C-56 THYRISTOR POWER SYSTEMS

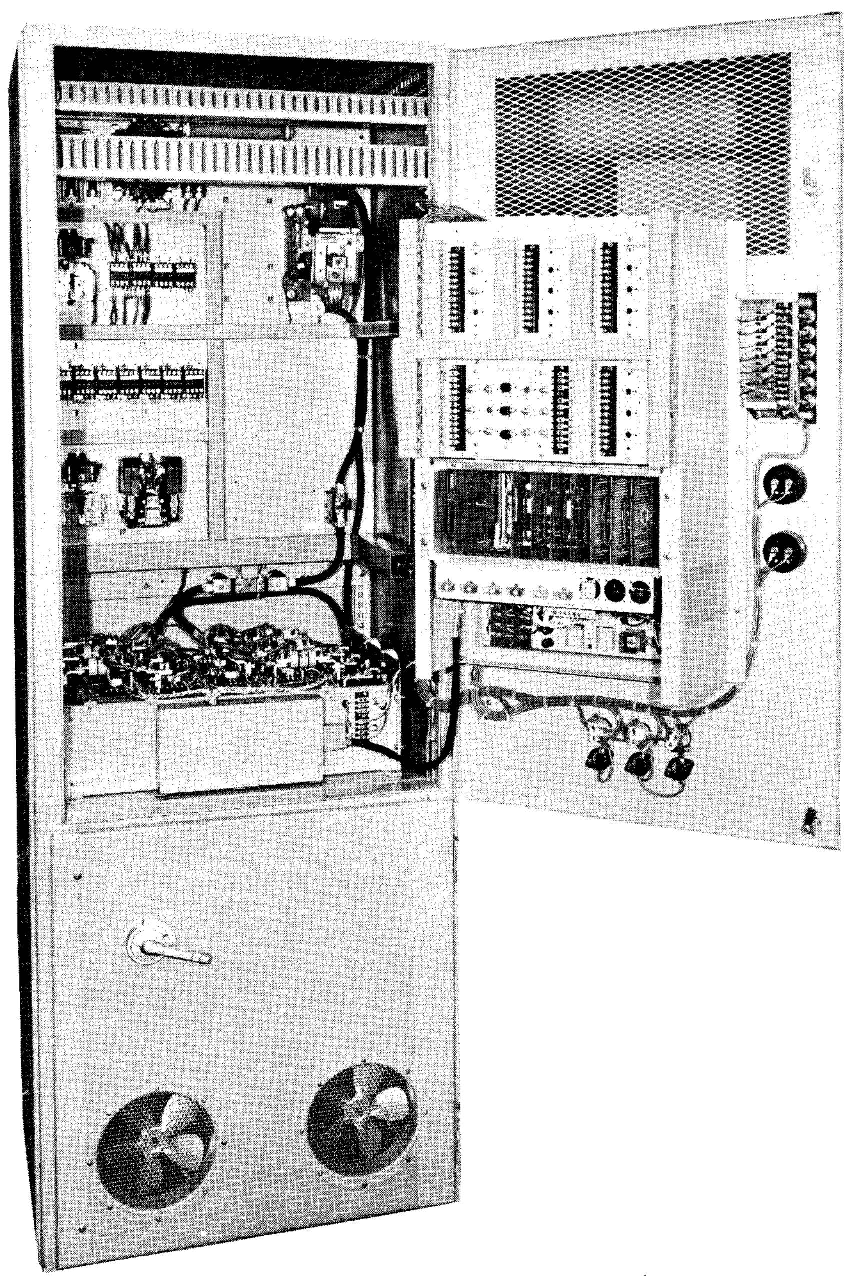


FIGURE I-1
C-56 THYRISTOR POWER SYSTEM

INDEX

I. INTRODUCTION

C-56 thyristor power systems (TPS) are primarily designed to provide adjustable-voltage power for armatures and fields of dc machines. These systems may be broken into two main parts:

(1) Thyristor power converter, consisting essentially of a thyristor power modulator (TPM), a thyristor power transformer, a basic regulator (gate control, sensors, reversing logic, ±24-vdc power supply, etc.) and of converter sequencing and protective elements.

(2) Variable regulator (process regulator), consisting of operational amplifiers, function modules, and referencing and director logic elements.

There are three distinct types of converters:

(a) Dual converter for dc machine armatures or fields. This type can provide output voltage and current of both polarities. The reverse converter can be of equal or smaller current rating than the forward converter. In the latter case, one speaks of an asymmetrical dual converter.

(b) Single converter for dc motor armatures. The output voltage is reversible in this type, but the current is restricted to one direction.

