STATIC EXCITATION FOR A SYNCHRONOUS GENERATOR

A Thesis

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Master of Science in Electrical Engineering

By

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ABSTRACT

The design of a static excitation system used to regulate the terminal voltage of a small synchronous generator is presented. Considerable attention is paid to details of the control circuit to facilitate understanding of the system.

An examination of the existing literature dealing with static excitation units for industrial and utility systems was carried out. Some of the current ideas are presented herein to widen the scope of the study.

PREFACE

In order to provide a well-regulated high voltage D.C. supply for testing purposes at the University of Manitoba, a well-regulated low level A.C. voltage supply was required to be fed to two cascaded 220 KV rectifier transformers. It was suggested that a solid state excitation system be built to regulate the terminal voltage of a 12.5 KVA, 220 volt synchronous generator located in the Fetherstonhaugh High Voltage Laboratory.

The decision to build a static excitation system, rather than the conventional rotating machinery type, was prompted by interest in the static exciters being built for utility generating units. Although the requirements for the larger exciters are different in some respects, many similarities exist. An attempt has been made to explain any differences in the design and functions.

Although non-linearities exist in the excitation system, many of the control components have been analyzed mathematically to facilitate better understanding of the system. The ultimate aim of the project has been to construct a workable excitation system. A theoretical analysis was carried out first, with necessary practical modifications being made later.

Thanks are extended to Professor M. Z. Tarnawecky for suggesting the problem and for correcting the first draft, and to the National Research Council for its financial support.

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CHAPTER I

INTRODUCTION

1.1 GENERAL

The recent development of electrical power sources distant from load centres has resulted in increases in both the power transmitted, and the length of transmission line involved. These advances have demanded that more attention be paid to the problem of power system stability. Transmission costs are now a more significant percentage of total system costs, and every method possible should be used to utilize fully the capital investment involved. On long distance transmission lines, system stability rather than load carrying capability is the critical factor. Factors affecting the stability limit of a synchronous generator are initial loading and voltage of the generator, reactances of the generator and interconnected power system, generator inertia, type of fault selected as a design criterion, and the nature of the excitation system. It is the excitation system which is of concern in this thesis.

Recent developments in the excitation systems have been prompted by the higher levels of excitation voltage and power required, and by the need for improved generator and exciter operation. High performance excitation systems utilizing silicon-controlled rectifiers and solid state controls make possible significant improvements in power system performance. Although the major benefit of a solid state or static exciter is improved system stability due to the rapid control response, other advantages include:

1. High efficiency: a figure of 96% can be expected in comparison with 90% for a conventional rotating type.

2. Greater reliability: solid state equipment has no moving parts and, hence, eliminates the maintenance problems associated with the bearings, brushes, and commutators of conventional rotating exciters. Less maintenance increases the availability of the exciter and decreases the loss of revenue due to shutdown for maintenance.

3. Maintenance under load can be carried out with solid state components.

4. Elimination of the shaft driven exciter may result in a reduction in height of hydraulic plants and a small reduction in generator bearing costs in both hydraulic and steam plants.

Since it was not possible to demonstrate the effects of static excitation on an actual power system, it was decided to build a static exciter for a 12.5 KVA, 220 volt synchronous generator, whose characteristics are contained in Appendix A, page 65. The function of the exciter is to regulate the generator voltage at any set level between 0 and 220 volts. Two phases of the generator provide voltage for two isolating transformers, which, in turn, supply two rectifier transformers cascaded to give 440 KV D.C. Since the synchronous generator is driven by an induction motor, its speed varies with both loading and line voltage fluctuations. Therefore, the regulation system that was designed had to be frequency independent.

The high speed and forcing capability of static exciters allow them to be used on a power system as stability regulators rather than normal voltage regulators. Since voltage control of the generator is the chief function of the excitation system in this application, the following criteria should be considered:

1. Accuracy: voltage error at any level of loading.
2. Speed of response and overshoot: upon sudden application or withdrawal of load, it is desirable to restore the terminal voltage to the specified value as soon as possible. Voltage changes due to speed fluctuations must be quickly remedied.
3. Reliability: this includes the need to make periodic adjustments to reference settings in order to compensate for drift in components.
4. Economics and simplicity of construction and operation.

Since the function of the exciter used in long distance transmission systems is to improve system stability, rather than accurately control terminal voltage, its construction and operation will of necessity be different, although many of the underlying fundamentals are the same. Not only must it correct the effects of small dynamic disturbances, but it must also preserve stability under major fault disturbances. The more complex arrangement of the excitation system for power system applications will be discussed further in Chapter 5.

1.2 CONTROL SYSTEM CONCEPTS

The voltage regulator system can be reduced to the simple block diagram shown in Figure 1.

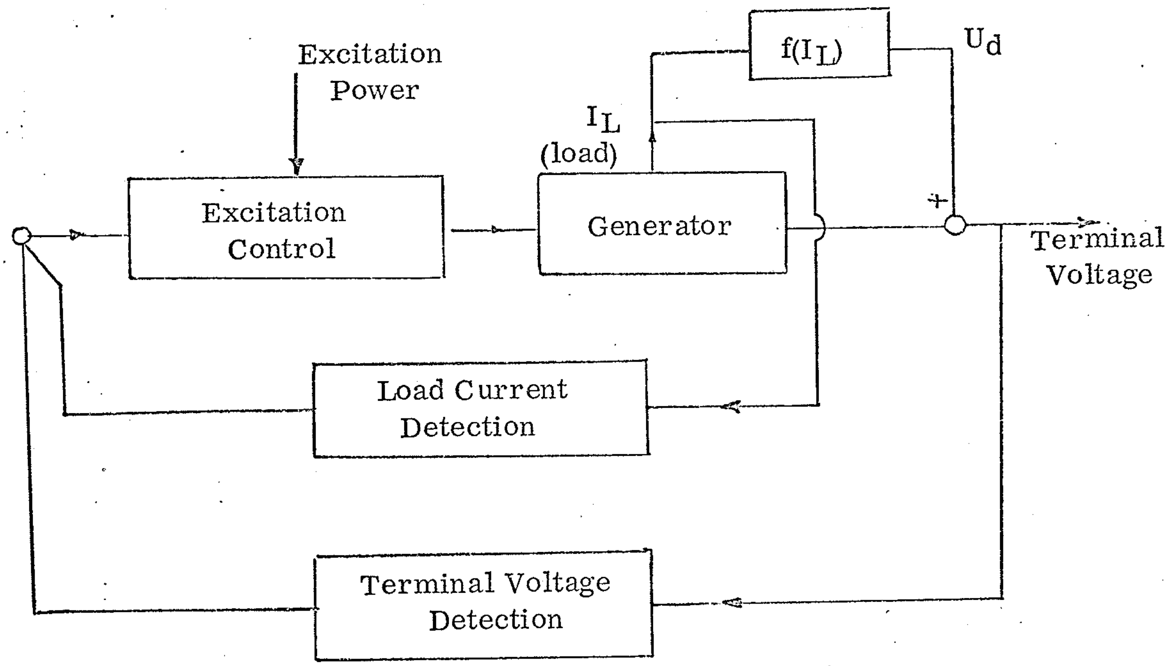


FIG. 1 FEEDBACK CONTROL SYSTEM

As mentioned, the purpose of the system is to maintain constant terminal voltage regardless of load and speed fluctuations. The main disturbance of concern is the load current, which causes a change, U_d, in terminal voltage due to its demagnetizing effect and the internal voltage drop of the generator. Signals proportional to load current and terminal voltage are used as feedback signals to maintain constant terminal voltage.

The desirability of detecting any change in the terminal voltage as quickly as possible is obvious, so delays in the detection circuit must be minimized. If voltage feedback only were used, increasing the gain of the feedback loop would mean greater sensitivity to error and hence more effective corrective action. The ideal regulator is one with very high feedback gain and zero time lag. An optimum value of gain exists, though, since too low a gain means that the full capacity of the regulator is not being utilized, and too high a gain results in instability. The current feedback must be classified as compensating action rather than control action, since its action doesn't depend on the terminal voltage deviation.

The generator itself has an inherent time lag due to the inductance of its field winding, and this characteristic is fixed by the machine design. Further delay in the corrective action could be caused by the forward control elements. Although a complete model of the system is not presented, values of the time lags encountered in various parts of the circuit are given in later chapters.

CHAPTER II

EXCITATION SYSTEM CONTROL ELEMENTS

2.1 GENERAL

Control of a synchronous generator's terminal voltage can be accomplished by regulating the generator speed or the excitation. Since fixed frequency is usually required, excitation control is the only practical method of controlling voltage. There are many solid state circuits which can supply a controlled D.C. voltage to the generator field. One of the simplest and most economical circuits is a phase - controlled silicon-controlled rectifier (henceforth referred to as an SCR) in series with a full-wave diode bridge rectifier. "Phase control is the process of rapid on - off switching which connects an A.C. supply to a load for a controlled fraction of each cycle."[7] By changing the firing angle of the SCR, the D.C. voltage applied to the field can be varied according to the formula:[4]

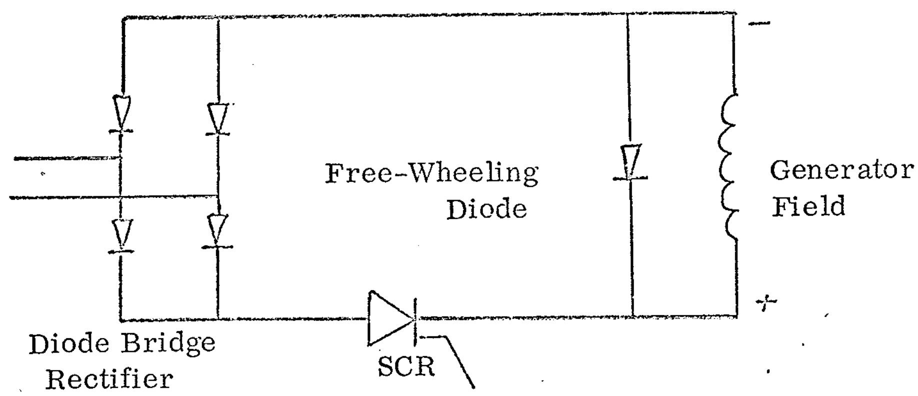
$$E_{dc} = \frac{E_m}{\pi} (1 + \cos \alpha) - \frac{E_o}{\pi} (\pi - \alpha)$$

where E_m = peak value of the A.C. voltage supplied to the bridge rectifier

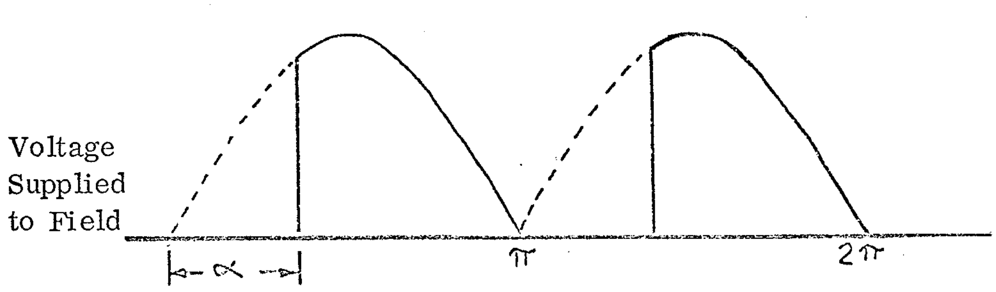
α = delay angle (varies from 0° to 180°)

E_o = voltage drop across SCR in its conducting state

Figure 2 shows the excitation system and the voltage applied to the field. The small voltage drop, E_o, across the SCR in its conducting state can be ignored. The free-wheeling diode is required for successful operation of the SCR with an inductive load. Its operation will be explained later.



2(a) Field Supply Circuit



2(b) Field Voltage Waveform

FIG. 2 GENERATOR FIELD SUPPLY

The generator field is rated at 64 volts and 6.2 amperes, (see Appendix A, page 65). To improve the transient response of the generator it is desirable to have an available ceiling voltage higher than the rated voltage of the field. Ceiling voltage is defined as "the maximum voltage that may be attained by an exciter under specific conditions."[29] Calculations carried out in the appendix indicate how the transient current response of the field is affected by ceiling voltage. Normal procedure is to choose a value of ceiling voltage, and then calculate the A.C. voltage required to give this value. Since line voltage of 120 volts was readily available, calculations were carried out to see what field current this would provide. The field current is given by:

$$I_{dc} = \frac{E_m}{\pi R} (1 + \cos \alpha)$$

R = field resistance - measured to be 8.6Ω

When the SCR conducts for the full half cycle, $\alpha = 0^0$ and $I_{dc} = \frac{120\sqrt{2}}{\pi\ (8.6)} (1 + 1)$ = 12.5 amps. Since the maximum available field current is applied only under transient conditions, the field winding is capable of the short time overload.

It should be clarified why an external source was chosen to supply the excitation power rather than the unloaded phase of the generator, rated at 127 volts to neutral. The main reason is that the terminal voltage was to be varied between 0 and 220 volts. The control analysis would become unnecessarily complicated if both the firing angle and the applied A.C. voltage were variable. Some error in generator terminal voltage could be expected due to fluctuations in the line voltage, but these disturbances were expected to be infrequent.

2.2 OPERATION OF THE SCR

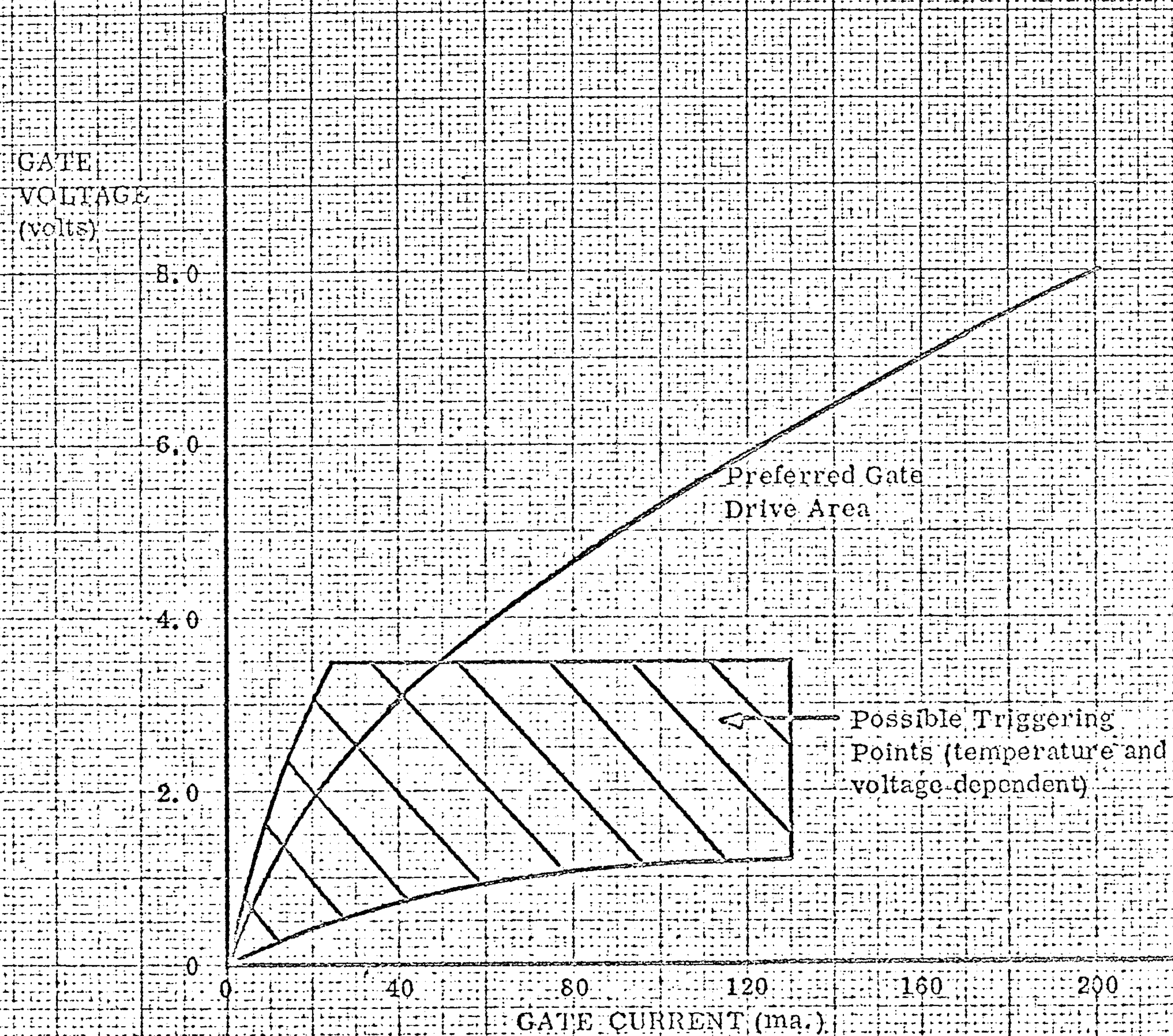
The SCR is a bistable, semi-conductor switch which blocks forward current until a positive triggering signal is applied to its gate to initiate conduction. If the forward anode current reaches a magnitude called the latching current, the SCR will conduct even after the gate signal has been removed. Conduction continues until the anode current drops below a value called the holding current. With reverse voltage applied, the SCR behaves like a semiconductor diode.

The SCR can be fired unintentionally by means other than the application of a gate signal. A sufficiently high anode voltage will cause avalanche breakdown and send the SCR into conduction even without a gate signal. The SCR should be operated well below the forward breakover voltage.. Due to the internal junction capacitance of the SCR, capacitive current will flow according to the relationship, $i = C\, dv/dt$. Large transient voltage surges may cause the current to reach the forward breakover value. A dv/dt withstand capability must be specified for each SCR in order to prevent such an occurence.

The SCR chosen for this application was a Philips BTY87-300R, rated at 16 amps (r. m. s.). Gate characteristics and other data for the BTY87 series are given in the appendix. Since the characteristics provided give a range of possible values, the characteristics were measured for the particular SCR chosen. Tests were carried out to determine the dependence of the firing point on the anode voltage. The required firing voltage was found to be virtually independent of the anode voltage, although very low anode voltages (less than 10 volts) required slightly higher trigger values. The gate charac-

GRAPH 1 GATE CHARACTERISTICS

(Philips BTY87-300R)



teristics were taken with zero anode voltage, and, although they indicate static values, the curve is valid for pulses down to a fairly short duration.

