a linear field discharge resistor and protective components for the power rectifier.

4.2. Operation of the A. C. Automatic Voltage Regulator:

Owing to the effects of magnetic saturation of the generator, changes in field resistance with temperature, inability to design the power components precisely and other secondary effect, the exciter does not furnish exactly the required excitation under all loads and conditions. An a.c. voltage regulator is provided, therefore, to adjust the exciter output by changing the direct current in SCT control winding.

A simplified a.c. regulator schematic block diagram is shown in Fig. 4.2. A 3-phase bridge rectifier 1 REC produces a signal voltage proportional to the average 3-phase a.c. machine voltage. This voltage is applied to a linear and nonlinear circuit.

The linear circuit consists of Resistors 1R, 2R and voltage adjusting rheostat 1P. The non linear circuit consists of resistor 3R and zener diode 1Z. Current conduction in the zener - diode occurs at a constant voltage V_{AB}.

The linear and nonlinear circuits are joined in a bridge connection with the regulator first stage magnetic amplifier control winding connected in the centre arm of the bridge.

The voltage V_{AC}, across the lower portion of 1P and 2R is proportional to the d.c. signal voltage. When this voltage is equal to the conduction voltage of 1Z, the bridge is balanced and no current flows through the control winding of the magnetic amplifier circuit. If the a.c. machine voltage rises, V_{AC} rises proportinnally and exceeds the constant voltage V_{AB} of 1Z, causing buck current to flow through the control winding of the magnetic amplifier.

Conversely, if the signal voltage decreases V_{AB} is greater than V_{AC}, the boost current flows through the magnetic amplifier circuit. Boost current through the first stage magnetic amplifier control winding reduces the output of the second stage magnetic amplifier, thereby reducing the control current I_c in the SCT. This decrease of I_c causes less magnetizing current I_m, Fig. 4.2, to flow through the SCT and allows more of the load current to flow through the rectifier to the generator field, raising the generator voltage towards normal.

Conversely, if the generator voltage rises, buck current flows in the first stage control winding, resulting in increased magnetizing current through the SCT and allowing less of the load current to pass to the a. c machine field, thereby reducing the terminal voltage towards normal.

4.3. Operation of the D. C. Manual Voltage Regulator:

Operation of the regulating equipment can be switched between a.c voltage regulator control and d.c voltage regulator control without a distrubance.

Referring to Fig. 4.1, when changing from regulating d.c. exciter voltage, the manual voltage adjuster is positioned so that the current from the exciter voltage through the manual - control adjuster to the dummy load, which simulates the SCT control field resistance, is equal to the current flowing through the SCT control winding from the a. c regulator. This equality is indicated by a meter.

The control switch may then be moved to the manual position, de-energizing contactor M, placing the machine under control on the d. c. voltage regulator.

When operation is on 'manual', if the d.c. exciter voltage rises, the current through the SCT control winding increases, allowing more magnetizing current to flow through the SCT so that less load current is available for the generator field. The decrease in field current lowers machine - terminal voltage towards the desired value. Conversely, if the exciter voltage decreases, the SCT control current decreases decreasing the magnetizing current, and allowing a greater proportion of the load current to flow in the generator field. Thus the manual regulator tends to hold exciter voltage constant.

If it is desired to transfer to a.c. regulator control, the a.c. voltage adjuster can be positioned to enable the current from the a.c. regulator through its dummy load resistor to equal the current flowing in the SCT control winding. The control switbh can then be turned to 'Auto'.

4.4. Excitation System Performance for a 3-Phase Short Circuit at the Generator Terminals:

Fig. 4.3, represents the time response of the generator field voltages with a 3-phase solid fault at the generator terminals.

The generator was initially operating at rated voltage and rated speed, at no load.

Exciter voltage, a.c. machine field current and a.c. machine terminal voltage are plotted as a function of time. The exciter reaches its ceiling voltage in approximately 0.3 sec. The average rate of rise for this period is 1,200 volts per second for this 250-volt exciter.

The sustained high value of armature current which is desirable for system relaying, can be noticed from the figure.

4.5. Machine A.C. Voltage Regulator System Response to a sudden change in the A.C. Voltage Adjuster setting:

The response to a sudden change in set point Fig. 4.4, was obtained by operating the a.c. machine under the control of the static exciter with the a. c. voltage regulator in service. The generator was operated at no load.

The setting of the a.c. voltage regulator was suddenly changed approximately 5 percent by a step change in the voltage adjusting - rheostat resistance. The time response of the a.c. generator voltage and the exciter voltage are illustrated. The test illustrates that generator voltage under control of the excitation system is well stabilized.

4.6. Load Rejection Performance with the A.C. Regulator in Service:

Fig. 4.5, represents the time response of the terminal voltage, field voltage and field current of the a.c. machine when an over excited reactive KVA load of approximately 0.6 p.u. KVA at rated voltage was rejected by opening the a.c. machine armature breaker. The test illustrates a maximum a.c. machine terminal voltage achieved for this severe test of approximately 115 percent of normal with a recovery time to normal voltage of approximately 1.5 sec. The Oscillogram illustrates the average rate of change of exciter voltage over the first half second to be approximately 210 volts per second.

4.7. Transient Performance on Air Craft Generator[7]:

A static excitation circuit as discussed in chapter III, is used with a 60 KVA, 120V, 0.75 p.f., 3-phase, 400 cycles, 6000 rpm air craft generator.

Fig. 4.6, shows the oscillograph of line current, line voltage and field current when full load, 0.75 p.f. at 6000 rpm was suddenly applied to the 60 KVA generater.

Fig. 4.7, shows the oscillograph of line current, line voltage and field current when full load, 0.75 p.f. at 6000 rpm was suddenly removed from 60 KVA generater.

Fig. 4.8, shows the oscillograph of line current, line voltage and field current when double load, 0.75 p.f. at 6000 rpm is applied to 60 KVA generater.

Also the steady state regulation obtained from no load to full load at 0.75 p.f. was ± 0.5 per cent.