(c) Single converter for dc motor field excitation. Again the output voltage is reversible, but the current is restricted to one direction. This is in some way a simplified version of the type (b) above.

C-56 thyristor power converters are normally supplied by three phase lines of 460 volt-60 Hz, 550 volt-60 Hz or 380 volt-50 Hz. They cover an output power range of approximately 28A to 510A continuous at rated voltages of 240 volts, 375 volts, and 500 volts. The variable regulator portion is needed to complete a system for such functions as bus voltage regulation, current regulation, speed regulation, or combinations thereof.

A constant potential or adjustable voltage exciter can be added to the armature supply versions of converters. They have a rating of up to 18 amps, and are used to excite the field of the dc machine whose armature is powered by the main converter.

The entire C-56 thyristor power system is normally contained in a single, self-ventilated, NEMA I enclosure (Figure I-1). The thyristor transformer, ac breaker, and main ac fuses (if used) are housed in the plenum chamber at the bottom. The fans exhaust to the front. The TPM mounts on top of the plenum chamber, with the thyristors easily accessible. The rear panels are accommodating relays, contactors, auxiliary transformers and similar equipment. The basic and variable regulators are mounted on a bay swinging from the door for easy rear access. Start and stop pushbuttons, main meters and faultfinder are found on the front of the door.

II. SCOPE OF APPLICATIONS

Phase-controlled thyristor converter circuits can be classified into three groups. In the semiconverter configuration, only part of the rectifying legs are thyristors; whereas, others are diodes. This yields a power system for one-quadrant operation, which means that neither output voltage nor current is reversible.

In the single-converter configuration, all legs are thyristors. The output voltage is reversible, but not the output current, resulting in two-quadrant operation.

Connecting two single converters back to back, yields a power system with four-quadrant capability providing current and voltage of both polarities. This configuration is commonly named dual converter.

C-56 thyristor power systems employ single and dual converters of the six-phase, double-way, circuit configuration. As all six legs are controlled, six pulses per cycle are produced in the dc output voltage. This results in lower ripple content in the armature current than is the case of the six-phase, double-way, semiconverter circuit. However, the cost advantage of the semiconverter make it often an attractive choice in the lower horsepower range if one-quadrant operation is sufficient and if the motor can tolerate the larger ripple content in the armature current. The S-56 system (I.L. 16-800-100) is designed for these types of applications.

C-56 thyristor power systems (TPS) are mainly designed to:

(a) supply power for armatures of dc motors in the intermediate-power range (10-250 HP), or
(b) supply power for fields of large dc machines (generally, more than 1000 kw rating).

Referring first to application (a), the TPS usually includes variable regulators to perform armature voltage, armature current, or speed-regulating functions. Although not restricted to this task, the general field of application lies in powering industrial machines. They may be employed singly or in multiples on a common bus. The command system may be part of the TPS, as is the case in simple applications, or part of a central director or computer.

TPS for application (b) is used to power shunt fields of large dc machines requiring substantial power for this purpose. Single-converter types are generally employed for dc-motor adjustable-field excitation, where the current does not have to be reversed. Because of the capability of a single converter to reverse its output voltage as long as the current remains unidirectional, good forcing in both directions can be obtained. On the other hand, large dc generators usually require dual converters for field excitation. Because their armature voltage may have to be adjustable to very low values, the field current may actually have to reverse slightly to overcome the magnetic hysteresis of the frame. Further, full field reversal may be required in reversing drive applications.

Dual converters in C-56 TPS can be of the symmetrical or asymmetrical kind. In the first case, forward and reverse channel have the same rating. In the second case, the reverse current rating is only a fraction of the forward rating. The selection of the type to be used depends on the application.

III. THYRISTOR POWER CONVERTER (TPC)

A. Phase-Controlled Converter Principles

A thyristor power converter is an apparatus which by means of phase-controlled gating of thyristors (or other controlled rectifier cells) converts an ac supply line voltage into an adjustable dc voltage; this process is known as rectifying. Inversely, dc voltage can be converted back into the ac line voltage; this mode of operation is called inverting. A converter which only can perform one of these functions is called a rectifier or an inverter, respectively.

Once a thyristor is turned on, it can only be turned off by reducing the anode current to a very small value. In the phase-controlled converters, the ac line voltage performs the function to end the conduction period by commutating the anode voltage.