The cross-hatched area shown in Graph 1 indicates possible triggering points which are a function of junction temperature and, to some extent, anode voltage. For example, on the gate characteristics in Appendix B, there is indicated a minimum value for the gate voltage required to trigger all SCR's in the BTY87 series. Also shown is the minimum gate current required to trigger the SCR. This limiting value is a function of the junction temperature. To avoid dependence of firing on temperature and anode voltage, it is best to have the triggering point outside the shaded area in the "preferred" gate drive area.

2.3 "TURN - OFF" OF THE SCR

In order to maintain control of the field voltage, the SCR must be turned off at the end of each half cycle. In a resistive load, the current is in phase with the voltage. When the anode voltage drops to zero, the anode current drops below the holding current value, and the SCR switches off.

When the load is highly inductive, as is the case with the generator field, turn-off is not as simple. Because of the stored electromagnetic energy, current still flows when the anode voltage goes to zero. When the next half cycle of positive voltage is applied to the SCR, it conducts immediately and control of the SCR is lost. A free-wheeling diode placed across the load, as in Figure 2, Page 7, will preserve control of the SCR. An inductive voltage equal to L di/dt is created across the field with polarity opposite to that of the applied voltage. When the inductive voltage becomes greater than the decreasing applied voltage, the positive voltage across the diode causes the diode to conduct. Since a path for the field current is thus provided, the SCR current drops to zero, and the SCR switches off.

The fact that the current drops to zero is not sufficient to ensure turn-off of the SCR. Since the base regions of the SCR are still saturated with minority carriers, a negative voltage must be applied to bring about recombination of the minority carriers. When this is accomplished, the SCR again blocks forward voltage, i.e., control is regained. The output voltage of the diode bridge rectifier swings negative for a short duration due to the recovery time of the diodes. This ensures that the blocking state of the SCR is restored.

The current rating of the free-wheeling diode is given by the expression:[1]

$$I = 0.16 \left(\frac{2E}{\pi R}\right)$$

where E = peak value of applied A.C. voltage = $\sqrt{2}(120)$ volts

R = field winding resistance

therefore $I = 2.0$ amperes

It should be noted, however, that this rating represents the average current through the diode. The diode is required to switch into the full rated field current of 6.2 amps (higher values under transient conditions). The diode must have a sufficiently high rating to withstand the peak values of field current. A diode rated at 10 amperes is used to give a measure of safety.

2.4 TRIGGERING CIRCUIT FUNDAMENTALS

The scheme chosen to fire the SCR must satisfy the following requirements:

1. It must be capable of firing the SCR for a wide range of anode voltage (especially at the low voltage at the beginning and end of each half cycle).

2. The triggering pulse must be long enough to permit anode current to build up to the latching value.

3. Timing for the triggering circuit must be synchronized with the line voltage applied to the SCR.

To permit the exciter to be adaptable to automatic feedback control, it was necessary to have a control system which responded to electrical signals. A unijunction transistor circuit which offered the following features was chosen:

1. Low firing current and stable triggering voltage

2. High power gain

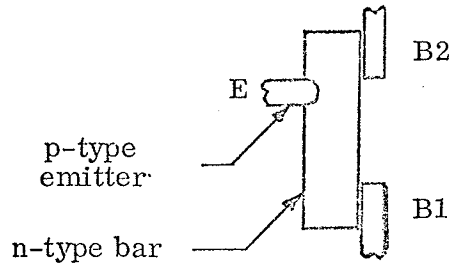
3. High pulse capability

4. Economy

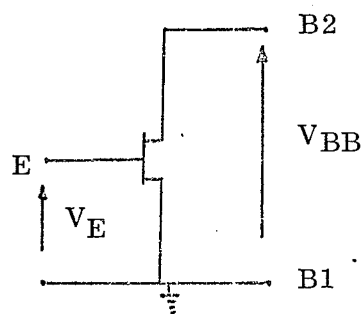
5. Simplicity and compactness.

Physically, the unijunction transistor (referred to as a UJT, see pages 14 and 69), is a bar of n-type silicon with ohmic contacts B_1 and B_2 at opposite ends of the bar. A p-type rectifying contact on the side of the bar close to B_2 forms the emitter contact. A positive voltage is applied to base two (B_2) with base one (B_1) grounded.

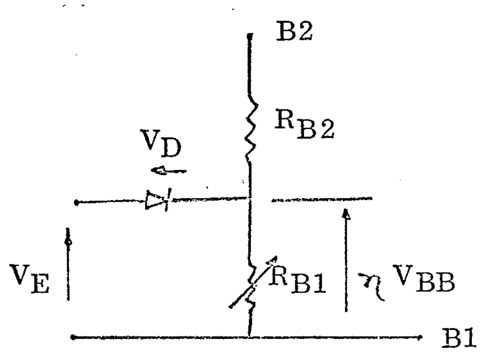
The UJT is a voltage-ratio activated device. With no emitter current flowing, the UJT acts as a voltage divider, with a certain fraction η (called the intrinsic stand-off ratio) of the interbase voltage V_{BB} appearing at the emitter. Refer to Figure 3, Page 14, for the UJT's symbol and equivalent



3(a) Physical Representation



3(b) UJT Symbol



3(c) Equivalent Circuit

FIG. 3 UNIJUNCTION TRANSISTOR

circuit. The emitter - base one junction, represented by a diode, is reverse biased until the emitter voltage V_E exceeds $V_D + \eta V_{BB}$. The diode voltage V_D is about 0.5 volts. Forward biasing of the junction causes holes to move from the emitter into the base one region, creating an equal number of electrons. The resulting decrease in resistance causes the emitter current to increase as the emitter voltage falls. The surge of current through a resistor connected to the B_1 contact provides a pulse which will trigger the SCR.

The fundamental principles of the UJT circuit used can be illustrated by considering the oscillatory circuit of Figure 4, Page 16. R_t is a variable resistance which affects the charging rate of capacitor C. When $V_E = \eta V_{BB} + V_D$ (denoted as the peak value V_P), the capacitor discharges through R_1, the emitter current limiting resistor, to provide a pulse which can be directly coupled to the SCR gate. When the capacitor voltage drops to a minimum value V_V, the emitter ceases to conduct and the capacitor can be recharged, repeating the cycle.

The diode voltage V_D has a negative temperature coefficient, while the interbase resistance R_{BB} (consisting of $R_{B1} + R_{B2}$ as shown in Figure 3) has a positive coefficient, resulting in an increase in V_{BB} with temperature. The net increase in V_P can be compensated for by the proper choice of R_2.

The actual circuit used to trigger the SCR is more complex, as shown in Figure 5, Page 17. The unijunction transistor selected is a Texas Instruments TIS43 whose measured parameters are $\eta = .81$ and $R_{BB} = 5.1\ K\Omega$. Specification sheets are contained in the appendix.

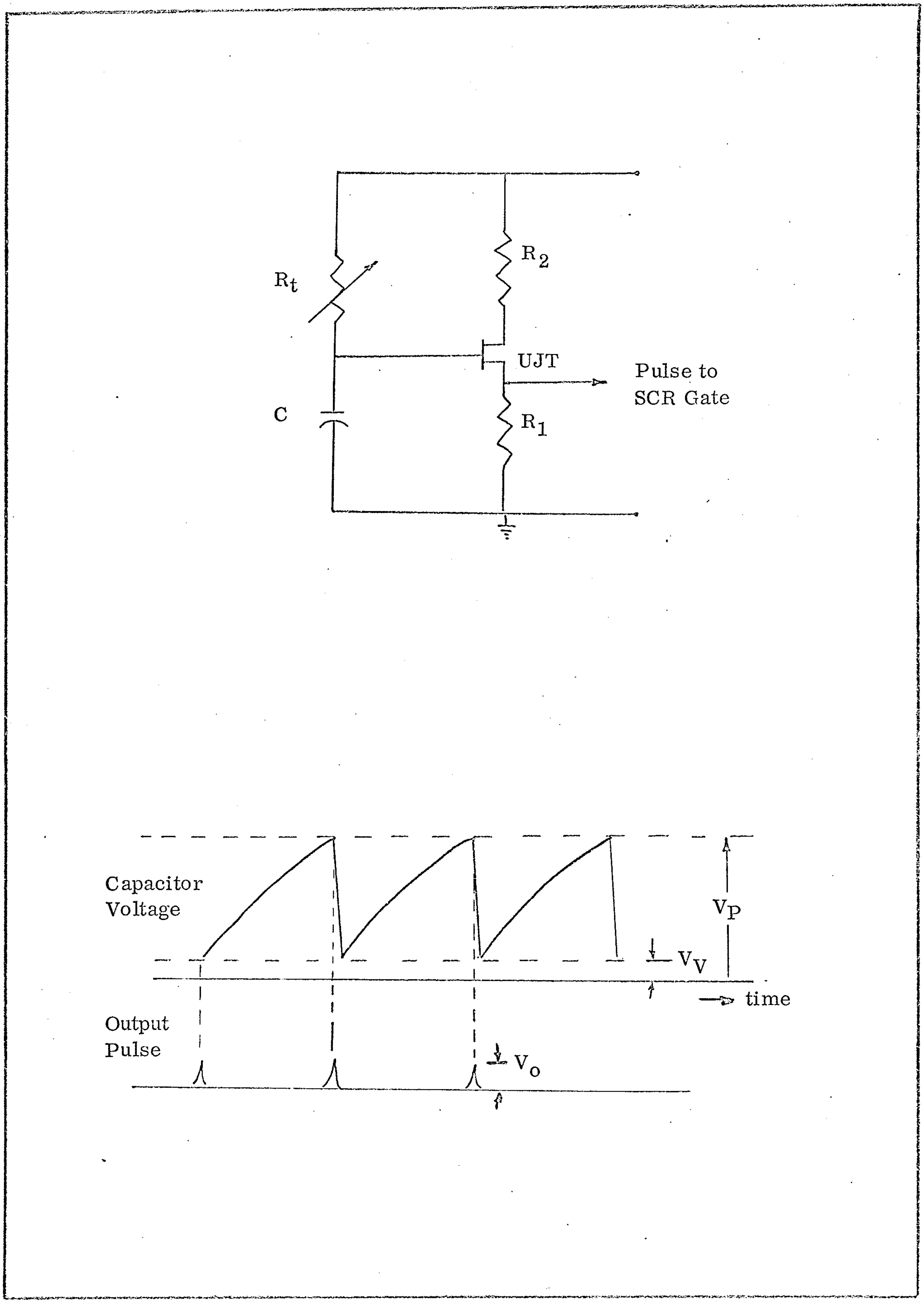


FIG. 4 BASIC UJT CIRCUIT

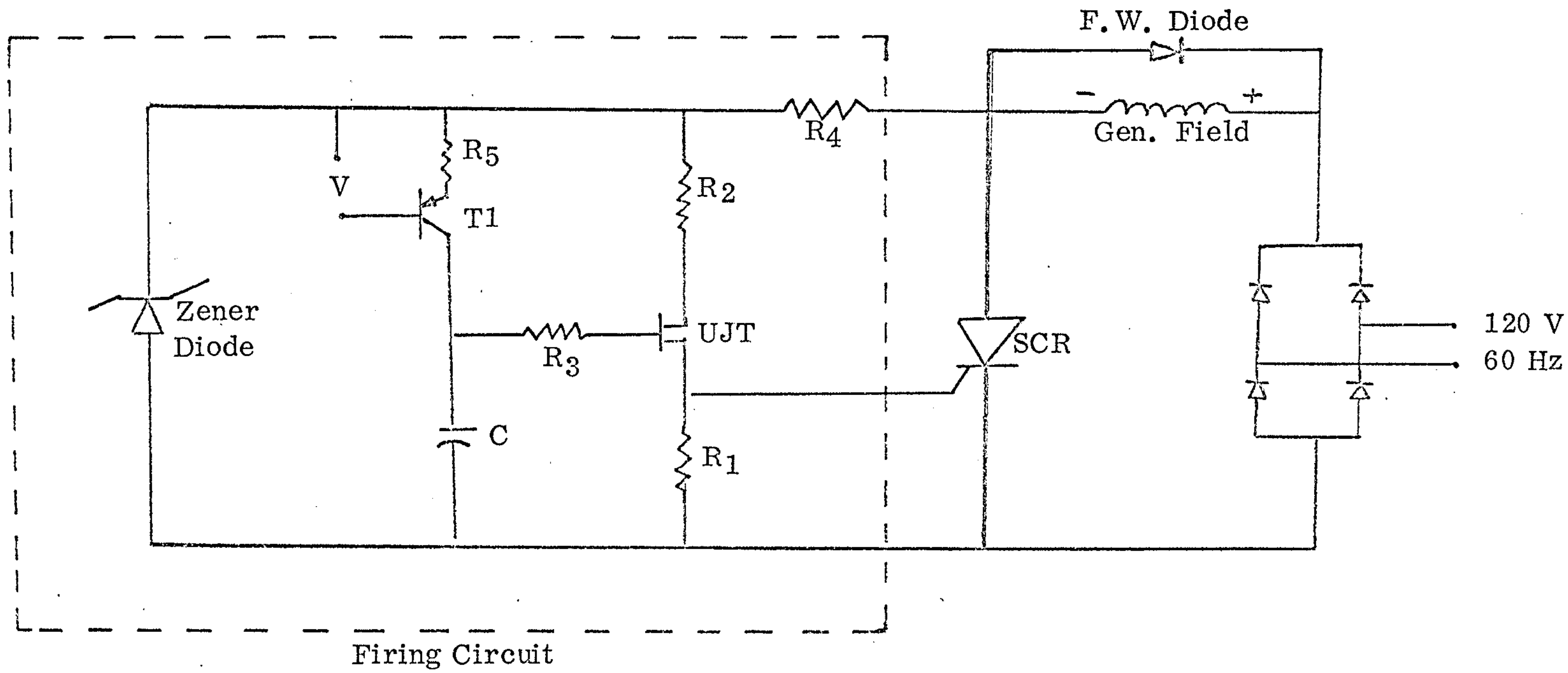


FIG. 5 FORWARD CONTROL ELEMENTS

Since the trigger signal must be synchronized with the SCR supply voltage, power for the trigger circuit is taken from the voltage across the SCR. In order to provide a constant voltage across the UJT for as much of the half cycle as possible (to simplify control), a Zener diode is placed across the UJT. The choice of the interbase voltage V_{BB} is limited on the high side by power dissipation, and on the low side by the required magnitude of the pulse to the SCR. Since a fairly large pulse is required by the SCR, the Zener diode is rated at 24 volts.

The following formula gives an approximate value for the temperature compensating resistor R_2:[27]

$$R_2 \cong \frac{0.4\ R_{BB}}{\eta\,(V_{BB})}$$

$$R_2 \cong \frac{0.4\ (5100)}{.81\ (24)} = 108\ \Omega$$

A 100 Ω resistor was chosen for R_2. Resistor R_1 is intended to limit the emitter current. Care must be taken to ensure that the stand-by voltage across R_1 is less than the maximum voltage that will not trigger the SCR. The leakage current through R_1 is given by:

$$I \cong \frac{V_{BB}}{R_{BB} + R_2} = \frac{24}{5100 + 100} \approx 4.5 \text{ ma.}$$

The maximum voltage that will not trigger the SCR at a junction temperature of approximately 100°C, is 0.3 volts. The maximum allowable value of R_1, then is:

$$\frac{0.3\ (1000)}{4.5} = 67\ \Omega$$

R_1 was selected to be 50 Ω.

Resistance R_4 must be placed in series with the Zener diode to limit the current after the diode breakdown. Ratings of the diode chosen are 24 volts and 1.5 watts.

Maximum allowable diode current $= \frac{1.5}{24} = 62.5$ ma

Peak voltage across $R_4 = 120\sqrt{2} - 24 = 146$ volts

Minimum value of $R_4 = \frac{146}{62.5} = 2.34\ K\Omega$

R_4 was chosen to be $2.4\ K\Omega$.

To provide adequate triggering at very small angles, or angles close to 180^o requires that the sine wave rise as quickly as possible to the Zener voltage level. Examination of Figure 5 reveals that R_4 attenuates the voltage applied to the Zener diode. The attenuation factor is given by:

$$K = \frac{R_1 + R_{BB} + R_2}{R_1 + R_{BB} + R_2 + R_4}$$

$$= \frac{50 + 5100 + 100}{50 + 5100 + 100 + 2400} = .686$$

Figure 6, Page 21, indicates how the period of constant UJT voltage is narrowed by the addition of R_4 to the circuit. Θ_1 and Θ_2 are the phase angles at which the level of 24 volts is reached for $K = 1$ and $.686$, respectively.

$$\Theta_1 = \arcsin \frac{24}{120\sqrt{2}} = 8.1^o$$

$$\Theta_2 = \arcsin \frac{24}{120\sqrt{2}\,(.686)} = 11.9^o$$

The range of control of D. C. voltage is limited to the period in which the UJT interbase voltage is constant at 24 volts. This places a limit on the minimum D.C. voltage that can be obtained. Consider the following rough calculation:

When $\Theta = 168^{\circ}$, $I_{DC} = \frac{170}{\pi(8.65)} (1 + \cos 168^{\circ})$

$$I_{DC} = .138 \text{ amps}$$

On the open circuit saturation curve of the generator (located in Appendix A), this corresponds to a terminal voltage of 14 volts. A lower field current could be obtained by firing the SCR at a phase angle greater than 168°, but the interbase voltage is less than 24 volts beyond this point, and analysis is much more complex. Firing the SCR at very small angles will occur only when the forcing ceiling voltage is required. The SCR will certainly fire at angles less than 12°, but here control analysis is also complex. It should be noted that $\cos 12^{\circ} = .979$, so that E_{DC} is very close to the maximum attainable D.C. voltage, E_{max}.

$$\text{i.e. } E_{DC} = \frac{170}{\pi} (1 + \cos 12^{\circ})$$

$$\frac{E_{DC}}{E_{max}} = \left(\frac{1 + .979}{2}\right) \times 100 \cong 99\% \text{ at } \alpha = 12^{\circ}$$

The use of a higher power Zener diode would permit a lower value for R_4, and a longer period of constant interbase voltage would be obtained. However, the additional two or three degrees obtained would probably not outweigh the extra cost involved.