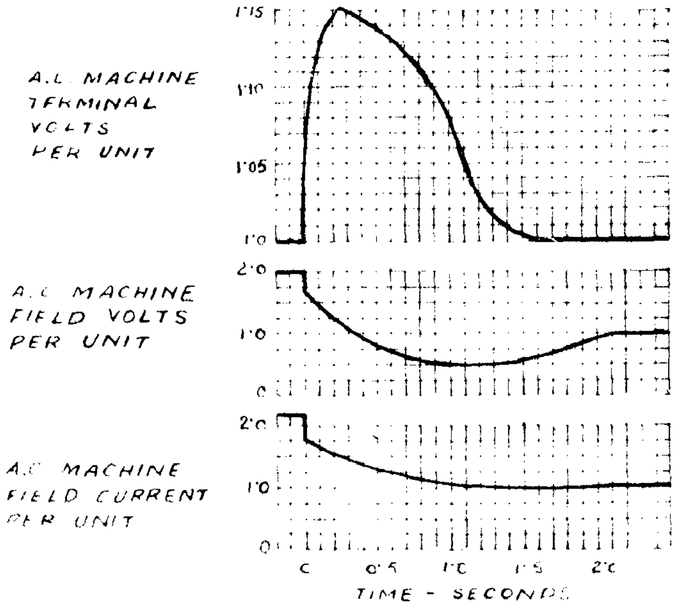


FIG. 4.5 LOAD REJECTION PERFORMANCE

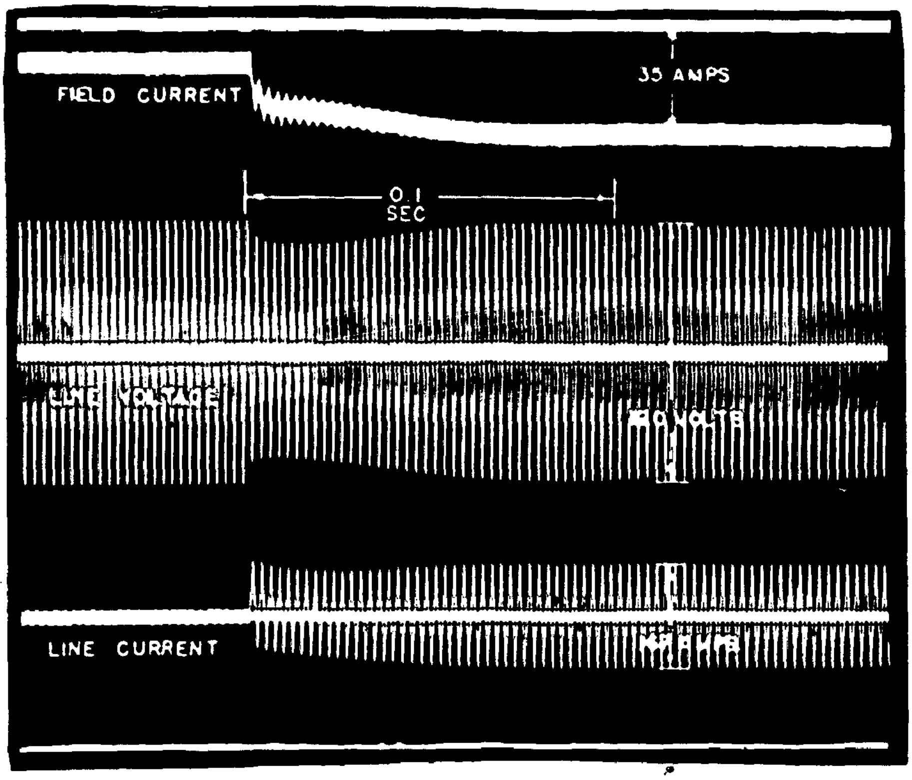


Fig. 4.6. Application of Full Load 0.75 pf at 6000 rpm to 60 KVA generator.

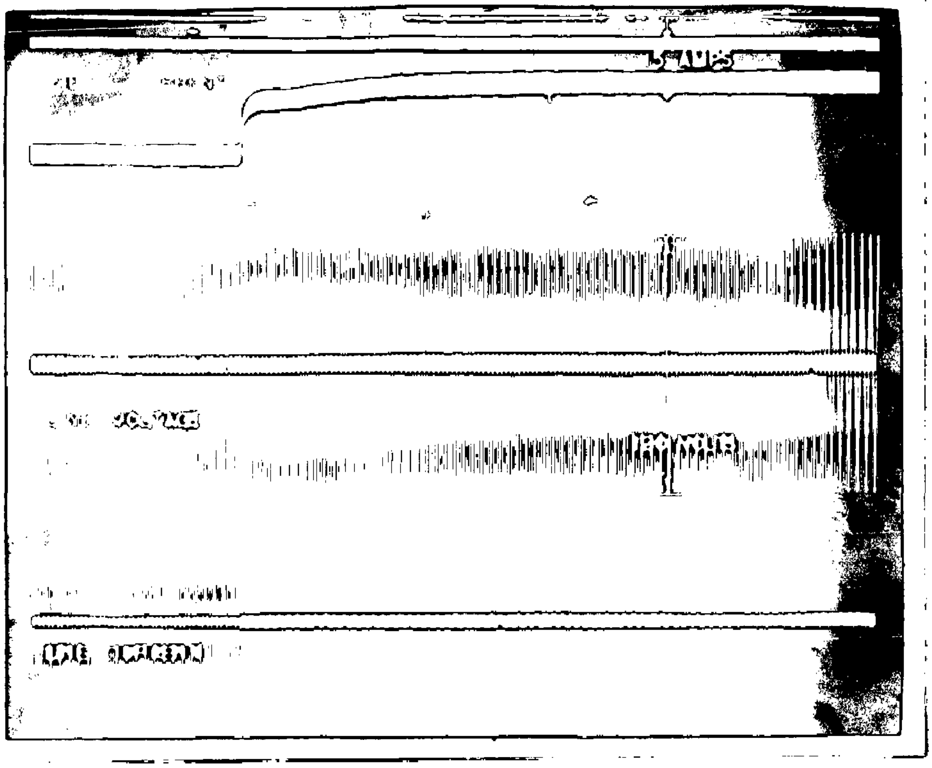


Fig. 4.7. Removal of Full Load, 0.75 pf at 6000 rpm from 60 KVA generator.

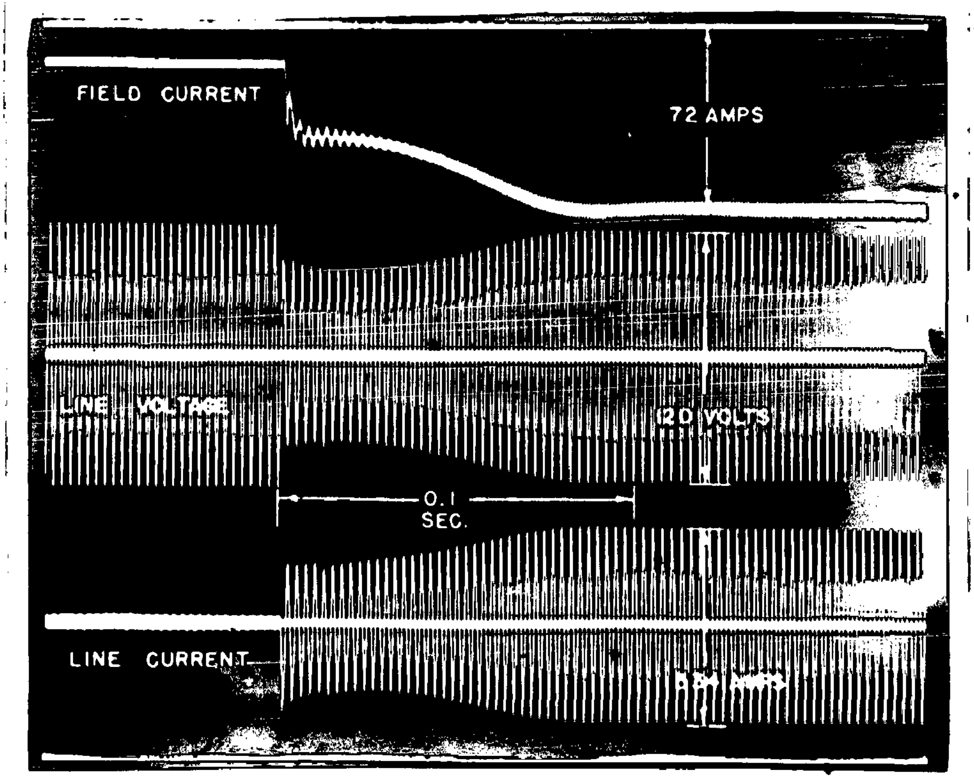


Fig. 4.8. Application of double load, 0.75 pf at 6,000 rpm to 60 KVA generator.

CHAPTER V

DESIGN CONSIDERATION AND CONSTRUCTION OF COMPONENTS FOR STATIC POWER MAGNETIC EXCITERS

5.1. To meet the excitation system design objectives of increased reliability and lower maintenance relative to retating exciters, it is necessary to design the power magnetic components considering the construction and thermal specifications.

5.2. Power Potential Transformers[8] (PPT):

The power potential transformers are normally furnished as three single phase dry-type air cooled units, although a three - phase design can be manufactured. The use of three single - phase transformers offers the advantage of smaller investment in spare parts.

The primary voltage of each of the three single phase PPT's is the line - to - neutral voltage of the a.c. machines since the three single phase units are connected in star on the primary. For a typical 25,600 KVA, 13,800 volt steam turbine generator, the transformer primary voltage is 8,000 volts. The dielectric test on the primary windings is co-ordinated with a di-electric test of the a.c. machine. Also the basic impulse insulation level (BIL) of this winding is 110 KV.