Many converter configurations have been developed. The six-phase, double-way circuit (three-phase bridge) has evolved as the preferred arrangement for thyristor power supplies. It is simple and offers the best thyristor and transformer utilization. Figure III-1 shows the elementary schematic of such a converter. The transformer is delta-wye connected. Such a transformation (or the inverse of it) is desirable because it eliminates flux ripple of the third harmonic in the core. The main purpose of the transformer is to adjust the line voltage to the proper level, to provide isolation and to introduce inductance into the converter current path. This inductance is required to control the rates of currents during commutation and faults as will be seen later. The dc output side of the converter is connected to a load circuit consisting of a counter emf e_a resistance R_d and inductance L_d.

The significant current paths and waveforms can now be developed (Figure III-2). The uppermost traces show the secondary line voltages, measured from the first terminal letter to the second terminal letter. Initially, all thyristors are assumed to be in the blocking state. At $\omega t = 15^o$, a pulse is simultaneously applied to the gates of thyristor No. 6 and 5. Both of these cells become conductive and a path exists from W to P through the load to N and then to V. Thus, the line voltage e_{wv} is applied to the load. However, 60 degrees later, at $\omega t = 75^o$, gate pulses are applied to cells No. 1 and 6; No. 6 is already conducting. Cell No. 1 is turned on and the load current will commutate from No. 5 to 1 because the voltage e_{uv} is larger than e_{wv} at this instant. Again 60^o later, No. 2 and 1 are gated and a similar commutation will take place on