2.5 TRIGGER CIRCUIT CONTROL SCHEME

Instead of using the manually controlled variable resistance in Figure 4, Page 16, to vary the charging rate of the capacitor, a current source was introduced which would respond to feedback control. The collector current of a p-n-p transistor, T1, shown in Figure 5, is controlled by the applied base-emiter voltage. In analyzing this control scheme, certain assumptions were made:

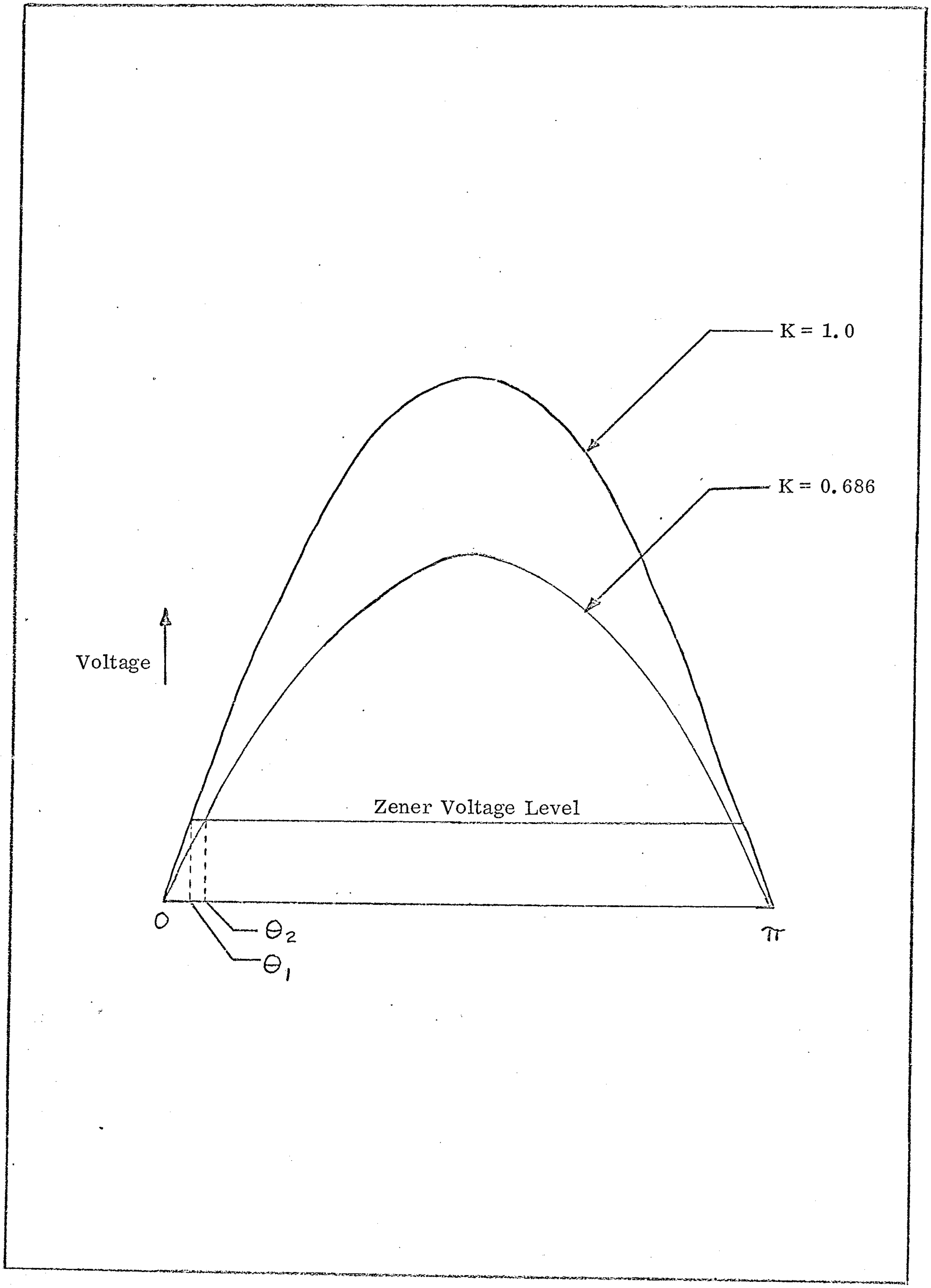


FIG. 6 ATTENUATION OF ZENER DIODE CURRENT LIMITING RESISTOR

1. The control voltage "v" was assumed constant over each half cycle.
2. Leakage currents in the transistor and capacitor were ignored.
3. The SCR switches on instantaneously, with no voltage drop across it while conducting, i.e., a perfect switch. This is reasonable since the switching-on time is in the order of microseconds and the drop across the conducting SCR is less than a volt.
4. The capacitor voltage was zero at the beginning of each half cycle.

The terms used in the following discussion are defined here:

v = control voltage applied to base of T1

q = accumulated charge on capacitor C

t = time in seconds from beginning of each half cycle

α = firing angle of the SCR

f = frequency of the supply voltage (Hz.)

ω = angular frequency = $2\pi f$

If the transistor T1 is operated in a heavily degenerate mode, the collector current is appoximately equal to the emitter current. The collector current is given by:

$$i_c = v/R_5$$

Since v, and hence i_c, is constant, the capacitor will charge at a uniform rate. When $V_c = \eta V_{BB}$ (neglecting the small diode voltage V_D), the UJT fires. At this time, $\omega t = \alpha$.

$$V_c = \eta V_{BB} = \frac{v \cdot t}{R_5 C} = \frac{v \cdot \alpha}{2\pi f R_5 C}$$

Solving, $\alpha = \dfrac{2\pi f R_5 C \eta V_{BB}}{v}$

$$\text{Recall that } E_{DC} = \frac{E_m(1+\cos\alpha)}{\pi}$$

$$\text{Hence, } E_{DC} = \frac{E_m\left[1+\cos\left(\frac{2\pi f R_5 C \eta V_{BB}}{v}\right)\right]}{\pi}$$

Still unspecified are the values of v and R_5. Since collector current, $i_c = v/R_5$, is the variable of concern, it would seem that any ratio of v/R_5 that gave the maximum desirable collector current would be satisfactory. However, examination of the portion of control circuit shown in Figure 7 reveals that the maximum allowable value for v is $(1 - \eta)V_{BB}$, and that there is, therefore, an upper limit for R_5.

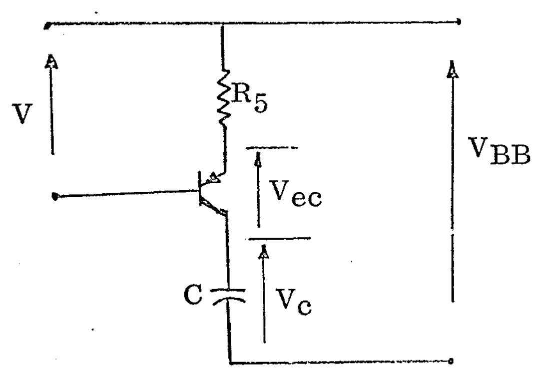


FIG. 7 PORTION OF THE CONTROL CIRCUIT

The following simplifying assumptions will be made:

1. If the voltage drop from base to emitter of T1 is ignored, all the applied voltage v appears across R_5.

2. Capacitor C discharges when $V_c = \eta V_{BB}$.

At the beginning of the half cycle, C is uncharged, so the potential drop from the emitter to collector is $(V_{BB} - v)$. As the capacitor charges, the emitter-collector voltage drops. When $V_c = V_{BB} - v$, the voltage $V_{ec} = 0$, and the transistor cuts off, i.e., collector current ceases to flow. Since the maximum voltage the capacitor can attain is $(V_{BB} - v)$, this value must be at least equal to ηV_{BB}, or the capacitor will not discharge and the SCR will not fire.

Hence, $\eta V_{BB} \leq V_{BB} - v$

Rearranging gives $v \leq (1 - \eta) V_{BB}$ as the upper allowable limit for v. In this case, with $V_{BB} = 24$ volts and $\eta = .81$, $v_{max.} = 4.56$ volts. Since a limit of 12^{o} was set as the earliest desired firing angle for the SCR, the maximum desired collector current is found from:

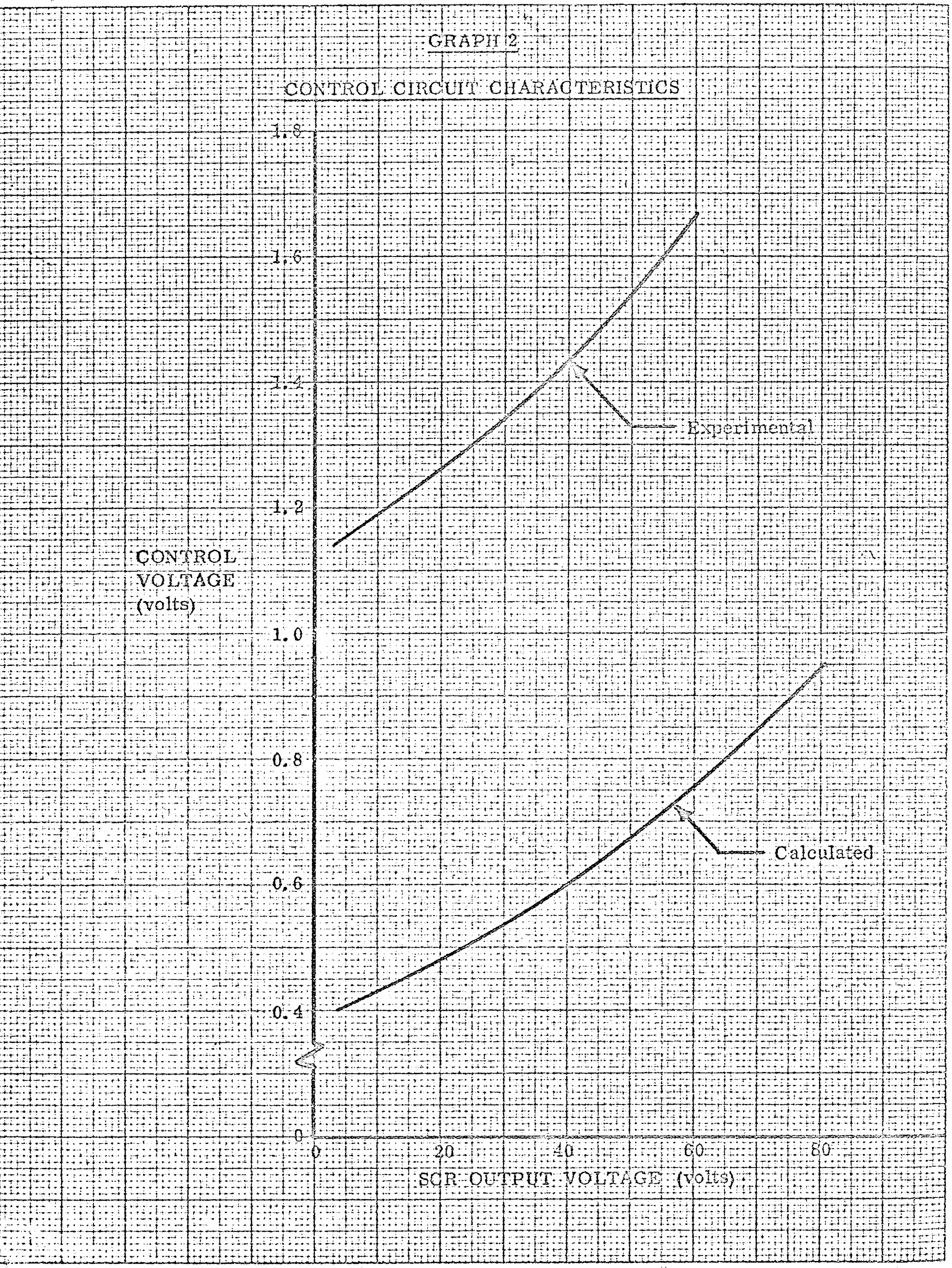
$$\frac{\pi}{15} = \frac{2\pi(60)\ (10^{-6})\ (.81)\ 24}{i_c}$$

$$i_c = 35.0 \text{ ma.}$$

$$R_5 = \frac{4.56}{35.0} \times 10^3 = 133\Omega$$

A 150 ohm resistor is used since some of the other measured values are approximate .

Graph 2, Page 25, compares the calculated and experimental curves of the control voltage plotted against the SCR D.C. output voltage (applied to the field of the generator). It is apparent that there is a great discrepancy between the two curves. The main reason for this is the voltage drop across the emitter-base junction, a factor which was not considered in deriving the transfer function. The drop was measured to be in the order of 0.75 volts. Using (v - 0.75) rather than v in the transfer function would give better correlation between the two curves. It is possible that the leakage currents cannot be ignored and that they contribute to the lack of agreement between theoretical and experimental values.



GRAPH 2
CONTROL CIRCUIT CHARACTERISTICS
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
CONTROL
VOLTAGE
(volts)
Experimental
Calculated
0
20
40
60
80
SCR OUTPUT VOLTAGE (volts)

Since the SCR can be considered to fire instantaneously, the only time lag involved in the firing circuit is the charging time of the capacitor. It is difficult to put a value on the time lag of the firing circuit, but it is apparent that the charging rate of the capacitor is affected immediately by a change in control voltage. Little error is involved in assuming that the firing angle of the SCR and hence, its output voltage, is changed immediately by a change in control voltage.

2.6 SYNCHRONIZATION OF TRIGGER CIRCUIT

It has been mentioned that the UJT is supplied from the same source as the SCR to ensure synchronization. One of the advantages of using the UJT circuit in this manner is that it automatically resets itself at the end of each half cycle. If, for any reason, the SCR does not fire during a particular half cycle, the voltage across the SCR, and, hence across the UJT, falls to zero at the end of the half cycle. If the capacitor has charged to any value, the capacitor voltage will eventually (before $\alpha = 180^{\circ}$) be greater than the voltage at the UJT emitter, and the capacitor will discharge.

Once the SCR has fired, the voltage drop across it is less than one volt. The interbase voltage V_{BB} is even smaller due to the attenuation of R_4. Examination of the circuit shows that the transistor's emitter-collector junction is reverse biased under these conditions, and the transistor cuts off. Since the control voltage is still applied, current will flow through the base rather than through the emitter. The capacitor will not charge and the circuit is set for the next half cycle of voltage.

CHAPTER III

FEEDBACK SYSTEM

3.1 CHOICE OF FEEDBACK SYSTEM

In order to have automatic or closed loop control in the excitation system, it is necessary to measure the magnitude of the generator terminal voltage. Comparison with a reference voltage provides an error signal which can initiate corrective action. The rapid response of the forward control elements has been discussed; the problem now is to provide as rapid an indication of error as possible. The method of detection chosen was rectification and filtering of the generator terminal voltage to produce a D.C. voltage proportional to the terminal voltage. Since only two phases of the generator are loaded, the three phase voltages are unbalanced. A single phase rectifier has to be used across the two loaded phases.

To avoid the time lag inherent in the filter circuit, the possibility of comparing the terminal voltage to an A.C. reference was considered. For such a scheme, it is essential that the reference voltage and terminal voltage be in phase at all times. The fact that an induction motor was driving the generator meant that the generator speed was a function of load. Although this obstacle could be overcome by using a shaft-mounted, 4-pole, A.C. tachometer generator as the reference source, another problem arose. The phase angle of the main generator with respect to a rotating axis varied with load, whereas that of the tachometer generator did not. No simple solution to this problem was apparent, and the advantages to be gained from an A.C. reference supply in this particular application, did not encourage further research in this direction.

3.2 DESIGN OF RECTIFIER AND FILTER

The requirements of the detector circuit are:

1. To change the A.C. terminal voltage to a D.C. voltage with small ripple.
2. To minimize the delay between a change in terminal voltage and the corresponding change in D.C. voltage.

The reduction of ripple and time lag are conflicting factors in the filter design. Minimization of ripple is essential to provide a sufficient degree of sensitivity in detecting error. The second factor may be the limiting factor in determining the speed of response of the excitation system.

The ripple factor is defined as the ratio of the r.m.s. value of the alternating components of the wave to the average, or D.C. value of the wave. The higher the order of fundamental ripple frequency that is attained, the more thorough is the filtering. With no filter present, a full wave bridge rectifier has a ripple factor of 48%, fundamental ripple frequency of 120 Hz, and a D.C. output voltage of $2E_m/\pi$, at no load. A half wave rectifier would give much greater ripple (121%) at a frequency of 60 Hz, making filtering much more difficult. Since a small current is to be drawn by the detector, a high resistance, 50 KΩ, was chosen as load. A capacitor input filter provides a high D.C. voltage and low ripple at light load. The capacitor placed across the load provides a low impedance path for harmonics. Since the fundamental ripple frequency is 120 Hz, the capacitor is chosen such that its reactance is $\ll$ 50 KΩ at that frequency.

$$\frac{1}{2\pi f C_1} \ll 50 \text{ K}\Omega$$

Therefore, C_1 should be much greater than .026 ufds. C_1 was chosen to be 10 ufds. An R-C section added between the input capacitor and the load resistor will further reduce the ripple, although it also attenuates the D. C. voltage, dissipates power, and increases the time lag of the circuit. The reactance of C_2 must be small with respect to R_1 in order to provide attenuation for ripple present across C_1. R_1 should be small with respect to R_2 so that attenuation of the D. C. voltage is not too great. An L-C section would also diminish the ripple, but is undesirable from the point of view of speed of response.

For a π-section filter, the value of the ripple factor is given by:[28]

$$r = \sqrt{2}\left(\frac{X_{C_1} \quad X_{C_2}}{R_1 \quad R_2}\right) \times 100\%$$

The capacative reactances are calculated at the fundamental ripple frequency of 120 Hz. The reactances will be less for the higher harmonics, so that higher frequency components of the ripple will be more effectively suppressed. If a half-wave rectifier had been used, the fundamental ripple frequency would have been one half as great, and the filter would only have been one quarter as effective in reducing the ripple voltage. The filter will not be effective in eliminating stray 60 Hz pick-up voltage.