The secondary voltage is determined by the parameters of the circuit. It is usually in the order of 200 or 300 volts. The insulation level of this winding is compatible with that required by the power rectifier and the field winding in accordance with ASA requirements, which specify a high potential test of 10 times the exciter voltage.

The PPT's are designed to withstand mechanical stresses associated with generator short circuits. The high BIL construction helps the transformer to withstand the voltage transients which may accompany these short circuits. Fig. 5.1, illustrates one of the single-phase PPT's which was used in static excitation system of the turbine generator discussed above. The high voltage windings are cast in epoxy resin. This construction gives high BIL rating to this device. This cast primary winding is placed over the secondary winding, as illustrated. Secondary winding construction is similar to that used on conventional low voltage circuits. Secondary leads are connected to a terminal board.

The short circuit reactance of the PPT can be relatively high, since the reactance of the linear reactor can be adjusted to give the proper overall circuit reactance.

5.3. Saturable - Current Transformer(SCT):

Each SCT has its primary winding in the alternator line on the neutral side as illustrated in Fig. 4.1. The primary winding must be able to withstand the same dielectric test as the a.c. machine. The cast coil construction is used on the primary to provide for this dielectric test. This construction also gives a higher BIL rating.

Fig. 5.2, illustrates the SCT construction. The transformer consists of 2 cores B and C, the cast coil primary winding A; the secondary windings D and E and the control

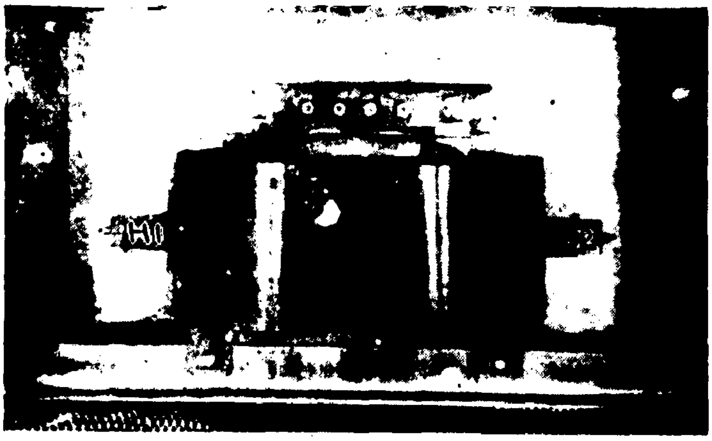


Fig. 5.1. Power Potential Transformer.

Fig. 5.2. Saturable Current Transformer.

winding F. The configuration of the cores and coils are made so that the a.c. windings do not induce high a.c. voltage of fundamental frequency in the d.c. winding. The two cores, each with individual a.c. secondary windings, are positioned with the d.c. coil surrounding both a.c. secondary windings. The cast primary winding also consists of two individual a.c. coils, although the costing makes this difficult. Proper a.c. connections of the primary and secondary a.c. coils cause the fundamental a.c. magneto motive force in the two cores to cancel, thus minimizing fundamental a.c. voltage in the d.c. coil.

Since this device is basically a saturable reactor, the a.c. coils are connected in series for fast saturable - reactor action. Since the impedance of the d.c. supply to the d.c. control winding is low, there is little danger of high voltage pulses in the d.c. circuit.

The basic design of the excitation system requires operation of the generater under all load conditions with a very small change in d.c. control winding current. Therefore it is necessary to select core material properly, to design core configuration properly and to couple primary, secondary, and control windings closely.

As illustrated in Fig. 5.2, the SCT is ruggedly constructed and strongly braced to provide for the high currents which can occur under a.c. machine short circuit conditions.

5.4. Linear Reactors. (x_L)

The linear reactors are low voltage devices which are designed to the same insulation and construction standards as the power rectifier and generator field. The reactor saturat-

-ion voltage must be co-ordinated with the SCT saturation voltage to achieve a desired ceiling excitation voltage.

5.5. Power Rectifier:

The rectifier equipment employed in Fig. 4.1 consists of two 3-phase bridge rectifiers. Each bridge is provided with isolating switches to permit maintenance of one bridge under load. The rectifier diodes are water cooled and insulated from ground. The insulation can withstand a dielectric test of ten times the nominal rating of the generator field. The rectifiers are mounted in a metal enclosure and co-ordinated with other excitation system component enclosure.

With the two bridge rectifiers in service, excitation can be provided for generator operation at rated KVA, rated power factor and 105 percent of generater voltage and followed by a generater armature three phase short circuit. Excitation at normal ceiling voltage is provided for 1 minute. With loss of cooling water flow starting from normal load and temperature conditions, the rectifiers can operate for atleast 10 minutes. This time permits application of an alarm and corrective action by an operater.

With one bridge rectifier in service, field current can be provided to obtain maximum turbine kw output at 1.0 power factor.

5.6. Power Rectifier Protection:

The most probable causes of silicon diode failure are:-

1. Natural mortality.
2. Excessive forward current.
3. Overheating.
4. Excessive reverse voltage.

5.6.1. <u>Natural Mortality</u>:

The graph in Fig. 5.3, shows a typical type of failure - rate curve for silicon diodes. A greater percentage of failures occur among diodes which have operated a short time than among diodes which have operated a longer time. These early life failures are caused mainly by manufacturing difficulties. Many manufacturers operate each diode for a time shown as T_1 in Fig. 5.3, so that those marketed are very likely to have survived the early failure phase.

Although the natural failures are unavoidable, the failure of one diode in the power-rectifier does not constitute failure of this static exciter. As illustrated in Fig. 4.1, the power rectifier consists of two bridge rectifiers connected in parallel. Each bridge rectifier contains six legs, each leg actually consists of several diodes in series. If a diode open circuits, the corresponding leg in the other bridge carries the load current; if a diode short circuits, the diodes in series with it provide ample reverse voltage capacity. Since either bridge can provide excitation for a specified generator operating condition, the faulty bridge can be isolated on both the a.c. input side and the d.c. output side for replacement of the faulty diode. Diodes can be checked manually by means of an oscilloscope, a voltmeter or an ohmmeter. Whenever an abnormally ceiling excitation for 1 minute determines the ratings of the diodes.

A fault on the d.c. side of the power rectifier can not cause excessive forward current because the current input to the power rectifier from the PPT's Fig. 4.1, is limited by the linear reactors and the current input to the power rectifier from the SCT's is limited by the amount of current flowing in the generator lines. Therefore, this excitation system inherently protects the power rectifier diodes from being subjected to excessive current.

The other cause of overheating is a failure of the rectifier cooling system.

5.6.3 Excessive Reverse Voltage:

High rectifier reverse voltage can be caused by a lightning stroke, an out - of - synchronism condition, a sudden short circuit on the alternator terminals, a switching surge, other line faults or field breaker operation. To aid in protection of the power rectifier from excessive reverse voltage, each rectifier diode is shunted by a resistor and a capacitor.

Fig. 5.4, illustrates a leg of the bridge rectifier Each leg has four diodes in series. The capacitors which are in parallel with the diodes for reverse - voltage protection perform another protective function which is necessary when silicon diodes are connected in series.

When a silicon diode carries current in the forward direction, the base region of the semi-conductor is filled with current carriers. When reverse voltage is applied at the functioning diode is discovered that diode should be replaced as soon as practicable.

5.6.2 Excessive Forward Current and Overheating:

When the diode is operated within its rating, its junction temperature is below the maximum permissible junction temperature. A momentary current surge causes heat energy to be applied to the semi-conductor, but because of the thermal time constant of the mass of the semi-conductor, the junction temperature rises exponentially towards a high value. Since the normal operating junction temperature is below this maximum permissible junction temperature, time is required for this excessive current to raise the junction temperature to a damaging level. Consequently the silicon diode does have a current surge rating which is specified by the manufactuner. Of-course, a sustained excessive value of current causes rectifier failure by raising the junction temperature above its maximum allowable value.