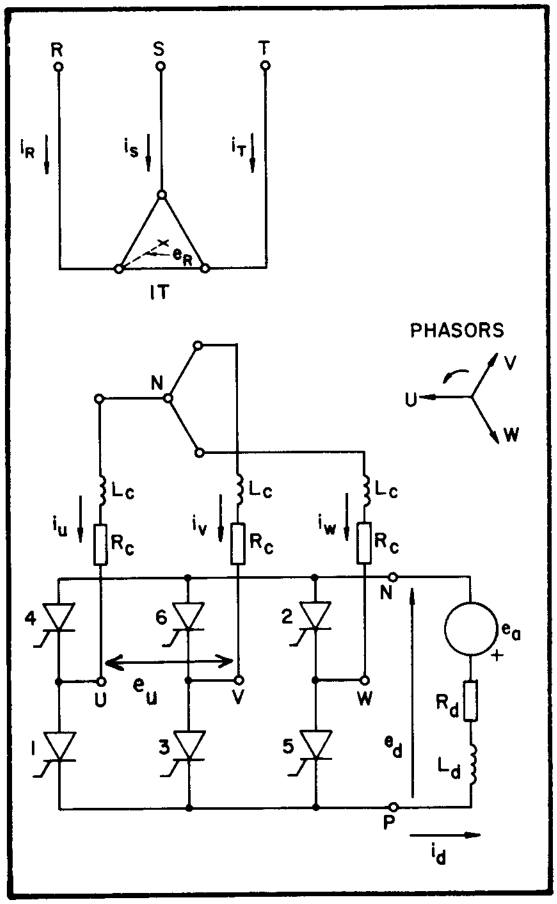


FIGURE III-1

SIX-PHASE, DOUBLE-WAY CIRCUIT

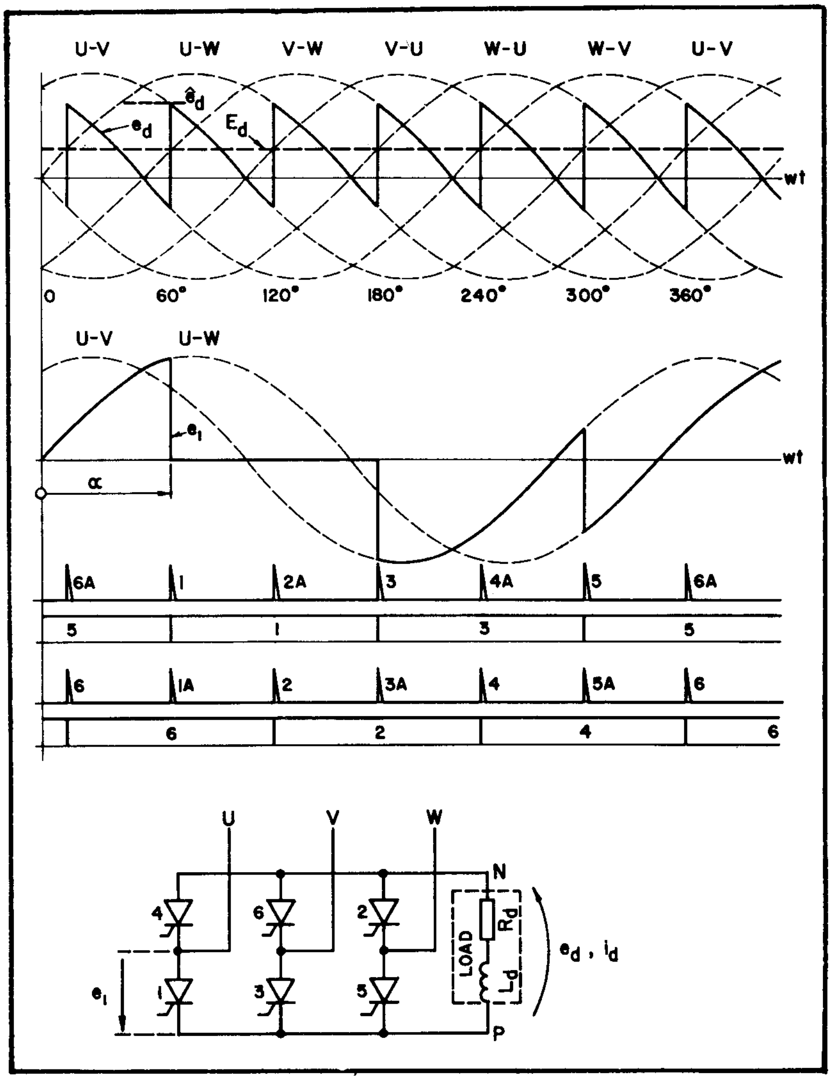


FIGURE III-2

WAVEFORMS OF THYRISTOR CONVERTER AT $\alpha = 75^{0}$

the even numbered (negative) side of the bridge circuit. Assuming that the load is highly inductive, the dc current will reach a steady value after a number of cycles, and each thyristor will then conduct a 120^{0} wide current block each cycle. The respective waveforms of the thyristor anode-cathode voltages can now be easily developed. Figure III-2 illustrates this for a gating angle of $\alpha = 75^{0}$. Note that α is measured from the point where the anode-cathode voltage of the respective cell swings positive. Hence, for $\alpha = 0$, the thyristors do not have to absorb any positive voltage anymore and are then comparable to simple diodes. It is apparent from the waveshapes of the output voltage that its average value E_d is a function of the gating angle. It reaches a maximum at $\alpha = 0^{0}$, is zero for $\alpha = 90^{0}$ and assumes negative values back to $\alpha = 180^{0}$. This transfer curve can be obtained by integrating the waveforms. The result is:

$$E_d = E_{do} \cos \alpha$$

where the saturated output voltage is

$$E_{do} = \frac{3\sqrt{2}}{\pi} E_u$$

where E_u ··· line-to-line rms ac voltage.

Since the load current cannot reverse, the average power flow will change its sign with the voltage. Rectifier operation ($\alpha < 90^0$) renders motoring in the load circuit whereas inverter operation ($\alpha > 90^0$) requires the load to be generative.

Figure III-3 illustrates the range of operation on a time basis. In the beginning, the converter is operated in its rectifying mode with $\alpha = 0$. Then α is steadily increased into the inverter mode of operation. The lower trace shows the voltage across one of the thyristor legs.