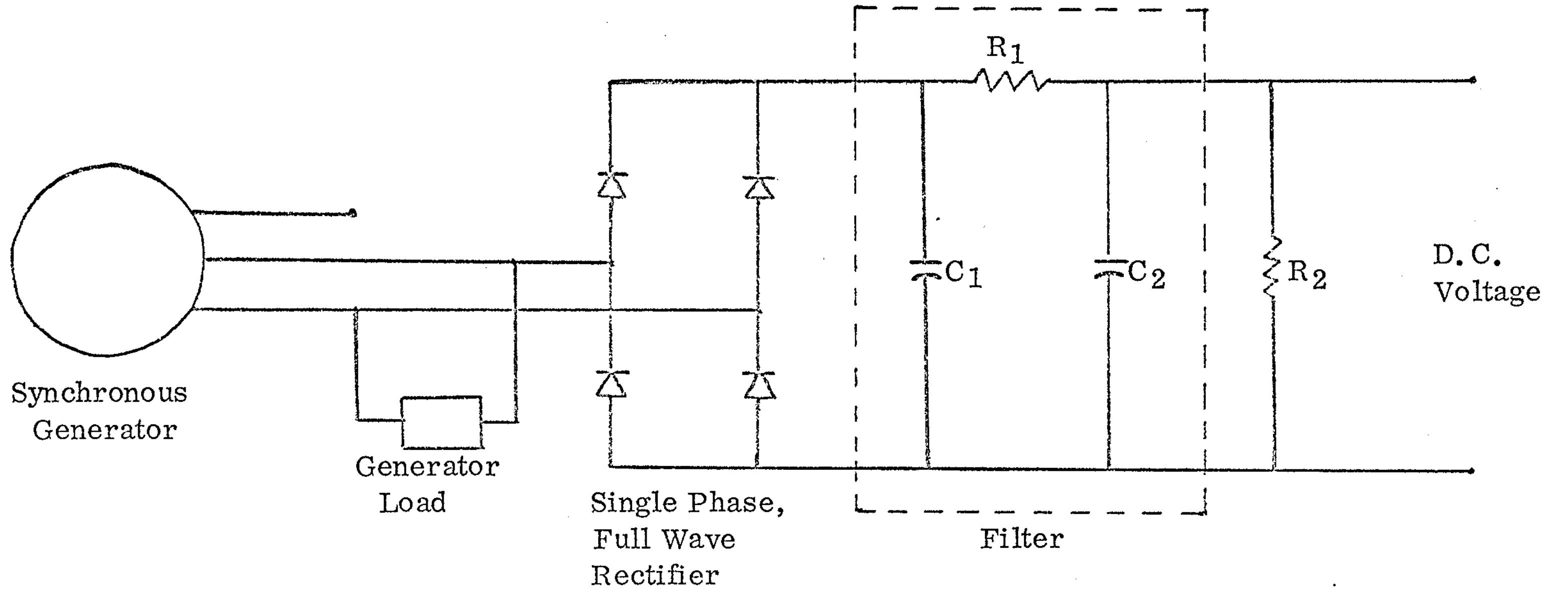


FIG. 8 DETECTION CIRCUIT

Still to be considered is the time lag involved in changing from A.C. to D.C. Deriving the transfer function of the detector circuit, and making appropriate simplifying approximations will give a good indication of the time lag. The rectifier will be considered as an ideal voltage source in series with an internal impedance R_o.

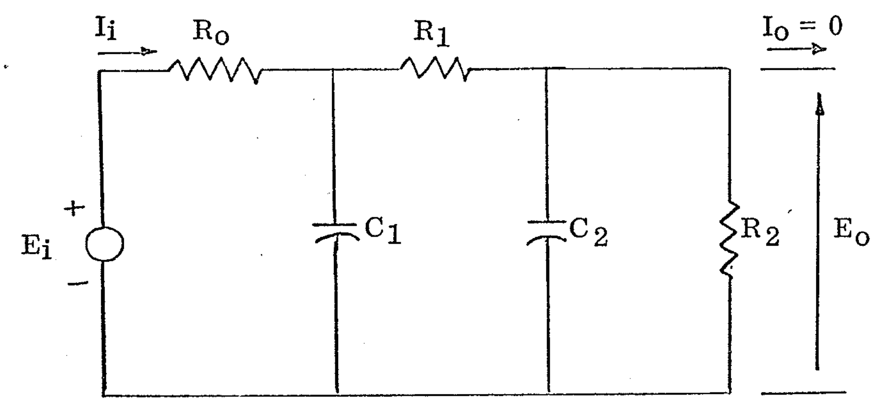


FIG. 9 REPRESENTATION OF DETECTOR CIRCUIT

Considering this as a ladder network, and using Laplace Transforms gives:

$$\begin{bmatrix} E_i \\ I_i \end{bmatrix} = \begin{bmatrix} 1 & R_o \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ sC_1 & 1 \end{bmatrix} \begin{bmatrix} 1 & R_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ sC_2 + 1/R_2 & 1 \end{bmatrix} \begin{bmatrix} E_o \\ 0 \end{bmatrix}$$

Of interest is the transfer function E_o/E_i, and, after some manipulation, this can be shown to be:

$$\frac{E_o}{E_i} = \frac{R_2/(R_o + R_1 + R_2)}{1 + s\left[C_1R_o\left(\frac{R_1 + R_2}{R_o + R_1 + R_2}\right) + C_2R_2\left(\frac{R_1 + R_o}{R_o + R_1 + R_2}\right)\right] + s^2C_1C_2\,\frac{R_1\,R_o\,R_2}{R_1 + R_o + R_2}}$$

Since the information desired from the transfer function was the time lag, it was desirable to try to represent the transfer function in the form $K/(1 + sT)$. The forward resistance of the diodes is very small compared to R_1 and R_2. The second term in the denominator of the transfer function becomes negligible, and the transfer function can be approximated as:

$$\frac{E_o}{E_i} = \frac{R_2/(R_o + R_1 + R_2)}{1 + s\left[C_1R_o + C_2(R_1 + R_o)\right]}$$

It can be seen that the two most important parameters in determining the forward time response of the network are C_2 and R_1. The analysis has shown that increasing C_2 and R_1 increases the time lag but decreases the ripple. Values which gave a satisfactory compromise were C_2=4 ufds. and R_1=2. 2 $K\Omega$.

However, when there is a drop in terminal voltage, the voltage across capacitor C_1 is greater than E_i, and the diodes do not conduct in the forward direction. There are now two discharge paths for the capacitors, R_2 and the very high reverse impedance of the diodes. The simplifying approximations previously made to the transfer function are no longer valid. In the worst case, with R_o very much larger than R_2, the transfer function is approximated by:

$$\frac{E_o}{E_i} = \frac{R_2/(R_o + R_1 + R_2)}{1 + s\left[C_1(R_1 + R_2) + C_2R_2\right]}$$

In effect, this assumes that none of the discharge takes place through the diodes. R_2 has a very significant effect on the time constant. Although increasing R_2 decreases the ripple factor, it was necessary to constrain its maximum value in order to keep the time constant within reasonable limits.

3.3 PERFORMANCE OF RECTIFIER AND FILTER

One of the advantages of the capacitor input filter is the high D.C. output voltage with small ripple at light loads. The ripple is usually approximated, for calculation purposes as the sawtooth wave shown in Figure 10. For the purpose of illustration, the magnitude of the ripple has been exaggerated.

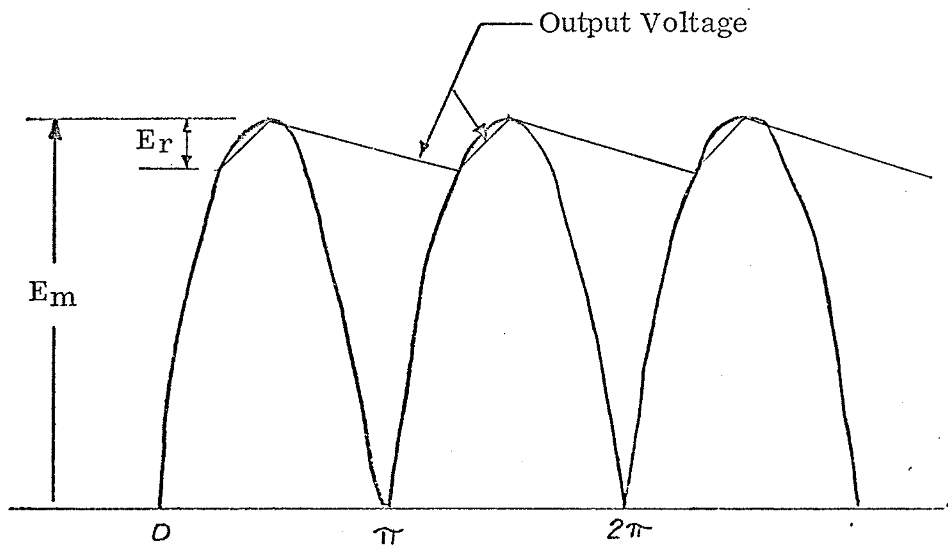


FIG. 10 DETECTION CIRCUIT OUTPUT VOLTAGE

For such an output voltage wave, the r. m. s. value E_{ac} is $E_r/2\sqrt{3}$ where E_r is the peak-to-peak value of the ripple voltage. For the circuit parameters that were chosen, the ripple factor is .057%, or roughly 1 part in 1750.

$$\therefore \frac{E_{ac}}{E_{DC}} = \frac{1}{1750}$$

$$E_r = \frac{2\sqrt{3}\ E_{DC}}{1750} \cong \frac{E_{DC}}{500}$$

The D.C. value of the output voltage wave can be approximated by:

$$E_{DC} = E_m - E_r/2$$

where, E_m = peak value of the sinusoidal wave.

$$\therefore E_{DC} = E_m - \frac{E_{DC}}{1000}$$

$$E_{DC} = E_m \frac{1000}{1001} \cong E_m$$

This is confirmed by Graph 3, Page 35, which shows the output voltage of the rectifier and filter plotted against the r. m. s. value of the A. C. terminal voltage. The $R_1 - R_2$ combination can be considered as attenuating the actual peak voltage of the sinusoid. It would therefore be expected that:

$$E_{DC} = E_m = \frac{50\ (1.414)\ E_{rms}}{(50 + 2.2)}$$

$$E_{DC} = 1.354\ E_{rms}$$

where E_{rms} = the root mean square value of the generator terminal voltage.

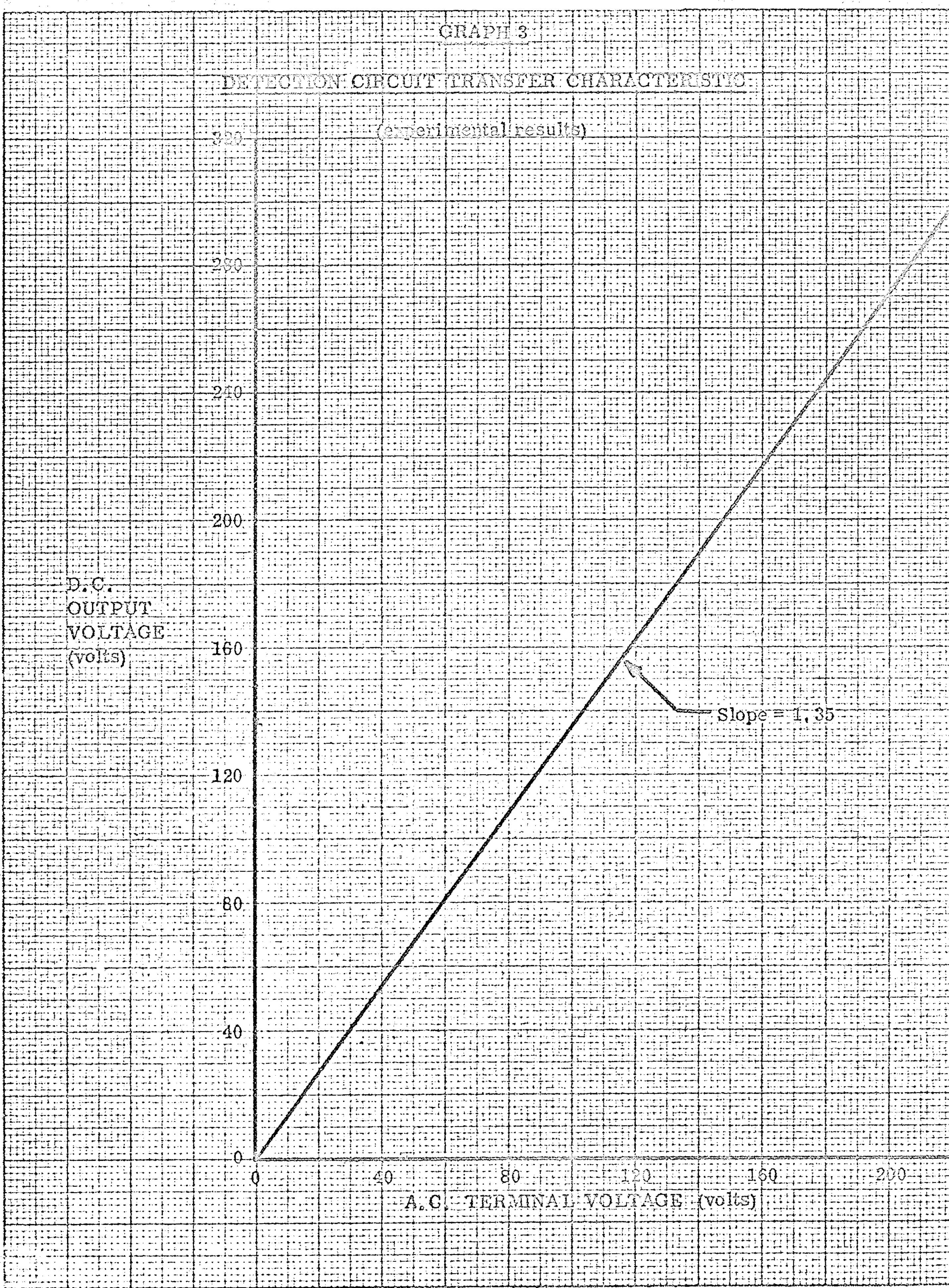
This agrees with the result that was obtained experimentally.

The forward time constant was calculated to be $(C_1 + C_2)R_o + C_2R_1$. The C_2R_1 product is $(4 \times 10^{-6})\ (2.2 \times 10^3) = 8.8$ msec. An oscilloscope was used to observe the wave when a step function of 100 volts was applied to the rectifier and filter. The measured time constant of roughly 9 msec. confirms the approximation that R_o and R_2 have little effect on the forward time constant.

The oscilloscope was used to observe the wave when a voltage of 100 volts across the output of the filter was allowed to decay to zero. Traces were taken with $R_2 = 50\ K\Omega$ and $100\ K\Omega$ to show the improvement made by reducing R_2. Due to the nonlinearity of the reverse impedance of the diodes, no attempt was made to compare theoretical and experimental values. However, if R_o were considered infinite, with $R_2 = 50\ K\Omega$, the reverse time constant would be:

$$= C_2(R_1 + R_2) + C_2R_2$$

$$= .72 \text{ seconds}$$


GRAPH 3
DETECTION CIRCUIT TRANSFER CHARACTERISTIC
(experimental results)
D.C. OUTPUT VOLTAGE (volts)
A.C. TERMINAL VOLTAGE (volts)
Slope = 1.35
0
40
80
120
160
200
240
280
320

If 100 K were used for R_2, the time constant would have been 1.42 seconds. The oscillograph tracings gave time constants of .7 and 1.4 seconds for R_1 = 50K, and 100K respectively, indicating that the approximation gave a good indication of the time lag.

CHAPTER IV

CLOSED LOOP OPERATION OF THE EXCITATION SYSTEM

4.1 VOLTAGE FEEDBACK SCHEME

A variety of schemes are available for operating the excitation system as a closed loop system. The scheme first tried used terminal voltage as a feedback signal. Although this system did not provide satisfactory regulation, it had the advantage of requiring no external D.C. voltage source as a reference voltage. A description of the system has been presented here as an aid to understanding the scheme that was ultimately developed.

Reference to Figure 11, Page 38, will aid in understanding the circuit operation. Only the relevant parts of the circuit are shown in the sketch. In Chapter 2, Pages 20 - 23, it was pointed out that voltage V_{ab} controlled the charging time of the capacitor, and, hence the firing angle of the SCR. Voltage V_{ad} is fixed at 24 volts (for most of the cycle) by the Zener diode. The generator terminal voltage, which has been rectified and filtered, is fed to the series combination of 20K and the 30K potentiometer (which together comprise the 50K filter load mentioned in Chapter 3). The voltage V_{bd} can be varied by changing the potentiometer setting or by varying the terminal voltage. Since V_{ab} is just the difference between V_{ad} and V_{bd}, the excitation can be controlled.