High forward current can be caused by a fault at the machine terminals or by a fault on the d.c. side of the power rectifier. During the first few cycles of a fault on the machine terminals, a high surge of line current, limited by the generator subtransient reactance occurs, this current surge is followed by a high level of steady-state line current until the fault is rejected.

When the machine is subjected to a fault on its terminals, the SCT's of this excitation system supply high currents, proportional to the power rectifier. The combination of the high surge current for the first cycles of the fault and steady state ceiling excitation for 1 minute determines the ratings of the diodes.

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Fig. 5.4, illustrates a leg of the bridge rectifier Each leg has four diodes in series. The capacitors which are in parallel with the diodes for reverse - voltage protection perform another protective function which is necessary when silicon diodes are connected in series.

When a silicon diode carries current in the forward direction, the base region of the semi-conductor is filled with current carriers. When reverse voltage is applied at the beginning of the next half-cycle, these current carriers cause the diode to conduct current in the reverse direction. This reverse current sweeps the current carriers out of the semi-conductor, permitting it to regain its ability to block the current in the reverse direction. Sweeping out the current carriers, that is, cleaning up the semi-conductor, usually takes a few micro-seconds.

The wave forms in Fig. 5.5, illustrate the manner in which one cell could be ruined by fast clean-up if the resistors and capacitors shown in Fig. 5.4, were omitted. The commutating time from T_0 to T_1 is caused by inductance in the a.c. input lines to the bridge rectifier Fig. 4.1. The time T_1 to T_2 is the clean-up time of the fastest cell diode A, Fig. 5.4. At time T_2 diode A blocks reverse current, the leg becomes an open circuit and the applied voltage V_1 is dropped across the rectifier leg. Since three diodes are still acting as short circuits at time T_2, all of the leg voltage is dropped across the diode A. The applied voltage V_1 exceeds the reverse - voltage rating of diode A and causes diode A to fail.

This type of failure can be prevented by use of capacitors connected as shown in Fig. 5.4. If a diode A cleans up and blocks first in the leg, capacitor A carries current i_{cu} around the diode A while current carriers are being swept out of the slower diodes. The capacitance value selected is sufficiently large to permit the capacitor to carry this clean-up current for a few micro-seconds without appreciable change in voltage across the capacitor.

The resistors in parallel with the rectifier cells serve two purposes. They provide a method of obtaining equal voltage distribution in spite of the fact that leakage current of the cells may differ greatly; and they provide an energy sink to prevent oscillations between the capacitors and the inductance of the linear reactors or between the capacitors and distributed inductance of the wiring. Consequently, the capacitors and resistors which shunt the diodes cause diodes to divide the reversely applied voltage equally so the reverse-voltage rating of the power rectifier leg is truly equal to the sum of the reverse-voltage ratings of the diodes in one leg of the rectifier bridge. Extensive testing verified that rectifier failure due to excessive reverse voltage is highly unlikely.

CHAPTER VI

DESIGN OF STATIC EXCITATION. SYSTEM FOR AN A.C. ALTERNATOR AND THE EXPERIMANTAL RESULTS OBTAINED:

6.1. For experimental work a static excitation system was designed and set up in the Electrical Engineering Department of the University of Roorkee, for the following Alternator.

6.2. **Specifications of Alternator:-**

ALTERNATOR TYPE S.S

1 phase, 240 watts, 80 volts, 1200 cycles.

Excitation 24 volts D.C.

Speed 2770 RPM.

MADE IN CANADA

BY

SMALL ELECTRIC MOTORS

(CANADA) LTD.

FOR

RESEARCH ENTERPRISES LIMITED

SERIAL NO. CAN. 14280

The above alternator was coupled to the following motor by means of belt and pulley drive.

6.3. Specifications of the Motor:

British Thomson Houston Co. Ltd.

RUGBY ENGLAND.

D. C. MOTOR

Type	D.2816.A	No.	G 766B.
WD	SHUNT	Volts	230
HP	7.5	R. P. M.	1490
AMP	30		

MADE IN ENGLAND.

6.4. Observations.

The readings for the open-circuit and short-circuit characteristics for the above mentioned alternator were taken and recorded in Tables I and II. From these readings O. C. and S. C. curves were plotted in Fig. 6.1., and from these curves the values of synchronous reactance (X_d) were derived and recorded in Table III.

Armature resistance of alternator = 0.55 ohms.

TABLE I

O. C. C. Of 1-phase, 240 W, 80 V ALTERNATOR

Speed = 2770 r.p.m.

Field Current I_f Amp.	O.C. Voltage E_o Volts
00	18.5
0.06	29.5
0.10	36.0
0.25	63.0
0.50	108
0.70	147
1.00	182
1.24	196
1.75	210
2.00	214

TABLE II

S.C.C. Of ALTERNATOR

Field Current I_f Amp.	S.C. Current I_{sc} Amps. ×2
00	00
0.20	0.65
0.40	1.30
0.75	2.50
1.00	3.4A

TABLE III

Synchronous Reactance (X_d) Of 240W, 80V ALTERNATOR

I_f (Amp)	E_o (Volts)	I_s (Amps) ×2	X_d (ohms) ÷2
0.20	40	0.67	60.5
0.40	82	1.36	60.5
0.60	125	2.06	60.5
0.80	161	2.74	58.7
1.00	182	3.40	53.5
1.20	194	4.05	48.0
1.40	202	4.75	42.5
1.60	206.5	5.45	38.0
1.80	211	6.15	34.3
2.00	214	6.80	31.5

6.5. Design of Static Excitation System.

The design of static excitation system is based on the theory and performance discussed in Chapters II and III.

6.5.1 Design of SCPT:

Taking 40 percent voltage drop across the linear reactor X_L.

Voltage drop across N_1 turns of potential winding = 60 percent of the rated voltage = 48 V.

Voltage per turn is given by,

$$e_t = 4.44\ f\ (K_i\ \ A_i\ \ B_m)\ X\ 10^{-8}\ \ V \qquad .. \ 6.1.$$

Taking K_i = 0.91

A_i = 4 sq. cm.

B_m = 8,500 guass.

f = 1200 cycles

$$\therefore \quad e_t = 1.64 \text{ volts per turn} \qquad .. \ 6.2.$$

Number of turns in the potential winding

$$(N_1) = 30 \qquad .. \ 6.3.$$

Choosing initially $\frac{N_3}{N_1} = 2$

Thus N_3 winding is designed for 70 turns with tappings at 50 and 60 turns.

6.5.2 No Load Exciter Transfer Characteristic:

Readings for no load exciter transfer characteristics for various values of control currents are recorded in Table IV. ..

TABLE IV

Readings For No Load Exciter - Transfer Characteristics for various values of Control Current.

I_c = 0A		I_c = 0.5A		I_c = 0.75A		I_c = 1.0A.	
i_F	E	i_F	E	i_F	E	i_F	E
0.25	38.0	0.2	36.0	0.18	36.7	0.16	39.0
0.33	50.5	0.26	46.5	0.25	51.0	0.22	53.5
0.42	63.5	0.33	59.6	0.31	61.0	0.28	68.0
0.51	77.0	0.42	76.0	0.39	80.0	0.34	82.5

No load generator and exciter transfer characteristics are plotted from Tables I and IV in Fig. 6.2.

From the curves of Fig. 6.2, it is concluded that the generator transfer characteristic matches the exciter transfer characteristic when a d.c. current of 0.75A flows through the control winding (N_c) having 40 turns.

6.5.3 **Measurement of R_o at $33^o c$.**

Current in control winding I_c = 0.75A.

Resistance of field winding R_f = 7.5 ohms.