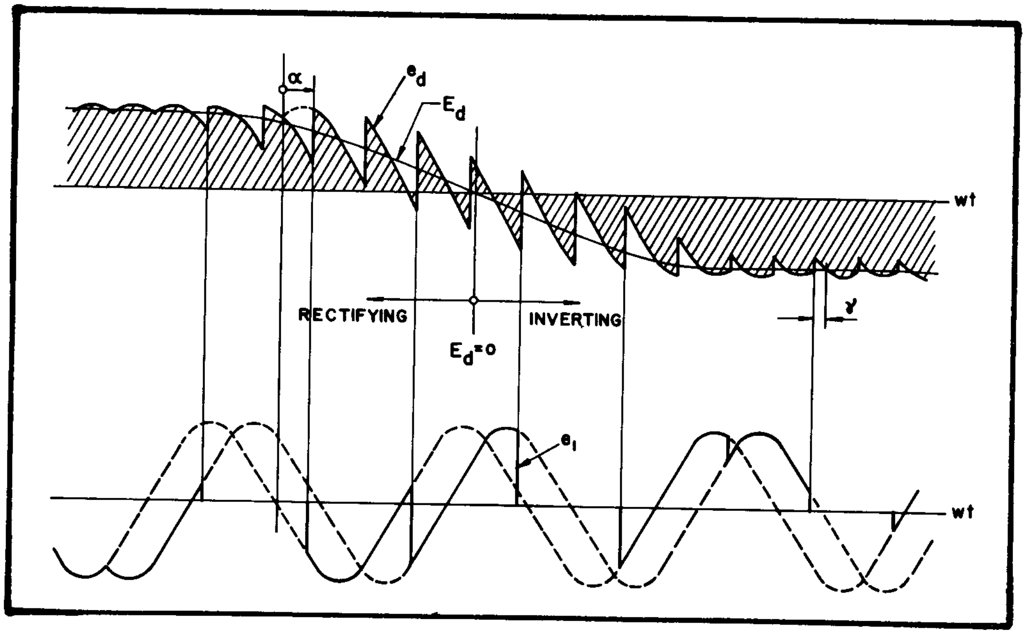


FIGURE III-3

RANGE OF OPERATION ILLUSTRATED ON A TIME BASIS
ON THE LEFT, $\alpha = 0$, RECTIFYING MODE.
α THEN INCREASES TO INVERTER MODE

Up to this point, the reactances offered by the transformer and the power line have been neglected. This so-called commutating reactance, however, is significant. Instead of instantaneously commutating the load current from one leg to another leg (upon gating of the latter), the current rate is limited and shaped by it. This means that both these legs conduct simultaneously for a period of time, shorting out effectively the ac source. This produces notches in the sinewave measured on points U-V-W, which, in turn, reduce the dc bus voltage.

Taking account of these commutation effects, one can derive a converter equation which includes this reactive drop:

$$E_d = E_{do} \cos \alpha - E_{do} \tfrac{1}{2} x_c \, I_d / I_{dn}$$

where x_c --- relative reactance of transformer (based on I_{dn})

I_d --- actual dc current

I_{dn} --- nominal (rated) dc current.

The assumption made so far was that the dc load current is continuous, and the equation applies for this condition only.

In a practical circuit such as commonly found with dc motor armatures as load, the actual operation always covers the range of discontinuous current at light load levels also. Reducing the load current, one finally reaches a level where the ripple amplitude is high enough to interrupt the current cyclicly. At this transition point, the regulation characteristic takes a sharp break and aims to a point equal to the peak converter voltage e_d at zero load current. This transition point depends on the gating angle α, the inductance and the losses in the load circuit.

Commutation from a first leg to a second must always be completed before the anode voltage of the second leg swings negative. If the latter should happen, the commutation is incomplete and the full-load current will commutate back into the first leg. This situation can only arise if the commutation was initiated at a high gating angle (in the inverter range) and if the load current is continuous.

The circuit described so far can provide voltage of both polarities. The current, however, can only flow in the conducting direction of the rectifying cells. This circuit is, therefore, classified as unidirectional or single converter.

If current reversal is required, a second converter can be added and connected to the first one in an antiparallel circuit as shown in Figure III-4. Since such a circuit can produce load current in both directions, this circuit is classified as a bi-directional or dual converter.