The voltage across the Zener diode is provided from an external 60 Hz source. Initially, the generator terminal voltage is zero, and hence V_{bd} is zero, while V_{ad} is fixed at 24 volts. The resultant high voltage across a-b produces a small firing angle, high initial field current, and a rapid build-up of generator

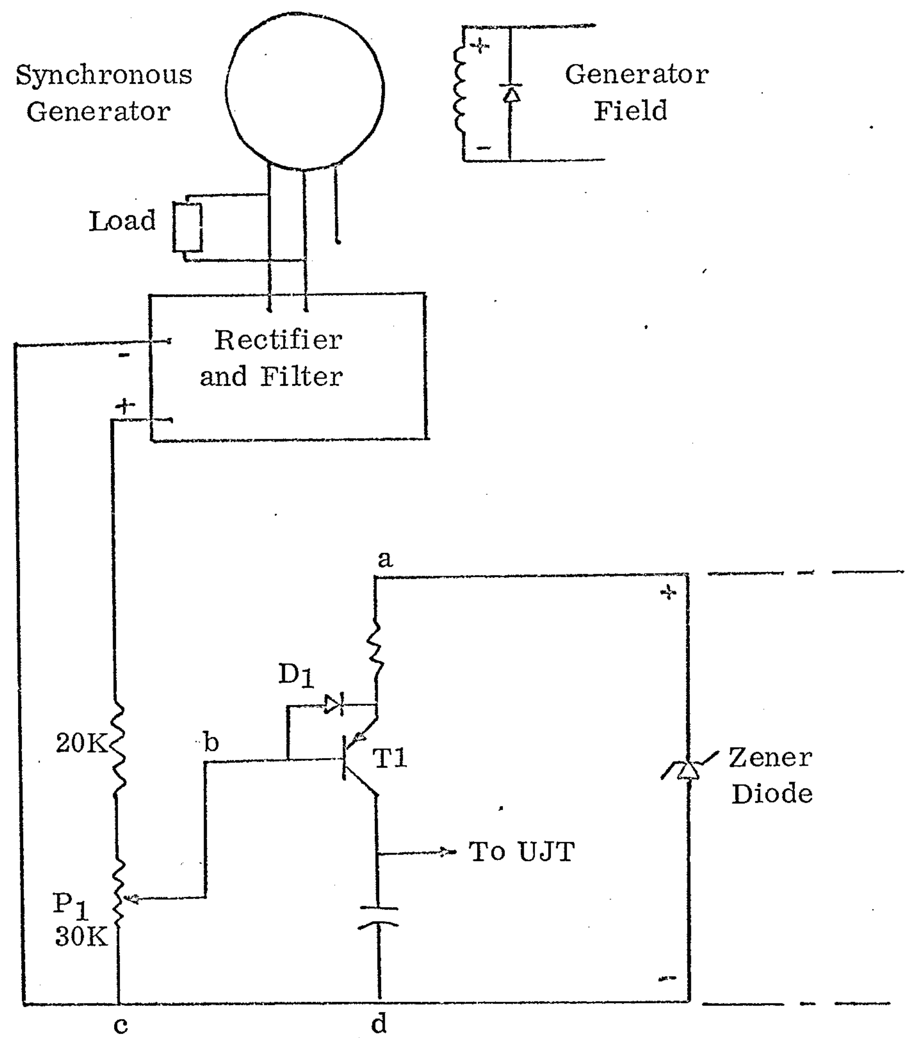


FIG. 11 VOLTAGE FEEDBACK CIRCUIT

voltage. Voltage V_{bd} increases and V_{ab} decreases until a steady - state operating point is reached. For each value of open circuit terminal voltage, there is required a certain value of field current and, therefore, a certain value for V_{ab}. To increase the terminal voltage, a lower value for V_{bd}, i.e., a lower setting of the potentiometer, is needed. Note that at a higher terminal voltage, there is a greater D.C. voltage available from which to tap off V_{bd}. The plot of open circuit voltage versus potentiometer setting is therefore not linear. Table 1, Page 40, gives the settings of potentiometer P1 for 10 volt intervals of open circuit generator terminal voltage.

The diode D1 placed across the base to emitter junction of transistor T1 was needed as a protective device. The voltage V_{bd} can be considered constant over each cycle, but the Zener diode voltage V_{ad} drops to zero at the end of each half cycle. Each time this happens, V_{ab} will have a negative value in the order of 20 volts. Also, once the SCR has fired, V_{ad} drops to zero, and there is a sustained (for the rest of the half cycle) negative voltage across the emitter to base junction. Since this junction has a limit of minus 4 volts, the diode was placed across the junction to bypass the negative voltage.

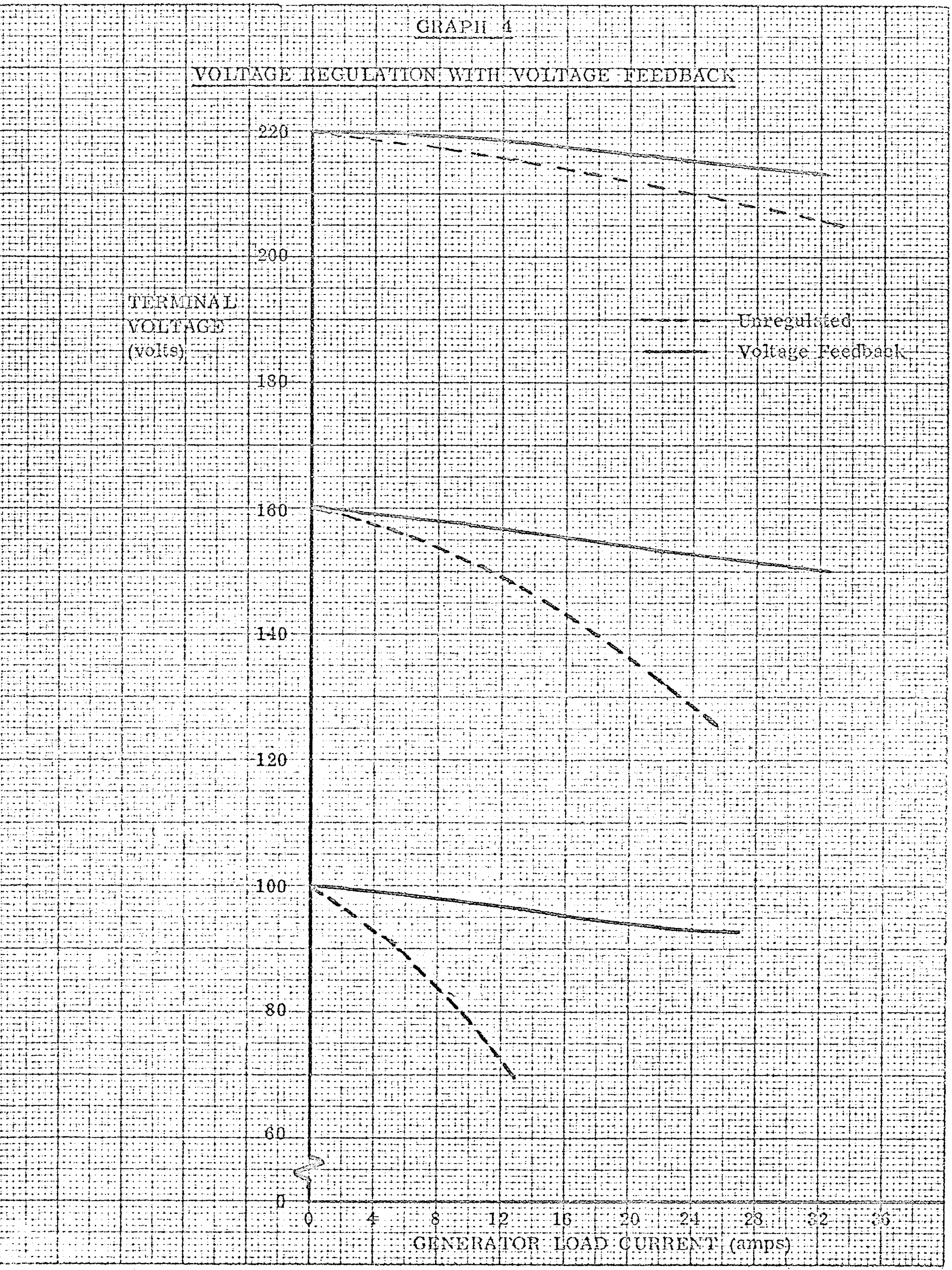
When load is applied to the generator, the terminal voltage drops, causing a decrease in V_{bd}. The resultant increase in V_{ab} advances the firing angle of the SCR, and increases the field current. This increases the terminal voltage which in turn reduces V_{ab}. A steady - state operating voltage is reached at a voltage level between the original terminal voltage and the voltage that would exist under load with no corrective action.

Graph 4, Page 41, compares the terminal voltage obtained with fixed excitation and with voltage feedback using static excitation. Obviously, the regu-

TABLE 1

SETTINGS OF POTENTIOMETER P1 FOR VARIOUS OPEN CIRCUIT TERMINAL VOLTAGES

Terminal Voltage (Volts)	P1 Setting (Dial Reading)
40	702
50	586
60	488
70	417
80	368
90	325
100	293
110	266
120	244
130	226
140	210
150	196
160	182
170	172
180	162
190	154
200	145
210	138
220	130
230	123
240	114


GRAPH 4
VOLTAGE REGULATION WITH VOLTAGE FEEDBACK
TERMINAL
VOLTAGE
(volts)
220
200
180
160
140
120
100
80
60
0
Unregulated
Voltage Feedback
0
4
8
12
16
20
24
28
32
36
GENERATOR LOAD CURRENT (amps)

lation has improved but is still far from satisfactory. Since a decrease in terminal voltage is required to increase the field current from the no load value, there will always be a steady - state error when the generator is loaded. A transistor amplifier could be built which would amplify any change in V_{bd} before applying it to the base of T1, thereby producing a greater change in field current. The steady - state error could thus be reduced to an acceptable magnitude.

An alternative method to improve the regulation by compensating for the effect of load current, is described in the next section.

4.2 GENERATOR LOAD CURRENT AS A FEEDBACK SIGNAL

When load current flows from a synchronous generator, the change in terminal voltage is brought about by:

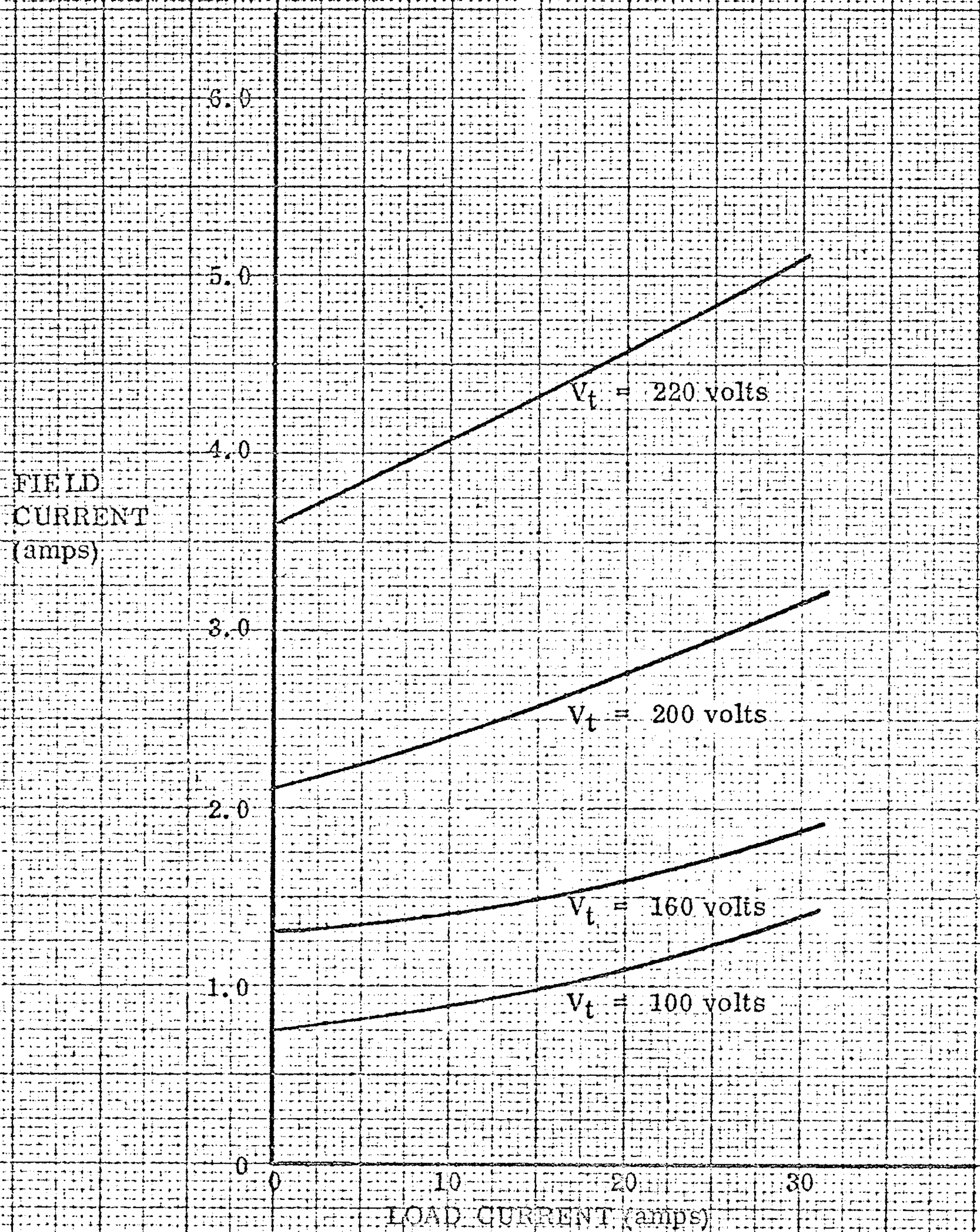
1. Voltage drop across the generator's internal impedance.
2. The demagnetizing effect of the armature current.

It was thought that a signal proportional to load current might be used to provide compensating action and reduce the voltage regulation. Examination of the compounding curves for the generator, shown in Graph 5, Page 43, (feeding a resistance load comprised of wire boxes) indicates a fairly linear relationship between load current and field current for a fixed value of terminal voltage. Re-examination of Graph 2, Page 25, shows a fairly linear relationship between the control voltage and field current up to about 60 volts for the D. C. voltage. Since the field voltage would not exceed this value under normal conditions, it was hoped that a scheme incorporating load current as a corrective signal could be devised.

GRAPH 5

GENERATOR COMPOUNDING CURVES

(Resistive Load)



Since voltage is the parameter controlling the transistor operation, a low value of D.C. voltage proportional to load current was required. An 800:5 ratio CT was used to step down the load current, which was then rectified and filtered. The circuit used is shown in Figure 12, Page 45. P2 is a 20Ω potentiometer across which ~ 3.7 volts were developed at a load current of 34 amps. Because of the very low value of resistance P2, the capacitors C_3 and C_4 had to be very large - 1000 ufds. each. Since attentuation of the voltage was of no concern in this case, R_6 was chosen as 11Ω in order to decrease the ripple. The ripple factor (calculated from the formula used in Chapter 3) was 1.1%. Note that the maximum voltage drop in the primary of the CT would only be 5/800 of the secondary voltage, so that the generator terminal voltage could be considered equal to the load voltage. As in the case of the voltage detection circuit, it is desirable to minimize power dissipation. The voltage across P2 of 3.7 volts indicated $3.7/20 = .185$ amps, so maximum power dissipation would only be, $(20 + 11)(.185)^2 = 1.06$ watts.

Analysis of the time lag of this circuit can be carried out in much the same way as was done for the voltage detection circuit. When load current is flowing, the diode bridge rectifier can be treated as a current source, i.e., an ideal current source in parallel with a large impedance R_o. This can be changed to an equivalent voltage source in series with impedance R_o as shown in Figure 13, Page 46.

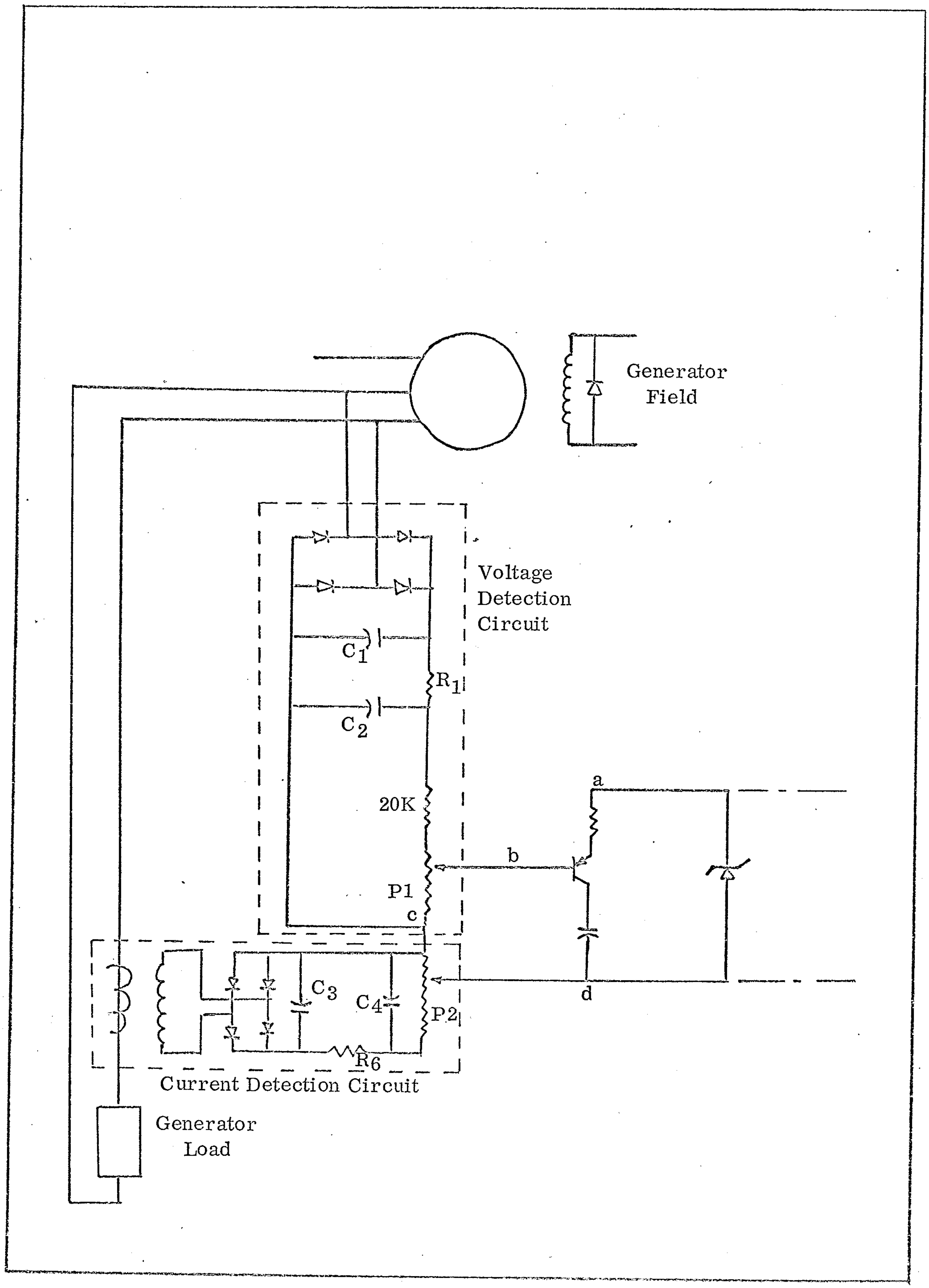


FIG. 12 VOLTAGE AND CURRENT FEEDBACK

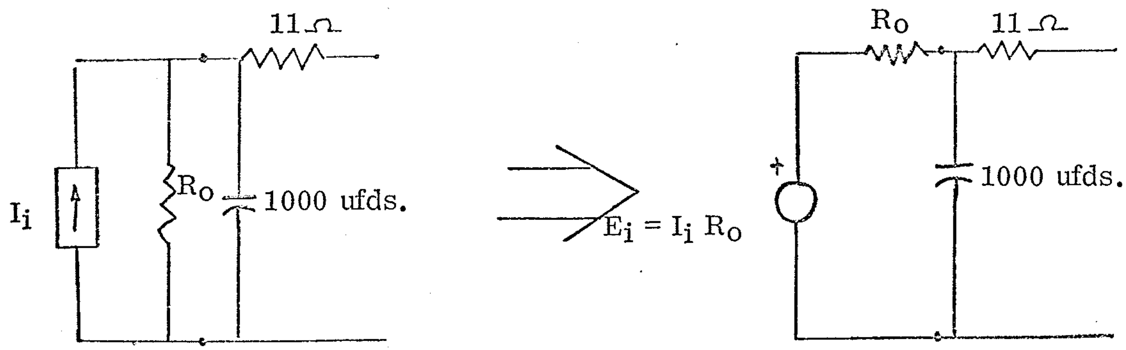


FIG. 13 REPRESENTATION OF C.T. AND BRIDGE RECTIFIER

With this equivalent circuit, the transfer function E_o/E_i is the same as that obtained in Chapter 3. The transfer function E_o/I_i is now needed. Making use of the fact that $E_i = I_i R_o$, gives the transfer function as:

$$\frac{E_o}{I_i} = \frac{R_2 R_o / (R_o + R_1 + R_2)}{1 + s\, C_1(R_1 + R_2)\left(\frac{R_o}{R_o + R_1 + R_2}\right) + C_2 R_2\left(\frac{R_o + R_1}{R_o + R_1 + R_2}\right) + s^2 C_1 C_2\left(\frac{R_o\, R_1\, R_2}{R_o + R_1 + R_2}\right)}$$

For the current detection scheme, R_6, P_2, C_3, and C_4 must be substituted for R_1, R_2, C_1, and C_2, respectively. Since the CT and bridge rectifier closely approximate an ideal current source, R_o is very large, certainly much larger than $R_6 = 11\Omega$ and $P_2 = 20\Omega$. This allows the transfer function to be approximated as:

$$\frac{E_o}{I_i} = \frac{P_2}{1 + s\left[C_3\,(R_6 + P_2) + C_4\, P_2\right]}$$

The forward time constant of this circuit is then $\left[1000 \times 10^{-6}\,(11 + 20) + 1000 \times 10^{-6}\,(20)\right] = 51$ msec.