D. C. current in field winding i_F = 0.39A.

A. C. current input to rectifier I_R = 0.46A.

So,

$$R_o = \left(\frac{i_F}{I_R}\right)^2 R_f$$

$$= \underline{5.25 \text{ ohm}} \qquad .. \ 6.5.$$

6.5.4 **Measurement of x_L and X_{mo}:**

Current in control winding I_c = 0.75A.

Current flowing through X_L and the potential winding I_{ac} = 0.38A.

Voltage drop across potential winding V_2 = 52 Volts

Voltage drop across X_L, V_1 = 31 Volts.

Neglecting the resistance of linear reactor (X_L) and the potential winding of SCPT,

$$X_L = \frac{V_1}{I_{ac}} = 81.5 \text{ ohms.}$$

$$x_L = \left(\frac{N_3}{N_1}\right)^2 X_L = 326 \text{ ohms.} \quad .. \ 6.6.$$

$$X'_{mo} = \frac{V_2}{I_{ac}} = 137 \text{ ohms.}$$

Where X'_{mo} is the reactance of the SCPT referred to N_1 winding.

So the magnetizing reactance of SCPT referred to N_3 winding,

$$X_{mo} = \left(\frac{N_3}{N_1}\right)^2 X'_{mo}$$

$$= 548 \text{ ohms.} \quad .. \ 6.7.$$

From equation 3.3.

$$i_F = K_{ir} \left| I_R \right|$$

$$\therefore K_{ir} = 0.84 \quad .. \ 6.8.$$

From equation 3.5.

$$K = \frac{\text{Amp.}}{\text{Volt}} \text{ (Constant)}$$

$$= 0.05 \quad .. \ 6.9.$$

From equation 3.7.

$$\therefore K_m = \frac{X_{mo}}{R_o} = 104 \quad .. \ 6.10.$$

From equation 3.8.

$$K_L = \frac{x_L}{R_o} = 61.7 \qquad .. \; 6.11.$$

From equation 3.10.

$$\frac{N_2}{N_3} = \frac{K \cdot X_d}{K_{ir} \; K_L} \sqrt{\left(1 + \frac{K_L}{K_m}\right)^2 + K_L^{\,2}}$$

$$= 0.36$$

$$\therefore N_2 = \underline{22 \text{ turns}} \qquad .. \; 6.12.$$

6.5.5 As such SCPT is built up with E and I type of silicon steel laminations with 2 cm. x 2 cm, outer limbs core section. Potential winding turns (N_1 = 30) are wound equally on the two outer limbs in series. Similarly current winding turns (N_2 = 22) and output winding turns (N_3 = 60) are wound equally on two outer limbs. Control winding turns (N_c=40) are wound on the central limb.

<u>TABLE V</u>

Full Load Generator Transfer-Characteristics.
Load Current = 3A (Kept-constant)
Speed = 2770 rpm.

i_F (Amp.)	E_t (Volts)
[redacted]	[redacted]
[redacted]	[redacted]
0.61	65.0
0.73	78.5

TABLE VI

Full - Load Exciter Transfer - Characteristic for Various values of Control Current

I_c=0A		I_c = 0.5A		I_c = 0.75A		I_c = 1.0A	
i_F	E_t	i_F	E_t	i_F	E_t	i_F	E_t
0.39	31.8	0.36	34	0.33	35	0.31	37
0.51	43.0	0.47	44.2	0.46	49	0.41	49
0.65	53.0	0.60	56.5	0.59	63	0.51	61
0.81	66.0	0.73	69.0	0.72	77	0.64	77

Full load generator and exciter transfer characteristics are plotted from Tables V and VI in Figure 6.2.

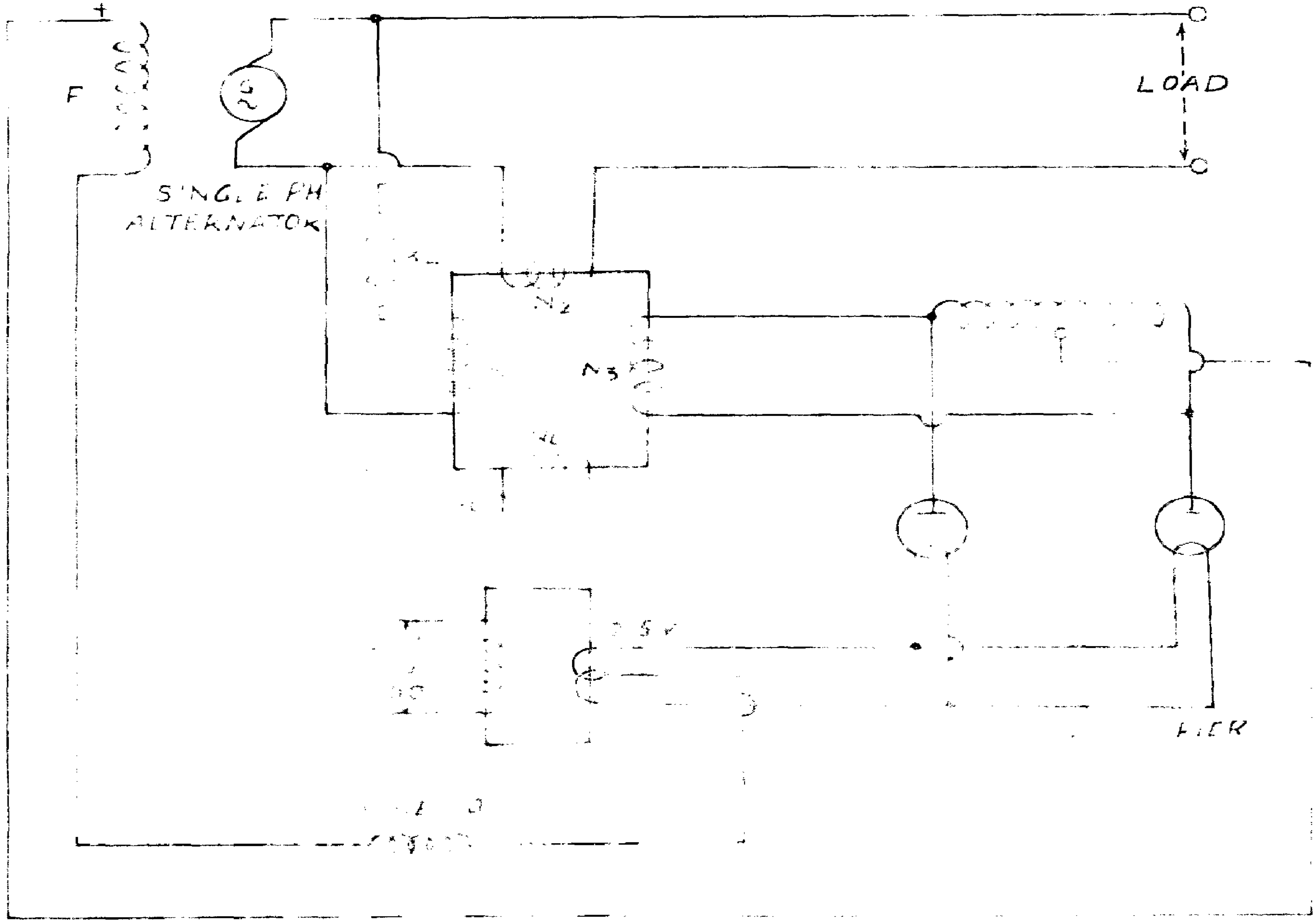


FIG. 63 SCHEMATIC ...
FOR SINGLE P...

6.5.6 Rectifier:

A full wave rectifier circuit is, connected up with the help of two half-wave tungar rectifiers. This full wave rectifier circuit could supply current in the load circuit upto a maximum of 3 amperes.

6.5.7 Control Winding Of SCPT:

The control winding current was supplied from a separate d.c. source. The value of the control current could be varied manually with the help of a variable rheostat in the control circuit. For automatic voltage control of the generator voltage the control winding could be connected to an a.c. voltage regulator in a manner discussed in para 4.2.