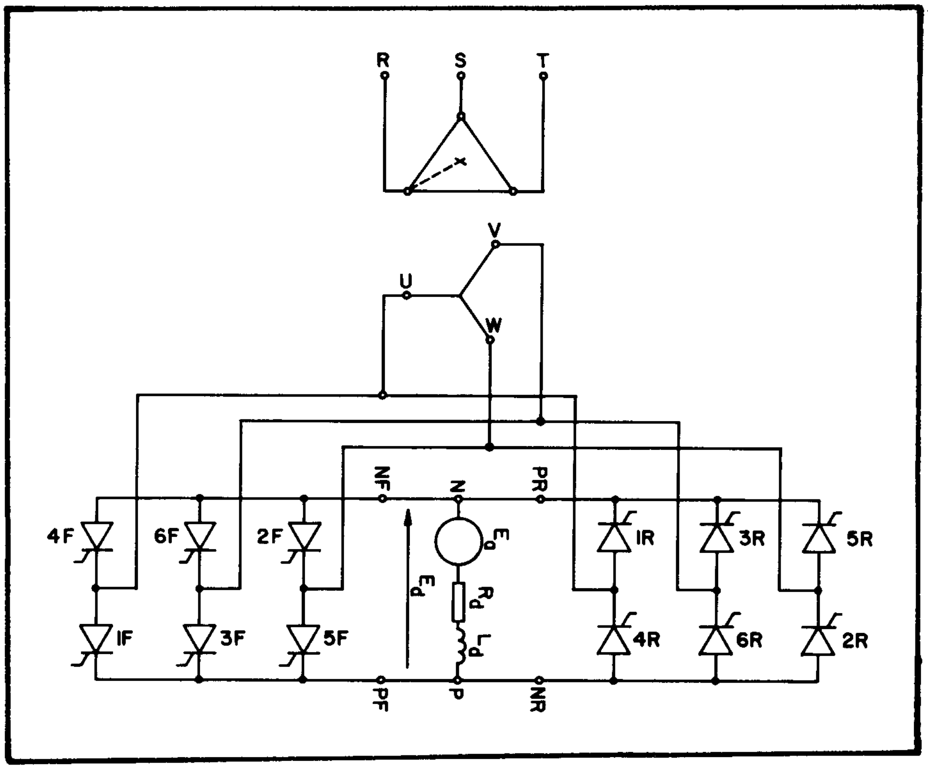


FIGURE III-4

DUAL CONVERTER, ANTIPARALLEL CIRCUIT

There are several ways to control such a dual converter. The principle used in C-56 is based on the recognition that only one converter channel has to be gated at any one time. Thus, one gate control system can be used on a time-shared basis for the two converters. This requires, however, a logic system to determine whether the forward or reverse converter should be gated at any particular time. The operation will now be explained with the help of Figures III-5 and 6. The systems diagram, Figure III-5, shows the main control elements of the dual converter, with the power circuit in single line diagram form.

A so-called inner voltage loop is closed. This regulating loop is not only utilized to develop the proper signals for current reversal, but also helps greatly to overcome the nonlinearities of the power converter characteristic when going from continous to discontinuous current. This loop makes it possible to consider the converter system for the outer (variable) regulator loops as a "black box" amplifier with nearly ideal characteristics.