The reverse time constant of this circuit is determined by examining the discharge path for C_3 and C_4 once load current has stopped flowing. If the reverse impedance of the bridge rectifier is assumed to be ∞, the time constant is just $C_3 (R_6 + P_2) + C_4 P_2$, i.e., the same as the forward time constant.

Figure 12, Page 45, indicates how the current detection circuit is connected into the control system. When the generator is loaded, field current must be increased, i.e., V_{ab} must increase. To accomplish this, the negative ends of P1 and P2 were tied together and point d was connected to the wiper of P2. When the generator is loaded, point d becomes positive with respect to point c, reducing V_{bd} and bringing about the desired increase in V_{ab}. When the generator is unloaded, point c is at the same potential as point d. Since the slopes of the compounding curves are not identical, P2 must be reset for each level of generator voltage. Table 2, Page 49, gives the settings of P2 for various voltage levels for a resistive load.

4.3 PERFORMANCE OF COMPLETE CIRCUIT

The use of the compensating signal proportional to load current improves the speed of response of the system. Recall that the voltage detection circuit has a reverse time constant (when responding to a reduction in terminal voltage) of .72 seconds or roughly 43 cycles. The forward time constant of the current detection circuit is just over 3 cycles. This means that indication of a disturbance is received much sooner, and corrective action can be initiated more quickly.

Use of the current compensation means that the voltage feedback is no longer needed to provide corrective action. However, as mentioned earlier, using the terminal voltage to provide a biasing voltage for the control transistor, eliminates the necessity of providing an external bias source.

Graph 6, Page 50, shows the vastly improved regulation characteristics obtained with the complete circuit as compared to the characteristics with voltage feedback only. Although the curves do not show it clearly, the maximum deviation from the required value was 0.5 volts, which, for the 50 volt curve, amounted to 1%. Deviation from the required value is due to the non-linearity of the control characteristics.

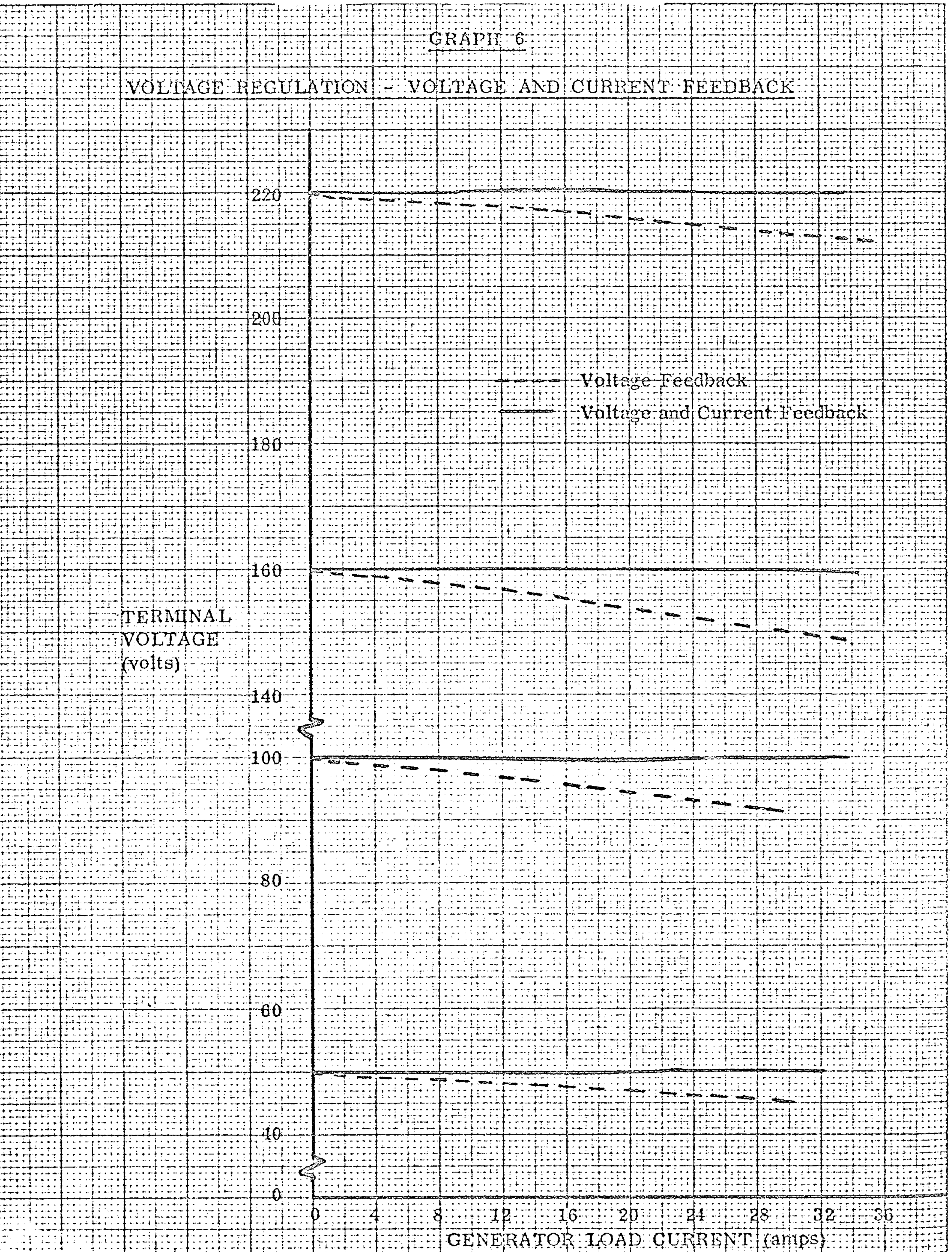
It was realized that the compounding curves for the generator are different for different power factor loads. However, typical compounding curves for a synchronous generator indicate approximately linear compounding curves for power factors other than unity.[30] Deviation from linearity occurs near rated load, but in this particular application, it was expected that load current would be small. Once the power factor of the generator load in this case has been established, potentiometer P2 can be re-calibrated to meet the requirements of the load. Satisfactory regulation can be expected.

A slight fluctuation is present in the generator terminal voltage, the magnitude of which is negligible. The frequency of this fluctuation varies from roughly 1/3 Hz to 3 Hz as the load current varies from zero to rated value. This corresponds to the slip frequency of the induction motor as it is being loaded. Elimination of this beat frequency pulsation could be accomplished by either driving the synchronous generator at synchronous speed, or supplying the field circuit power from the terminals of the generator. This would necessitate the addition of a starting circuit, and, as mentioned earlier, would complicate the analysis. It is difficult to see at what point of the circuit, or by what means this pulsation can be suppressed.

TABLE 2

SETTINGS OF POTENTIOMETER P2 FOR VARIOUS OPEN CIRCUIT TERMINAL VOLTAGES

Terminal Voltage (Volts)	P2 Setting (Dial Reading)
50	850
60	740
70	730
80	750
90	750
100	735
110	670
120	665
130	615
140	570
150	505
160	460
170	420
180	375
190	315
200	285
210	255
220	240
230	360


GRAPH 6
VOLTAGE REGULATION - VOLTAGE AND CURRENT FEEDBACK
Voltage Feedback
Voltage and Current Feedback
TERMINAL VOLTAGE (volts)
220
200
180
160
140
100
80
60
40
0
0
4
8
12
16
20
24
28
32
36
GENERATOR LOAD CURRENT (amps)

CHAPTER V

STATIC EXCITERS FOR LARGE UTILITY GENERATORS

5.1 POWER SYSTEM STABILITY

Power system stability is the quality of the system which enables the system to develop restoring forces, following a disturbance, which will allow the system to restore equilibrium. The restoring forces in an A.C. system are due to the synchronizing torques of the machines. Since the synchronizing torques decrease with increasing system reactance, the problem of stability becomes more acute with long distance transmission lines. The steady state stability limit of a synchronous generator is the maximum power that the machine can supply without falling out of synchronism. Transient stability limit refers to the system performance under fault conditions, and depends on the type of fault used as a design criterion. Some margin of power transfer capability over the rated operating conditions must be provided to allow the system to recover from finite disturbances. A figure of fifteen percent of normal full load has been suggested.[25]

The power transfer in a system is given by:

$$P = \frac{V_S \, V_R}{X} \sin \delta \qquad \text{(when resistance is neglected)}$$

where, P = power transfer

V_S, V_R = voltages at the sending and receiving ends, respectively.

X = total system reactance between the two voltages.

δ = phase angle between V_S and V_R

Maximum power transfer occurs when $\delta = 90^o$. Increasing the system voltage increases the power transfer, but involves higher costs in insulation and protective devices. Limiting the magnitude and duration of faults is very effective in increasing the stability limit. High speed circuit breakers and automatic reclosing devices are now in operation on many systems for this purpose. Decreasing the system reactance X will increase the power transfer. This can be accomplished in several ways, all of which are costly:

1. Generators and transformers can be designed with lower reactances.
2. Series capacitors in the transmission line will compensate for the inductive reactance of the line.
3. The use of bundled conductors will decrease the line inductance but will increase the line susceptance.

Perhaps one of the most economical methods of extending the various stability limits is improvement of the excitation system. "A continuous, fast-acting regulator in conjunction with subsidiary feedback can considerably influence the steady state, dynamic, and transient stability of a synchronous generator connected in a power system."[23] Studies carried out on the Peace River EHV transmission system in British Columbia, Canada indicated the following relative cost figures for means of increasing stability:[21]

1.	Use of series capacitors on transmission line	1.0
2.	Reduce reactance of transmission line	0.5 - 1.0
3.	Reduce generator transient reactance	0.4 - 0.5
4.	Increase the generator inertia constant	0.8 - 1.0
5.	Raise the static excitation system ceiling voltage from 5.0 pu. to 7.5 pu.	0.3 - 0.5

At Grand Rapids Generating Station in Manitoba, Canada, it was found that static excitation was the most economical way of achieving the increased power transfer until the transmission facilities were extended.

5.2 HOW EXCITATION SYSTEMS AID STABILITY

In the past, representation of a generator in power system studies consisted of a constant voltage behind the transient reactance. Since the constant voltage is proportional to flux linkages in the field, this implies constant field current and hence, no regulation of the field. If the exciter can maintain the terminal voltage at a relatively constant value, the terminal voltage rather than the internal machine voltage will be used in the power transfer equation. By thus making the power transfer independent of the generator reactance, the total effective reactance of the system has been reduced, with a consequent increase in the steady state stability limit. Although it is not necessary to control the generator voltage extremely accurately, keeping the voltage within reasonably close limits will ensure that the full synchronizing torque of the generator is available if a fault should occur. A regulator with no deadband is best suited to overcoming the effect of small voltage fluctuations. It should be noted, of course, that a much more complex representation of the machine is now used in stability studies.

Some margin must always be left between the generator operating point and the theoretical stability limit to allow for fluctuations in the hydraulic turbine output. Use of a static excitation system permits this margin to be reduced by operating in the dynamic stability region, i.e., at a torque angle greater than that allowed by a conventional exciter. This condition is statically unstable (like a child's spinning top) and depends on the rapid response of the excitation system. As the dynamic stability limit is approached, hunting occurs. The frequency of these oscillations increases as the power level is raised. A conventional exciter cannot react quickly enough to control the oscillations and the system would go unstable. Operation in the dynamic stability region demands a high degree of reliability for the excitation system, since loss of control brings about loss of stability.

When a fault occurs on a power system, both the generator voltage and power output suddenly drop. Because of the slow response of the speed governors, the mechanical power input remains essentially constant during the fault. The resulting accelerating power speeds up the generator, increasing the phase angle between the generator voltage and receiving end voltage. The fault can be cleared in three or four cycles, but normal operating conditions are not immediately restored. Since the acceleration of the generator can be diminished by increasing the transfer of electrical power from the generator during the fault, i.e., its electrical output, it is important to maintain the generator voltage as high as possible during this period. The forcing capability and high speed of response of a static excitation system enable it to overcome the barrier of the field time constant in quickly raising the internal flux of the machine, and hence the generator voltage, to limit the magnitude of the first swing. Although stability will be preserved on the first swing, damping on successive swings may not be sufficient to ensure stability. A subsidiary feedback is required which will develop sufficient damping torque to restore equilibrium.

5.3 EXCITATION SYSTEM DESIGN

Ceiling voltage, which was defined earlier in Chapter 2, is "the significant parameter defining the ability of the excitation system to produce transient adjustments to the machine field and flux levels".[10] When a fault occurs, a high current is induced in the field by the armature fault current. A large forcing exciter voltage will further increase the field current to provide the desired increase in flux. A very high level of ceiling voltage is relatively economical to obtain, but there are practical limitations to its magnitude. Due to generator saturation, increases in ceiling voltage beyond a certain point have little effect on the machine. Ceiling voltage is usually required only while the fault is present, and its purpose is to reduce the magnitude of the first swing. Typical values of ceiling voltage are from three to five times rated full load excitation. It was found in studies of the Peace River system that a ceiling voltage of 10 pu. resulted in regulator instability when the gain was adjusted to give ceiling voltage with one percent error in terminal voltage.

When a fault occurs, the large terminal voltage error will always drive the exciter to ceiling voltage. However, to correct small fluctuations in voltage, the sensitivity of the feedback must be adjusted to give optimum performance. In some systems, the availability of negative field forcing voltage may be useful to provide extra damping or to more quickly reduce terminal voltage following load rejection. In other cases, it may be sufficient just to drop the excitation voltage to zero. The additional cost required to provide negative voltage to the field rather than just positive voltage is minimal. This can be accomplished by use of a bridge rectifier consisting of six SCR's. When negative forcing is provided, special circuitry must be added to provide a path for the negative induced currents. Supplying negative field current from the excitation source, increases the line charging capability, but necessitates provision of a second bridge rectifier (of opposite polarity) and rather complex control equipment to transfer from one bridge to the other.

On older systems, the concept was rightly held that if the system were stable on the first swing, stability was assured. This was so because the time lag of the exciter behind a terminal voltage change provided a measure of damping. With the extremely rapid response obtained from static exciters, some additional damping must be introduced. Any parameter which provides an indication of the swing of the machine can be used as a reference for the stabilizing signal. The signal must meet the following requirements:[22]

1. It must act on the excitation in the right direction at the right time.
2. It should have some reasonable proportionality to the magnitude of the swing.
3. It should reset to zero in the steady state.
4. It should be fairly easy to obtain in actual practice.

Various signals could be used, including deviation from synchronous speed, rate of change of terminal voltage, and rate of change of field current. Analog computer studies indicated that if the gain of the dI_f/dt signal (rate of change of field current) were raised too high, regulator instability resulted. A time lag had to be introduced to control this instability and this meant that the feedback signal was not always in the right direction to aid stability. Since the stabilizing signal should provide damping, which is relatively independent of the impedance external to the generator, speed error was considered best.[18] The terminal voltage rate of change signal was found to give poor damping in comparison with the speed error signal. It eliminated its own source of signal, without producing the voltage deviation in the opposite direction, of which the frequency signal is capable.

A velocity deviation above synchronous speed is made to produce an increase in excitation since the increasing speed indicates accelerating power at the generator. Greater transfer of power from the generator results in reduction of the generator acceleration. When the speed drops below synchronous, the excitation is reduced.

The damping signal is of little importance during the fault, since the exciter voltage is driven to ceiling by the voltage error signal. It may hold the field voltage at ceiling for somewhat longer than with just the terminal voltage error applied.[21] When the fault is cleared, the exciter voltage follows closely the stabilizing signal. The ceiling voltage should be high enough so that the exciter voltage is not limited during the oscillatory swings. If the voltage were limited by the ceiling, an attempt would be made to maintain the ceiling voltage for a longer time to get the same amount of damping. Poor damping would result because of the resulting poor timing of the stabilizing signal.