The schematic diagram of static excitation system for single phase, 240 W, 80 V, 1200 cycles alternator is shown in Fig. 6.3.

6.6. Tests on the performance of Static Exciter:

6.6.1 Steady-State Performance:

First the static excitation circuit is tested under steady state to determine the amount of compensation provided by this system. Values of load curves for purely resistive, 0.8 power factor lagging and 0.8 power factor leading load are recorded in Table VII.

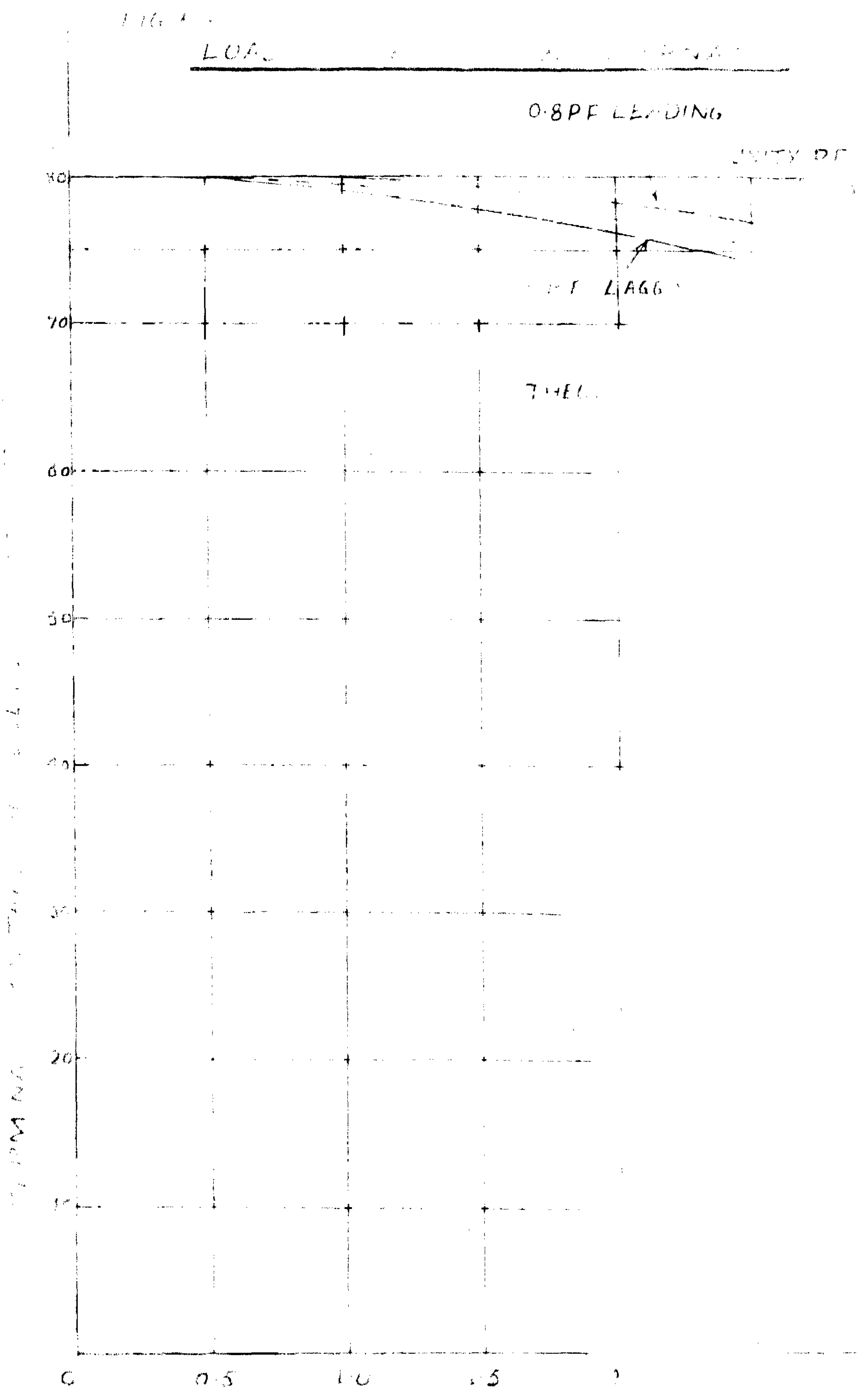

0·8PF LEADING
PF LAGG
30
70
60
50
40
30
20
0
0·5
1·0
·5
LOAD CURRENT IN A

TABLE VII

Load Curves Of 1-Phase, 240 W, 80 V, 1200 c/s, Alternator when statically excited as shown in Figure 6.3.

Speed = 2770 rpm.

Control Current I_c = 0.75 Amperes.

Purely Resistive Loading		0.8 PF lagging, load		0.8 PF leading load	
I, (Amps)	E_t (Volts)	I, (Amps)	E_t (Volts)	I, (Amps)	E_t (Volts)
00	80.0	00	80	00	80
0.6	79.6	0.5	79.8	0.8	79.8
1.5	78.2	1.4	78.3	1.6	79.0
2.1	76.6	2.0	76.0	2.2	77.8
2.6	75.0				
3.0	73.0	2.8	73.0	2.9	75.8
3.4	71.0	3.45	68.5	3.5	72.4

The load curves of the alternator are plotted from Table VI in Fig. 6.4. To compare the performance of the static excitation circuit with that of the separately excited system, the load curves of the same alternator when separately excited were taken and recorded in Table VIII.