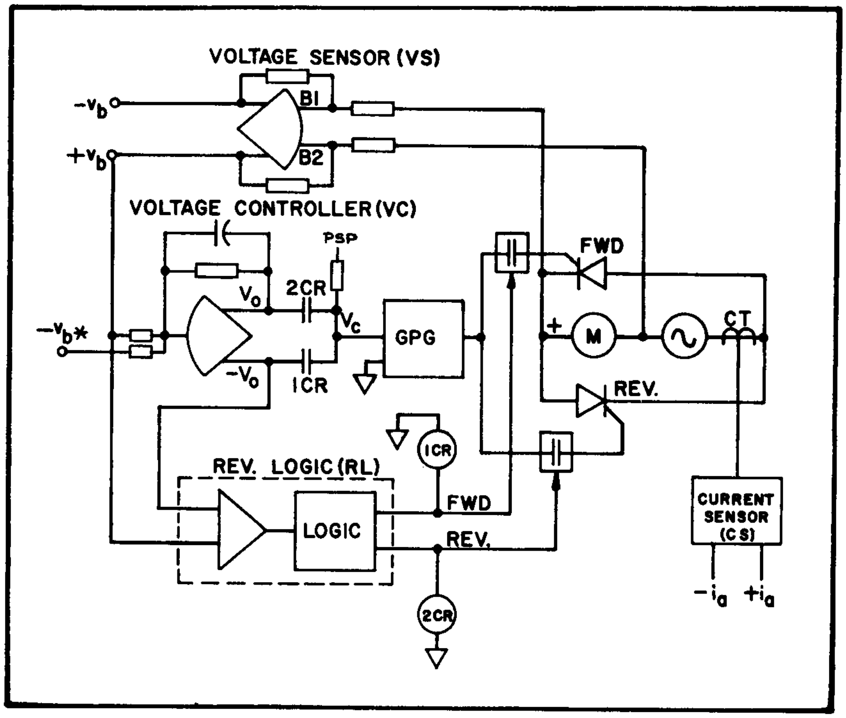


FIGURE III-5

DUAL-CONVERTER SYSTEM

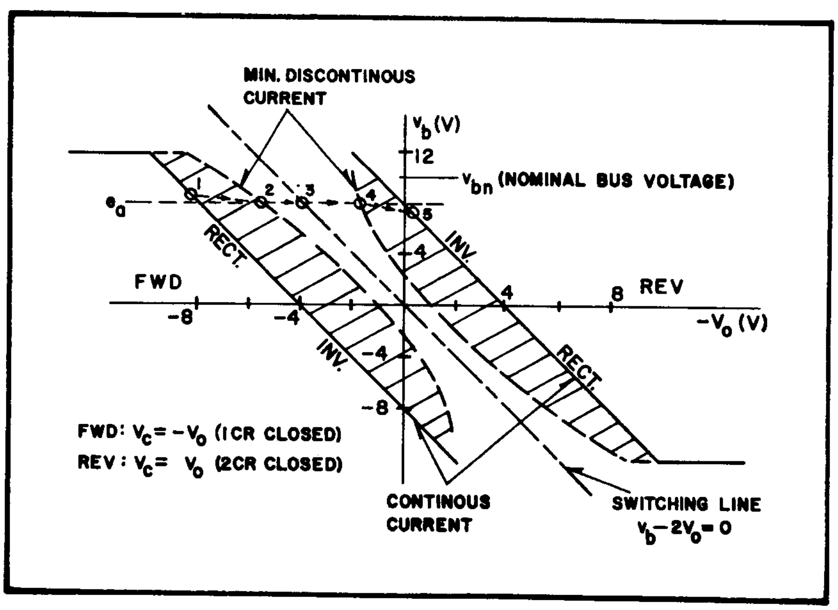


FIGURE III-6

DUAL-CONVERTER CONTROL CHARACTERISTIC

The bus voltage is picked up by the voltage sensor (VS) and brought to one input of the voltage controller (VC), which is a differential output amplifier. There it is compared with the reference voltage $-v_b*$ applied at a second input. Depending on the polarity of the difference of the two voltages, the output voltage $-v_0$ will swing negative or positive. By comparing this output voltage $-v_0$ with the bus voltage v_b, the polarity of converter conduction can be determined. For example, if the bus voltage v_b is smaller than the reference signal v_b*, forward load current conduction is indicated, and therefore the forward channel of the dual converter should be pulsed. Under this condition, $-v_0$ is negative, and compared with v_b at the input of the reversing logic (RL) module will result in its output picking up relay 1CR and closing the gate pulse distribution switch to the forward converter.

If now the reference v_b* is suddenly reduced to demand reverse current, the opposite sequence of events will take place.

Figure III-6 shows the output voltage of the power converter as a function of the input voltage to the gate pulse generator (GPG) for the cases of continuous current and minimal discontinuous (pulsing) current. The shaded area between represents the field of various possible states of conduction.

The case of minimal discontinuous current is mainly of interest for armature loads. It is representing the case for a gating angle adjustment where the peaks of the converter output voltage ($\hat{e}_d$) are just matching the counter emf of the motor (see Figure III-2). For any higher gating angle no current conduction can set in any more. This then means that no current flow can continue in the area passed the minimum discontinuous current line. Shifting into this area indicates that current of the opposite polarity is required. However, to simplify the sensing of this condition and to add some safety margin, actual switching is initiated when the indicated switching line is crossed.

With the converter initially in the forward conduction mode, a reversal shall now be described. The counter emf e_a of the load is assumed to be as shown in Figure III-6 with the forward converter rectifying at point 1. The relay 1CR is picked up and the forward gate pulse distribution switch is closed. Suddenly the reference v_b* is lowered to a value below e_a, demanding a current reversal. This will cause the VC output voltage $-V_0 = V_c$ to advance toward positive values. At point 2, the forward current will stop all together; and at point 3, the reversing logic sequence will be initiated. Relays 1CR will drop out and the forward pulse switch will open. Dropping 1CR in the voltage controller results in the voltage V_c assuming a value large enough to phase out pulsing in the GPG. About 3ms later, relay 2CR picks up and the reverse pulse switch closes, making the reverse converter ready for control. Closing 2CR has the effect of picking up a signal V_c at the output of VC which is equal to V_0. Now the transfer curves for the reverse converter in Figure III-6 apply. The transfer of the voltage V_c from $-V_0$ to V_0 is equivalent to a reversal of the feedback polarity, which is required to compensate for a similar reversal in the power converter. The voltage $-V_0$ continues toward positive values, and at point 4, the reverse converter starts to pick up current operating in the inverting mode. Finally at point 5, the new quiescent state of reverse conduction has been reached where v_b is matching again the reference v_b*.

The opposite sequence of events takes place in case of a change from reverse to forward current.

Figure III-7 shows an oscillogram of a current reversal in a dual converter with current regulator. The various traces are self-explanatory in connection with the description above and the one found in Chapter III-3 and with the help of the basic regulator diagram Figure III-9.

B. <u>Thyristor Power Modulator (TPM)</u>

This modulator assembly includes the thyristors connected in a six-phase, double-way circuit. The thyristors are mounted on heat sinks. Two thyristors are connected back to back in case of the dual-converter TPM. A typical diagram is depicted on Figure III-8. The thyristors are protected by current limiting fuses. The RC networks across the cells serve in conjunction with the ferrite reactors 1L thru 6L to attenuate excessive rates of voltage, which otherwise may lead to undesired turn-on of thyristors. There are RC networks across the ac phases and the dc output to damp the oscillations that would otherwise be produced by the commutation process.