As the ratio of the speed error signal to the voltage error signal increases, better damping is brought about at the expense of larger terminal voltage deviations. A compromise must be reached which gives satisfactory damping with acceptable voltage deviations. When maintenance of stability is the prime concern, very rigid control of terminal voltage does not help stability as much as biasing that control as a function of the stabilizing signal. Some limitation is required on the exciter to prevent excessive overvoltage upon load rejection when the resulting overspeed creates a large speed error signal. One authority[21] has suggested a limit of 110% of rated voltage.

5.4 PRACTICAL CONSIDERATIONS

Although, at this time, speed error is ideally the best stabilizing signal that can be used, some difficulty has been experienced in obtaining a suitable speed signal. Since a very small speed error (in one particular case, .04% error)[18] must drive the exciter voltage to ceiling, a very high degree of sensitivity is required. Using a flexible coupling or stroboscopic methods to obtain a speed signal are unsatisfactory due to lateral movements in the generator shaft. At low shaft speeds, conventional electrical filters will not block out this noise. The Ontario Hydro devised a speed sensing device for their Moose River plants which gives an output voltage proportional to frequency and eliminates any "noise" which would cause exciter voltage fluctuations.[18] Included in the device is a "washout" feature which cuts out the speed signal if prolonged (1 - 1.5 seconds) speed changes occur. This prevents overloading of the field circuit. The frequency of oscillations following a transient disturbance is such that the washout feature will have no effect during transients.

Some controversy exists as to whether the speed signal should be derived mechanically or electrically. The mechanical device is much more expensive due to the noise problems. An alternative method is based on the fact that when the generator speeds up, it gains kinetic energy. By integrating the rotor accelerating power, an indication is obtained of the swing of the machine. However, this does not give a good indication of speed variation near the steady state stability limit where power variations are small. A frequency measurement at the generator terminals may prove to be the simplest method.

One interesting point about the speed stabilizing signal is that, while it is essential for system stability, it prevents rapid changes of load. When it is desired to add more load to the machine, the generator must slow down to let the torque angle increase. Since the stabilizing signal opposes all speed changes, whether intentional or not, a relatively long time is needed to change load. Hence it will not be possible to use a generator to quickly pick up load dropped by another generator. The stabilizing signal cannot be eliminated for the interval of load changing, since the system may well be unstable without it. To overcome this, a signal proportional to gate position can be introduced during this period to cancel out the power change signal.

There exist several possibilities for supplying power to the static excitation system. Deriving the power from the generator terminals has the apparent disadvantage that, during a fault, when forcing voltage is needed most, the least terminal voltage is available. However, generator voltage seldom collapses completely during a fault and the excitation system can be designed so that a small percentage of rated terminal voltage will still provide ceiling voltage. Besides, the fast acting breakers available today can clear faults in several cycles. Since the peak of the first swing occurs anywhere from twelve to twenty-four cycles, sufficient time is available for the exciter voltage to increase the machine internal flux. In some industrial systems, total collapse of the terminal voltage could occur. A scheme has been devised whereby load current rather than terminal voltage provides the excitation during the fault.

The current transformer supplying the excitation power is normally saturated and hence nonconducting when rated voltage is supplied by the generator. The scheme is arranged so that excitation changes required by load changes are automatically compensated for. If sustained faults should occur on a system, the ceiling voltage must be automatically reduced to prevent overheating of the field winding due to high field current.

5.5 COMPARISON WITH CONVENTIONAL METHODS

A solid state exciter may not always be needed to improve system performance, although static systems are competitive economically in applications with no stability problem. In a particular system, conventional equipment may be adequate or may be extended to utilize its full capacity. Amplidyne exciters are certainly adequate in some situations since they possess a high power gain and can be designed for a high ceiling voltage. Where quick response is necessary, though, the high ceiling voltage of the amplidyne may be rendered ineffective by the time required to reach the ceiling. System studies on particular cases have shown that static excitation could preserve system stability while a conventional exciter with response ratio of 2.0 could not.[12, 22] Whereas with a static exciter, the ceiling voltage is available virtually instantaneously, the amplidyne has to build up the ceiling voltage when required. The requirements for quick response and low power level control are conflicting.

Cases exist where the replacement of rotating exciters with static exciters increased the power transfer capability of an existing transmission system.

Originally, electronic exciters were used to replace the conventional exciters because of the maintenance problems involved. Vibration of the main generator was transferred to the shaft driven exciter, and dirt and humidity increased the need for maintenance of commutators and brushes. These problems increased as the speed and excitation requirements of the A.C. generator grew. Advancing technology has created solid state components with power capability comparable to that of electronic tubes. The solid state exciters have the following advantages over electronic equipment:

1. No stand-by filament voltage required.
2. No warm-up time required.
3. No possibility of failure due to arc-back.
4. Smaller, lighter, and mechanically more rugged.
5. Less power dissipation and longer life.
6. Maintenance under load is possible.
7. Very little maintenance is required.

CHAPTER VI

CONCLUSIONS

An attempt has been made to design and analyze a static excitation system which would provide a low value of voltage regulation for a small synchronous generator. The system which was built works satisfactorily, but has definite limitations. Since its action is based on the principle of compensating for the effect of load current, rather than responding only to a voltage error, it depends on accurate calibration of circuit components for successful operation.

Many of the fundamentals governing the design of this circuit are used in building the static excitation systems for utility use, where the extremely fast response of the SCR is essential to counteract system disturbances. As pointed out in the appendix, doubling the ceiling voltage can reduce the field current response time to roughly 25% of its value with rated field voltage applied. Further increases in ceiling voltage would reduce the response time more. This will be a significant factor in a system where the field time constant is large compared to other time lags in the circuit. By raising the ceiling voltage the field time constant is, in effect, reduced. In a system such as this application, ceiling voltage has no effect on the steady - state regulation.

The time lag of the detector circuit was significant in this application. When a generator supplies a balanced three phase load, a three phase bridge rectifier is used to convert A.C. to D.C. With no filter present, the ripple is roughly four percent at a ripple frequency six times the fundamental (as compared to 48% for a single phase bridge rectifier at twice fundamental frequency). The higher frequency ripple can be effectively reduced with a smaller time lag in the filter circuit.

This particular application of the static exciter as a voltage regulator did not demonstrate the full capability of static excitation systems. Due to the induction motor drive, overspeed was no problem. Oscillations and loss of stability due to load changes didn't have to be considered. One of the useful features of the static excitation system is that signals such as the speed stabilizing signal can be incorporated into its control scheme to permit its use as a stability regulator in power systems. The approach to be taken when designing a regulating system for industrial or utility use would be to use analog or digital computer studies to determine the system requirements. The type of study presented in this thesis, however, is necessary at some time to determine the capabilities and limitations of components used in the circuit.

APPENDICES

APPENDIX A

GENERATOR INFORMATION

GENERATOR NAMEPLATE DATA

General Electric

Model 5 AT1 326E11

Serial No. 6931269

Type AT1, Frame 326

KVA 12.5, KW 10, P.F. 0.8

1800 r.p.m., 220 volts, 3 Ø, 4 pole

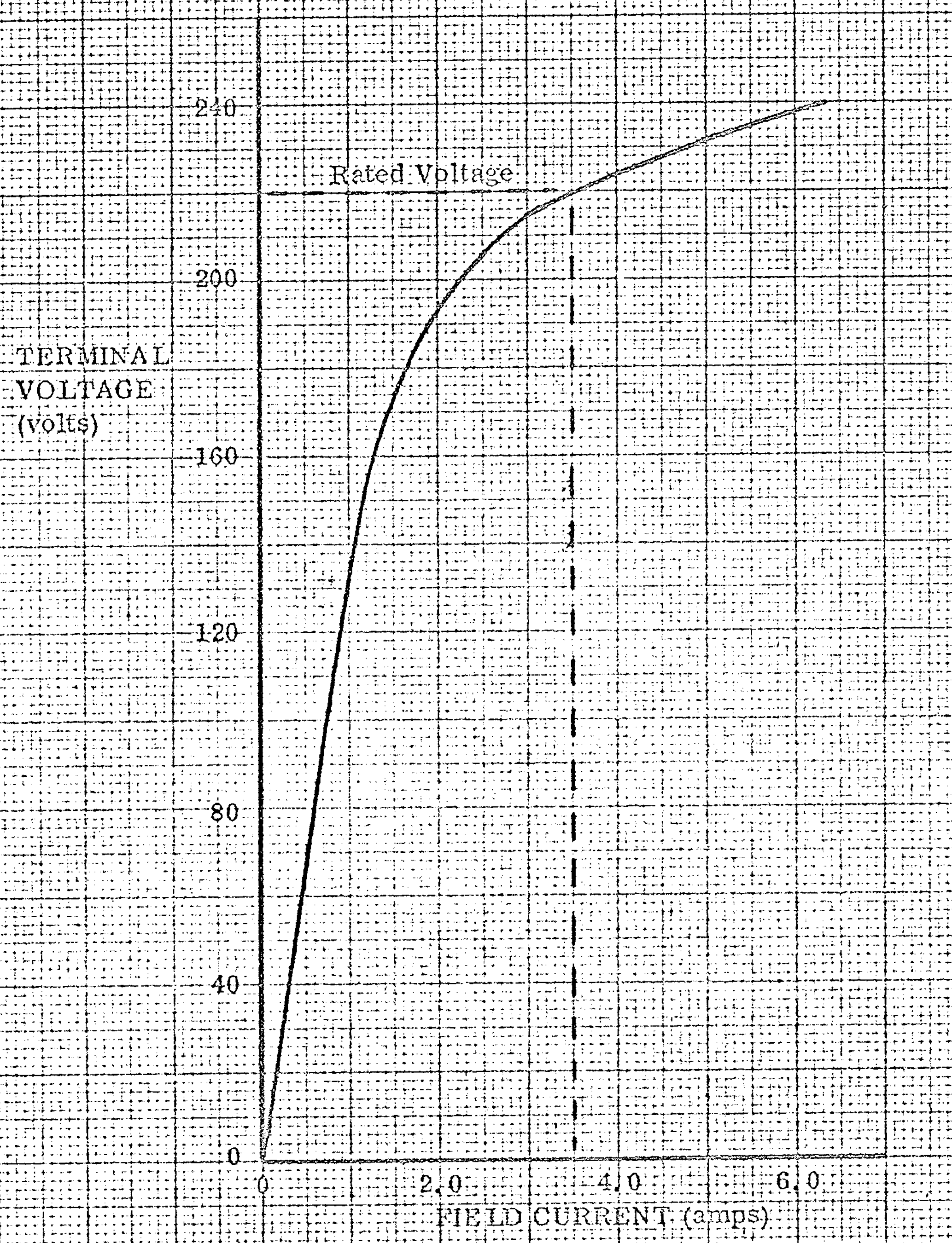
F.L. amps. 32.8, Encl. Dr. P.

Armature rise by therm. 50°C

Field rise by resistance 80°C

Field volts 64, Field amps. norm. 6.2

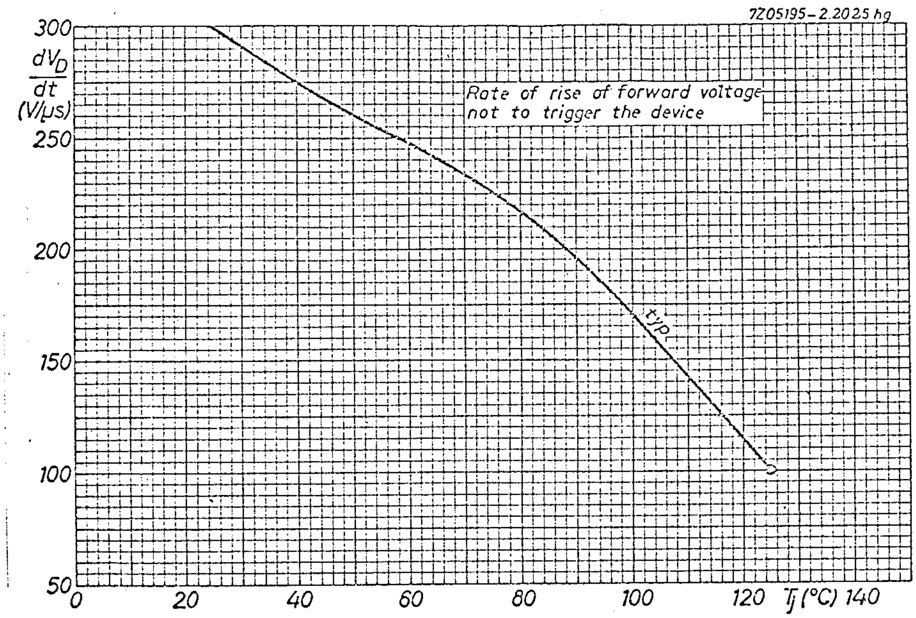
GRAPH A.1 GENERATOR OPEN CIRCUIT CHARACTERISTICS

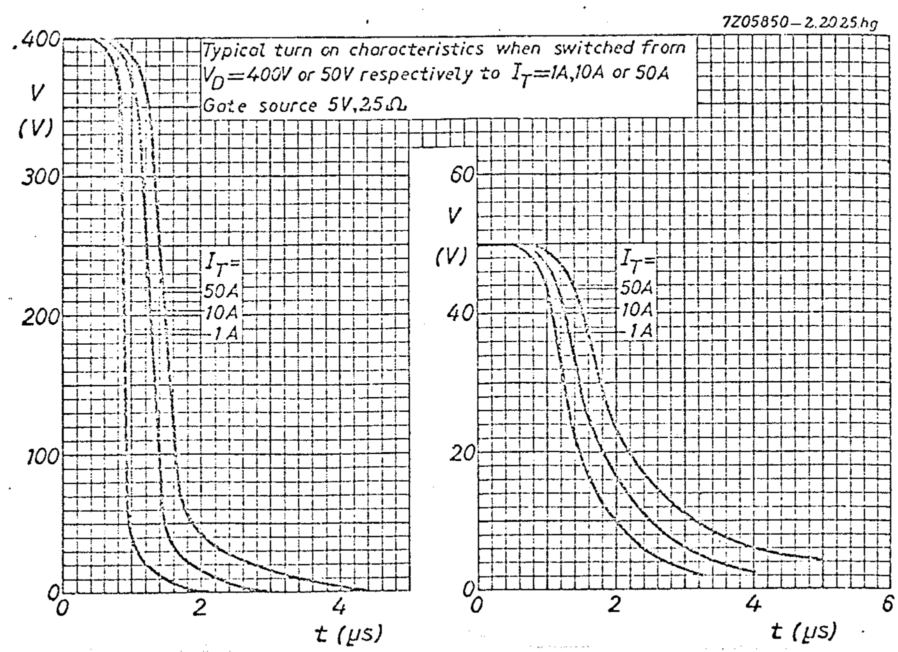


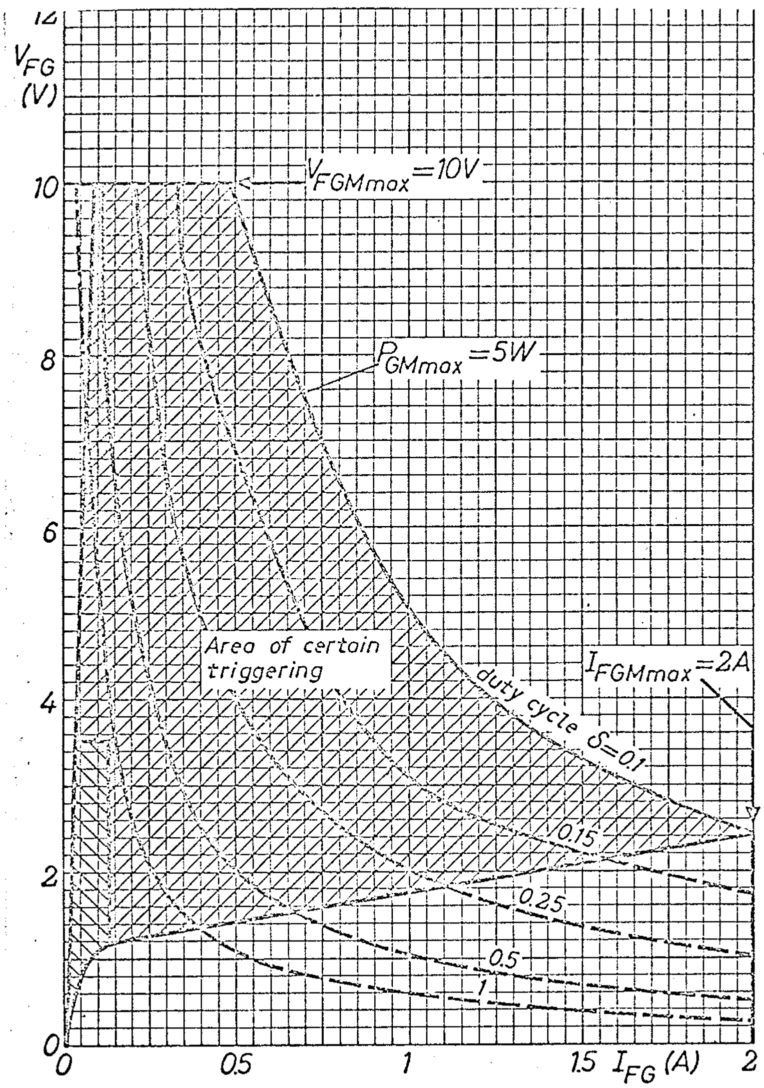
APPENDIX B

SOLID STATE COMPONENTS DATA

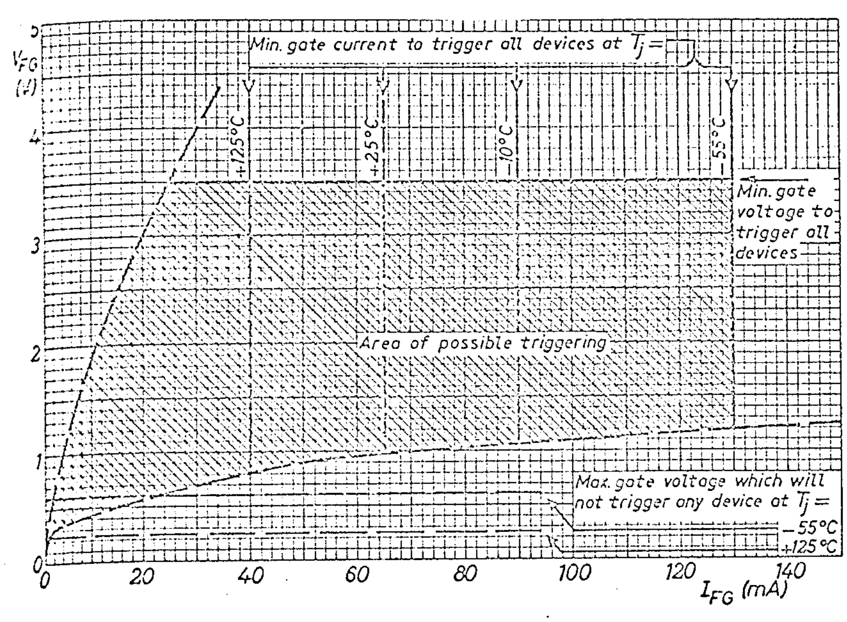
B.1 SCR DATA (BTY87-300R)







Gate characteristics with curves $P_{GAV}=0.5W$

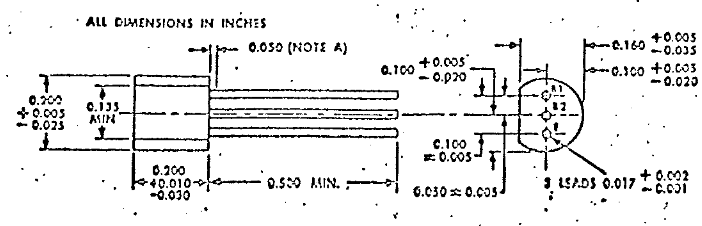


B. 2 UJT DATA (TIS43)

mechanical data

These transistors are encapsulated in a plastic compound specifically designed for this purpose, using a highly mechanized process‡ developed by Texas Instruments. The case will withstand soldering temperatures without deformation. These devices exhibit stable characteristics under high-humidity conditions and are capable of meeting MIL-STD-202C method 106B. The transistors are insensitive to light.