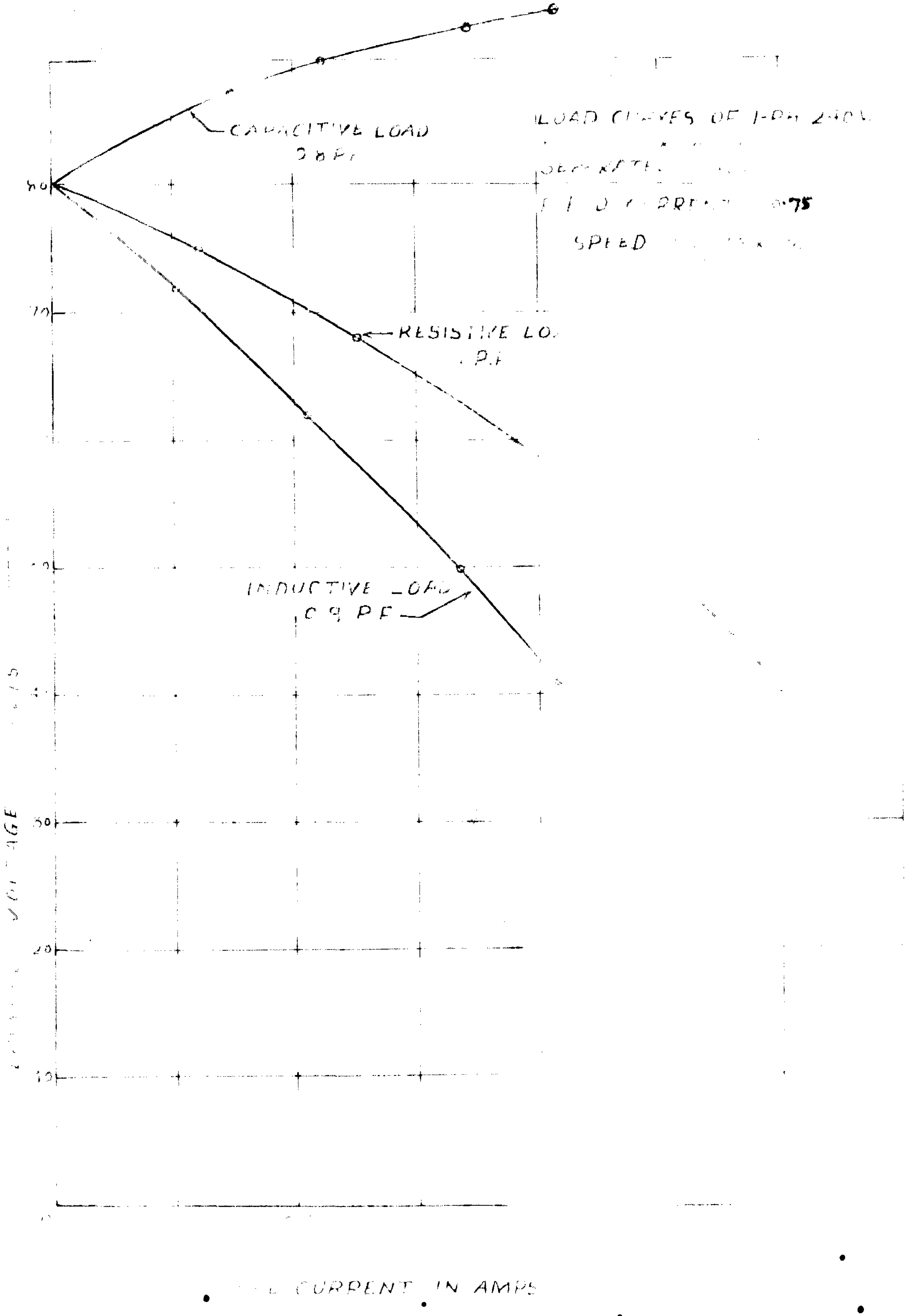

LOAD CURVES OF 1-PH 240V
SEPARATELY
FIELD CURRENT 0.75
SPEED
CAPACITIVE LOAD
0.8 P.F
RESISTIVE LOAD
P.F
INDUCTIVE LOAD
0.9 P.F
80
70
30
20
10
VOLTAGE
CURRENT IN AMPS

TABLE VIII

Load Curves Of 1-phase, 240 W, 80 V Alternator when separately excited.

Field Current = (Constant) 0.75 A

Speed = 2770 rpm.

Purely Resistive Load		0.8 PF Lagging Load		0.8 PF Leading Load	
I (Amp) ×2	E_t (Volt)	I (Amp) ×2	E_t (Volt)	I (Amp) ×2	E_t (Volt)
00	80	00	80	00	80.0
0.24	75	0.20	72	0.30	87.5
0.50	68	0.42	62	0.44	90.0
0.84	57	0.67	50	0.68	92.5
1.12	50	0.83	41	0.82	94.0
		0.99	31		

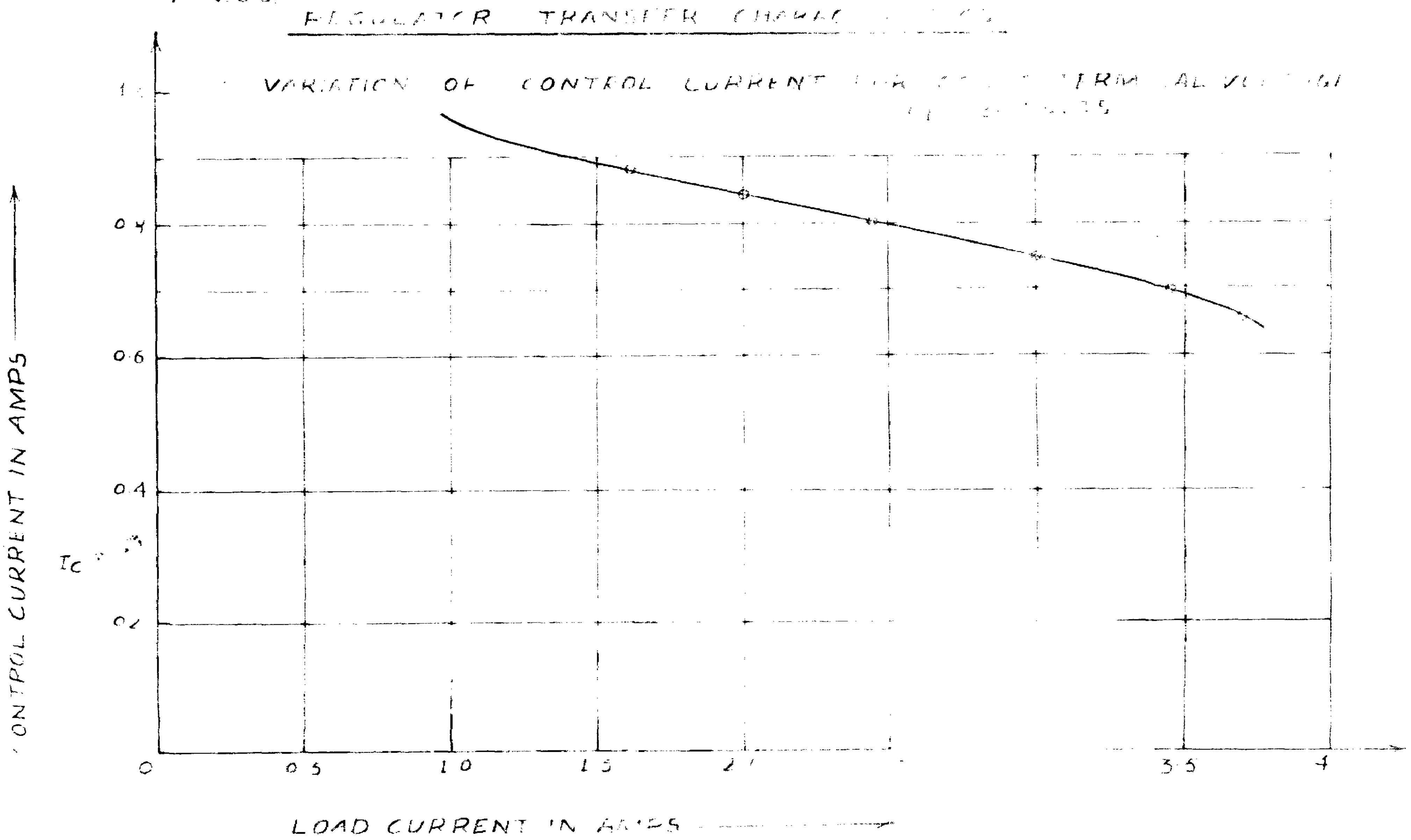
From Table VIII the load curves of alternator when separately excited are plotted in Fig. 6.4. The comparison of the load curves of Fig. 6.4 and Fig. 6.5 indicates that inherent compensation for voltage drop under all load conditions is achieved when statically - excited. Curves of Fig. 6.5 indicate that under lagging power factor the terminal voltage of the alternator drops very rapidly and under leading power -

-factor the terminal voltages rises. This means that if the alternator is separately excited there is very large drop in terminal voltage and as such very high gain voltage regulators shall be needed and stability of the system would impose severe problems. Stability of the system improves if the alternators are statically excited.

Further the curves of Fig. 6.4 indicate that the terminal voltage does not remain absolutely constant as it should have been as discussed in chapters II and III. The reasons for this are:-

1. With the static exciter of Fig. 6.3 no automatic voltage regulator was used to supply controlled direct current to the control winding.
2. It was assumed that reactors have negligible winding resistance and core loss. Also leakage reactance, winding resistance and core loss of SCPT are assumed to be negligible.
3. Armature resistance of the alternator was assumed to be zero.
4. Also due to the effects of magnetic saturation of the generator, changes in field resistance with temperature and inability to design the power components precisely, the exciter does not furnish exactly the required excitation under all loads and conditions.

FIG. 6.6.


REGULATOR TRANSFER CHARAC
VARIATION OF CONTROL CURRENT
CONTROL CURRENT IN AMPS
Ic
0
0.2
0.4
0.6
0.8
1.0
0.5
1.0
1.5
3.5
4
LOAD CURRENT IN AMPS

6.6.2 Regulator Transfer - Characteristic:

The terminal voltage of the alternator is maintained at 80 volts by varying the control current on loading the alternator by resistive load. A set of observations between the load current of the alternator and the control current is taken as indicated in Table IX.