ALL JEDEC TO-92 DIMENSIONS AND NOTES ARE APPLICABLE



NOTE A: Lead diameter is not controlled in this area.

absolute maximum ratings at 25°C free-air temperature (unless otherwise noted)

Emitter–Base-Two Reverse Voltage	30 V
Interbase Voltage	See Note 1
Continuous Emitter Current	50 mA
Peak Emitter Current (See Note 2)	1 A
Continuous Device Dissipation at (or below) 25°C Free-Air Temperature (See Note 3)	300 mW
Storage Temperature Range	−55°C to 150°C
Lead Temperature 1/16 Inch from Case for 10 Seconds	260°C

NOTES: 1. Interbase voltage is limited solely by power dissipation, $V_{B2\text{-}B1} = \sqrt{r_{BB} \cdot P_T}$. The r_{BB} range specified gives maximum values ranging from 35 V to 52 V.

2. This value applies for a capacitor discharge through the emitter—base-one diode. Current must fall to 0.37 A within 3 ms and pulse-repetition rate must not exceed 10 pps.

3. Derate linearly to 125°C free-air temperature at the rate of 3 mW/deg.

electrical characteristics at 25°C free-air temperature (unless otherwise noted)

	PARAMETER	TEST CONDITIONS	MIN	MAX	UNIT
r_{BB}	Static Interbase Resistance	$V_{B1\text{-}B2} = 3$ V, $I_E = 0$	4	9.1	kΩ
α_{rBB}	Interbase Resistance Temperature Coefficient	$V_{B2\text{-}B1} = 3$ V, $I_E = 0$, $T_A = -55°C$ to 100°C, See Note 5	0.1	0.9	%/deg
η	Intrinsic Standoff Ratio	$V_{B2\text{-}B1} = 10$ V, See Figure 1	0.55	0.82	
$I_{B2(mod)}$	Modulated Interbase Current	$V_{B2\text{-}B1} = 10$ V, $I_E = 50$ mA	10		mA
I_{EB2O}	Emitter Reverse Current	$V_{B2\text{-}E} = 30$ V, $I_{B1} = 0$		−10	nA
I_P	Peak-Point Emitter Current	$V_{B2\text{-}B1} = 25$ V		5	μA
$V_{EB1(sat)}$	Emitter — Base-One Saturation Voltage	$V_{B2\text{-}B1} = 10$ V, $I_E = 50$ mA, See Note 4		4	V
I_V	Valley-Point Emitter Current	$V_{B2\text{-}B1} = 20$ V,	2		mA
V_{OB1}	Base-One Peak Pulse Voltage	See Figure 2	3		V

NOTES: 4. This parameter is measured using pulse techniques, $t_p = 300\ \mu s$, duty cycle $\leq 2\%$.

5. Temperature coefficient, α_{rBB}, is determined by the following formula:

$$\alpha_{rBB} = \left[\frac{(r_{BB} @ 100°C) - (r_{BB} @ -55°C)}{(r_{BB} @ 25°C)}\right]\frac{100\%}{155\ deg}$$

To obtain r_{BB} for a given temperature $T_{A(2)}$, use the following formula:

$$r_{BB(2)} = [r_{BB} @ 25°C]\,[1 + (\alpha_{rBB}/100)(T_{A(2)} - 25°C)]$$

B.3 CONTROL TRANSISTOR DATA (Fairchild's 2N3638)

The 2N3638 is a PNP silicon PLANAR epitaxial transistor designed for digital applications at current levels to 500 millamperes. The high gain-bandwidth product, f_T, at high currents, makes it an excellent unit for line driving and memory applications.

ABSOLUTE MAXIMUM RATINGS [Note 1]

Maximum Temperatures

Storage Temperature	-55°C to +125°C
Operating Junction Temperature	+125°C Maximum
Lead Temperature (Soldering, 10 sec time limit)	+260°C Maximum

Maximum Power Dissipation

Total Dissipation at 25°C Case Temperature (Notes 2 and 3)	0.7 Watt
at 25°C Free Air Temperature (Notes 2 and 3)	0.3 Watt

Maximum Voltages and Current

V_{CBO}	Collector to Base Voltage	-25 Volts
V_{CES}	Collector to Emitter Voltage	-25 Volts
V_{CEO}	Collector to Emitter Voltage (Note 4)	-25 Volts
V_{EBO}	Emitter to Base Voltage	-4.0 Volts
I_C	Collector Current (Note 2)	500 mA

ELECTRICAL CHARACTERISTICS (25°C Free Air Temperature unless otherwise noted)

Symbol	Characteristic	Min.	Typ.	Max.	Units	Test Conditions	
V_{CE}(sat)	Collector-Emitter Saturation Voltage (pulsed, Note 5)		-0.38	-1.0	Volts	I_C = 300 mA	I_B = 30 mA
V_{CE}(sat)	Collector-Emitter Saturation Voltage (pulsed, Note 5)		-0.08	-0.25	Volts	I_C = 50 mA	I_B = 2.5 mA
h_{fe}	High Frequency Current Gain (f = 100 Mc)	1.0	1.5			I_C = 50 mA	V_{CE} = -3.0 V
C_{obo}	Common-Base, Open-Circuit Output Capacitance		12	20	pf	I_E = 0	V_{CB} = -10 V
V_{CEO}(sust)	Collector to Emitter Sustaining Voltage (Notes 4 and 5)	-25			Volts	I_C = 10 mA (pulsed)	I_B = 0

Additional Electrical Characteristics on page 2

NOTES:

(1) These ratings are limiting values above which the serviceability of any individual semiconductor device may be impaired.

(2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

(3) These ratings give a maximum junction temperature of 125°C and junction-to-case thermal resistance of 143°C/Watt (derating factor of 7.0 mW/°C); junction-to-ambient thermal resistance of 333°C/Watt (derating factor of 3.0 mW/°C).

(4) Rating refers to a high-current point where collector-to-emitter voltage is lowest. For more information send for Fairchild Publication APP-4.

(5) Pulse Conditions: length = 300 μsec; duty cycle = 1%.

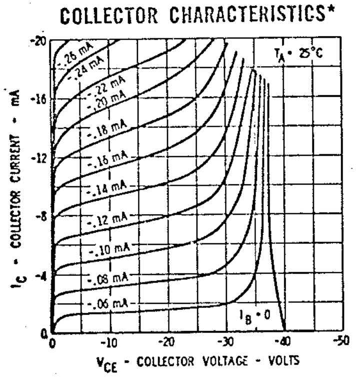
(6) See switching circuit for exact values of I_C, I_{B1}, and I_{B2}.

ELECTRICAL CHARACTERISTICS (25°C Free Air Temperature unless otherwise noted)

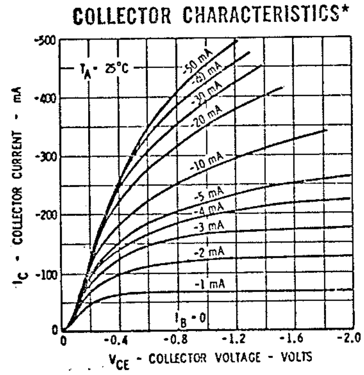
Symbol	Characteristic	Min.	Typ.	Max.	Units	Test Conditions
BV_{CBO}	Collector to Base Breakdown Voltage	-25			Volts	I_C = 100 μA I_E = 0
BV_{CES}	Collector to Emitter Breakdown Voltage	-25			Volts	I_C = 100 μA V_{EB} = 0
h_{FE}	DC Pulse Current Gain (Note 5)	30	67			I_C = 50 mA V_{CE} = -1.0 V
h_{FE}	DC Pulse Current Gain (Note 5)	20	40			I_C = 300 mA V_{CE} = -2.0 V
h_{FE}	DC Pulse Current Gain (Note 5)	20				I_C = 10 mA V_{CE} = -10 V
t_{on}	Turn On Time (Note 6)		28	75	nsec	I_C ≈ 300 mA I_{B1} ≈ 30 mA
t_{off}	Turn Off Time (Note 6)		110	170	nsec	I_C ≈ 300 mA, I_{B1} ≈ 30 mA, I_{B2} ≈ -30 mA
$V_{BE}(sat)$	Base-Emitter Saturation Voltage (pulsed, Note 5)		-0.9	-1.1	Volts	I_C = 50 mA I_B = 2.5 mA
$V_{BE}(sat)$	Base-Emitter Saturation Voltage (pulsed, Note 5)	-0.8	-1.25	-2.0	Volts	I_C = 300 mA I_B = 30 mA
BV_{EBO}	Emitter to Base Breakdown Voltage	-4.0			Volts	I_E = 100 μA I_C = 0
I_{CES}	Collector Reverse Current		0.1	35	nA	V_{CE} = -15 V V_{EB} = 0
$I_{CES}(65°C)$	Collector Reverse Current		0.002	2.0	μA	V_{CE} = -15 V V_{EB} = 0
C_{ibo}	Common Base, Open Circuit Input Capacitance			65	pf	I_C = 0 V_{EB} = -0.5 V

TYPICAL ELECTRICAL CHARACTERISTICS

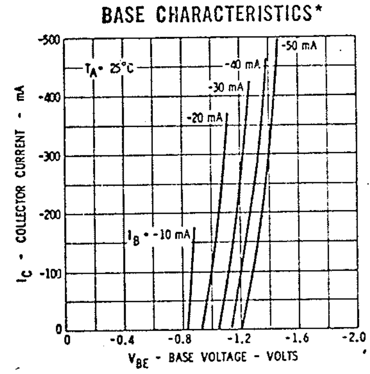
COLLECTOR CHARACTERISTICS*



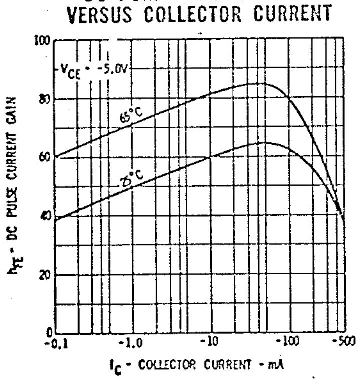
COLLECTOR CHARACTERISTICS*



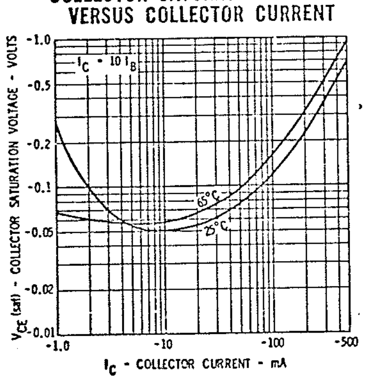
BASE CHARACTERISTICS*



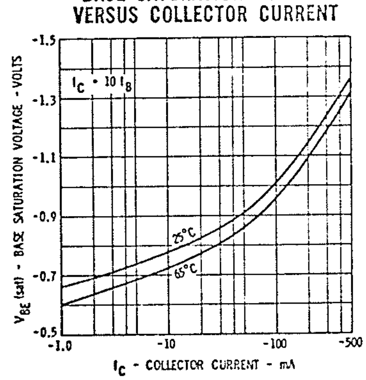
DC PULSE CURRENT GAIN VERSUS COLLECTOR CURRENT



COLLECTOR SATURATION VOLTAGE VERSUS COLLECTOR CURRENT



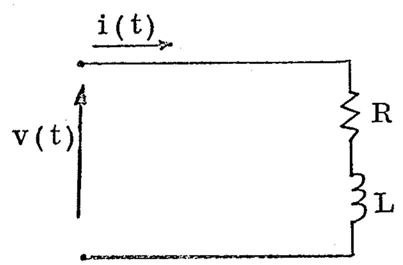
BASE SATURATION VOLTAGE VERSUS COLLECTOR CURRENT



* Single family characteristics on Transistor Curve Tracer.

APPENDIX C

CALCULATIONS SHOWING EFFECT OF CEILING VOLTAGE ON TRANSIENT CURRENT RESPONSE



Consider a circuit containing inductance and resistance with a step voltage applied.

FIG. C.1 R-L CIRCUIT

Kirchoff's Voltage Law gives:

$$v(t) = Ri(t) + L\frac{d\ i(t)}{dt}$$

Using Laplace Transforms with v(t) = a step voltage V gives:

$$V/s = (R + sL)\ I$$

Solving, $$i(t) = \frac{V}{R}(1 - e^{-\frac{R}{L}t})$$

$$T = L/R = \text{time constant of the circuit.}$$

The time required for the current to reach 90% of the steady-state value V/R can be calculated.

$$0.9\frac{V}{R} = \frac{V}{R}(1 - e^{-\frac{R}{L}t_1})$$

$$t_1 = 2.3\ (L/R)$$

If the magnitude of the step input was now doubled, the time for the current to reach 0.9 V/R is much smaller.

$$0.9\frac{V}{R} = \frac{2V}{R}\ (1 - e^{-\frac{R}{L}t_2})$$

$$t_2 = 0.6\ (L/R)$$

Hence, by doubling the applied voltage, the time required to reach 0.9 (V/R) is reduced by a factor of roughly 3.8. The following drawing indicates the improvement that is gained.

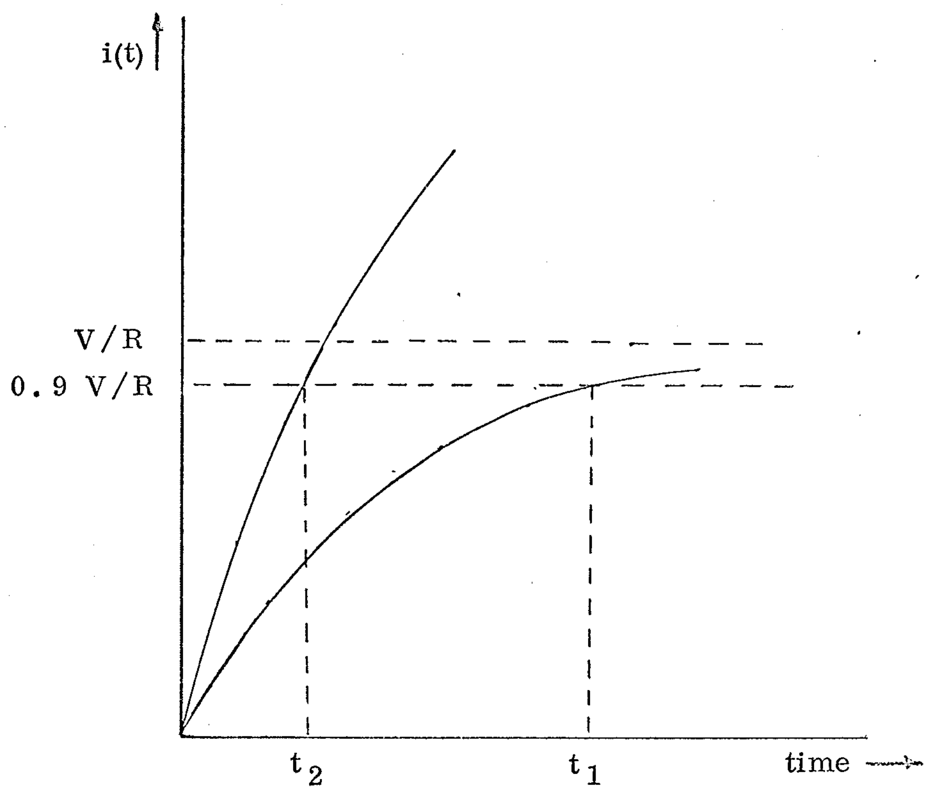


FIG. C.2 TRANSIENT CURRENT RESPONSE

APPENDIX D

OPERATING INSTRUCTIONS

These instructions outline the procedure to be used in operating the synchronous generator as a voltage regulator.

1. Start the induction motor.
2. Set potentiometers P1 and P2 to give the desired voltage.
3. Turn on the power for the field supply.
4. When changing to a higher voltage setting, adjust P2 first, then P1.
5. When changing to a lower voltage, adjust P1 first, then P2.

Caution:

1. When shutting down the system, turn off the field supply power before turning off the induction motor. Otherwise, excessive field current will result.
2. When observing waveforms in the circuit, use either a differential oscilloscope, or an oscilloscope which is isolated from ground.

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