TABLE IX

Observations For Regulator - Transfer Characteristic.

E_t = 80 volts

Speed = 2770 rpm.

I (Amp.)	I_c (Amp.)
1.08	0.87
1.6	0.84
2.0	0.82
2.45	0.80
3.0	0.75
3.45	0.70
3.7	0.63

From Fig. 6.6, it is clear that if the voltage regulator has such a characteristic that when the load on the alternator increases, its terminal voltage drops, the direct current supplied to the control winding of SCPT from the regulator should decrease so that alternator voltage may tend to remain constant. Conversely when the load current decreases, alternator voltage would increase and the direct current supplied to the control winding of SCPT should increase to make the alternator voltage constant. The magnetic amplifier voltage regulator is preferable for voltage regulation of synchronous machines due to the following special features:-

1. No moving parts
2. Maintenance free-operation
3. Long life
4. Ease of matching
5. Quick response
6. Higher over load capacity.

6.6.3 Transient - Performance:

The oscillograph in Fig. 6.7 was taken when 1-phase, 240 W, 80 V, 1200 cycles alternator was suddenly loaded to rated load from no load. The steady state voltage equal to 73 volts was attained in a few cycles and the field current rose to 0.95 amperes from 0.35 amperes.

The oscillograph in Fig. 6.8 was taken when rated load at rated speed from 1-phase, 240 W, 80 V, 1200 cycles alternator was suddenly thrown off. The field current of 0.95 amperes

Fig. 6.7. Application of Full Load on Unity P.F, At 1200 cycles, to 240 W, 80 V - Generator.

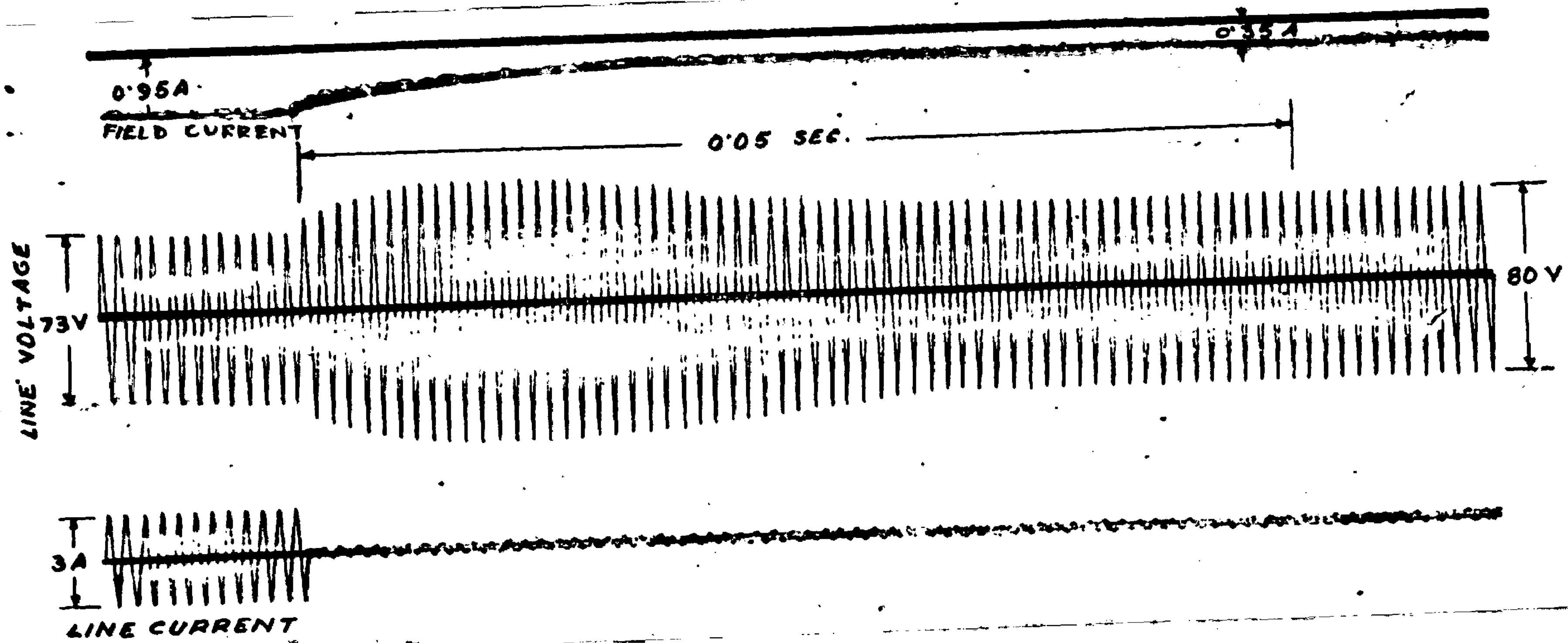


Fig. 6.8. Removal of Full Load, Unity P.F, At 1200 cycles

From 240 W, 80 V- Generator.

drops to 0.35 amperes in a few cycles and the terminal voltage rises from 73 volts to 80 volts.

CONCLUSION

The static excitation system for a.c. generators is better than usual conventional or rotating exciters as it permits flexibility of installation, produces simplicity in the a.c. generator design and provides excellent reliability and performance.

The static excitation system which was established for 1-phase, 240 W, 80 V and 1200 cycles alternator in the Electrical Engineering Department, University of Roorkee, could not be a perfect system due to the limitations of non-availability of better steel laminations for fabricating the SCPT and also due to the non-availability of an automatic voltage regulator. Yet the experimental results obtained closely tally with the theoretical results discussed. The SCPT acts as an impedance matching member between the generator output and the generator field. Also the SCPT combines voltage and current quantities in the correct proportion and controls magnitude of the resultant field current in the generator by means of d. c. saturation. As such inherent compensation for the voltage drop ΔE is obtained under all conditions of loading.

The other type of static exciter is electronic main exciter. In this system ignitron type of power rectifiers are used. Its use as main exciter for synchronous machines has been limited because it costs more than a conventional main exciter. Also it needs costly control, protective and regulating equipment. Further the ignitron and thyratron tubes in the electronic exciter are subject to deterioration and eventual failure and replacement.

Modern a.c. generators are capable of continuous operation over long periods without being shut down for maintenance. It is necessary, therefore that excitation system be capable of similar operation and that wearing parts be replaceable without requiring shut down or even unloading. The static exciters as discussed in Chapters II, III and IV possess the special advantage of being absolutely self contained and independent of separate energy sources, which in starting requires neither switching nor any special attention from the operator, which contains only static components, which needs no maintenance, which has an almost unlimited life and an easily understandable circuit design.

One objection to the static exciter circuit is due to high rectifier reverse voltage, which can be caused by a lightning stroke, an out of synchronism condition or a sudden short circuit on the alternator terminals. However each diode is shunted by a resistor and a capacitor to protect against excessive reverse voltage.

Further, the other reason for the choice of the static excitation system is the transient performance. When a sudden load surge occurs a magnetic flux component proportional to the load current is also produced at the first instant, thus causing a voltage of ample magnitude to build up the field without any delay. This voltage forces the current in the pole wheel to increase rapidly. The exciter current reaches its new steady state value within a few cycles. The exciter response achieved by this arrangement can not be obtained by normal exciter equipment using mechanical or magnetic regulators. Recent technologi-

-cal advances made in the field of improved semi-conductor rectifiers, better steels for use in magnetic amplifiers saturable reactors and the introduction of the silicon zener diode references for voltage regulators shall further improve the performance and increase the application of static-exciters.

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Lane, L.J., Rogers, D. F. and Vance, P. A. .. Design and Tests of a Static Excitation System for Industrial and Utility Steam Turbine Generators.