Three types of TPM's are used:

- Single Converter TPM
- Dual Converter, symmetrical TPM (identical thyristors forward and reverse)
- Dual Converter, asymmetrical TPM (reverse thyristors smaller than forward thyristors).

All types have a pulse distributing module (PD) attached to the front. It is in some way an extention of the gate pulse generator, and it is described in conjunction with it. To provide the necessary isolation and further shape the gate pulses, pulse transformers are inserted between the PD module and the thyristor gates. All C-56 TPMs are equipped with a thermo-switch mounted on the surface of a heat sink. This device monitors the sink temperature and shuts down the system in case of loss of cooling air.

For more details and ratings, refer to I.L. 16-800-135.

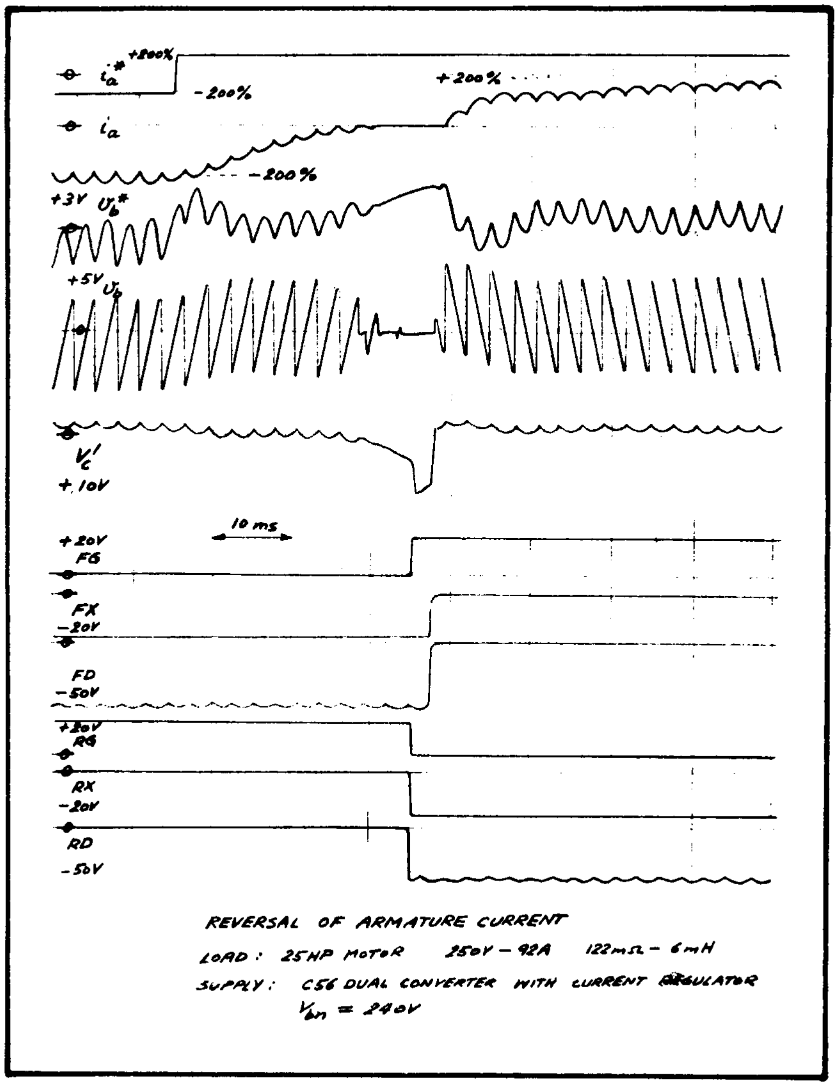


FIGURE III-7

C. Basic Regulator

The basic regulator contains all components required for controlling the thyristor power modulator. There are three basic styles, namely, for:

(1) Dual Converters. The basic regulator houses all components required to close an inner-voltage loop, to sense bus voltage and current, to sense the demand and execute current reversals, and to provide gate pulses to the TPM. An internal dc power supply provides all internal circuits, and is also available for external use (variable regulator, etc.).

(2) Single converters for motor armature supplies. The basic regulator houses the same components as above, except the ones for current reversal are deleted.

(3) Single converter for motor field excitation. In this case, no inner-voltage loop is closed. Therefore, the components for voltage sensing and current reversal are deleted.

Styles (1) & (2) can be extended to incorporate also a gating and current controller module for a small field exciter.

Figure III-9 shows a signal distribution diagram of a basic regulator for dual converters. It has been selected for the step-by-step description below. The other two versions are simpler derivatives of it.

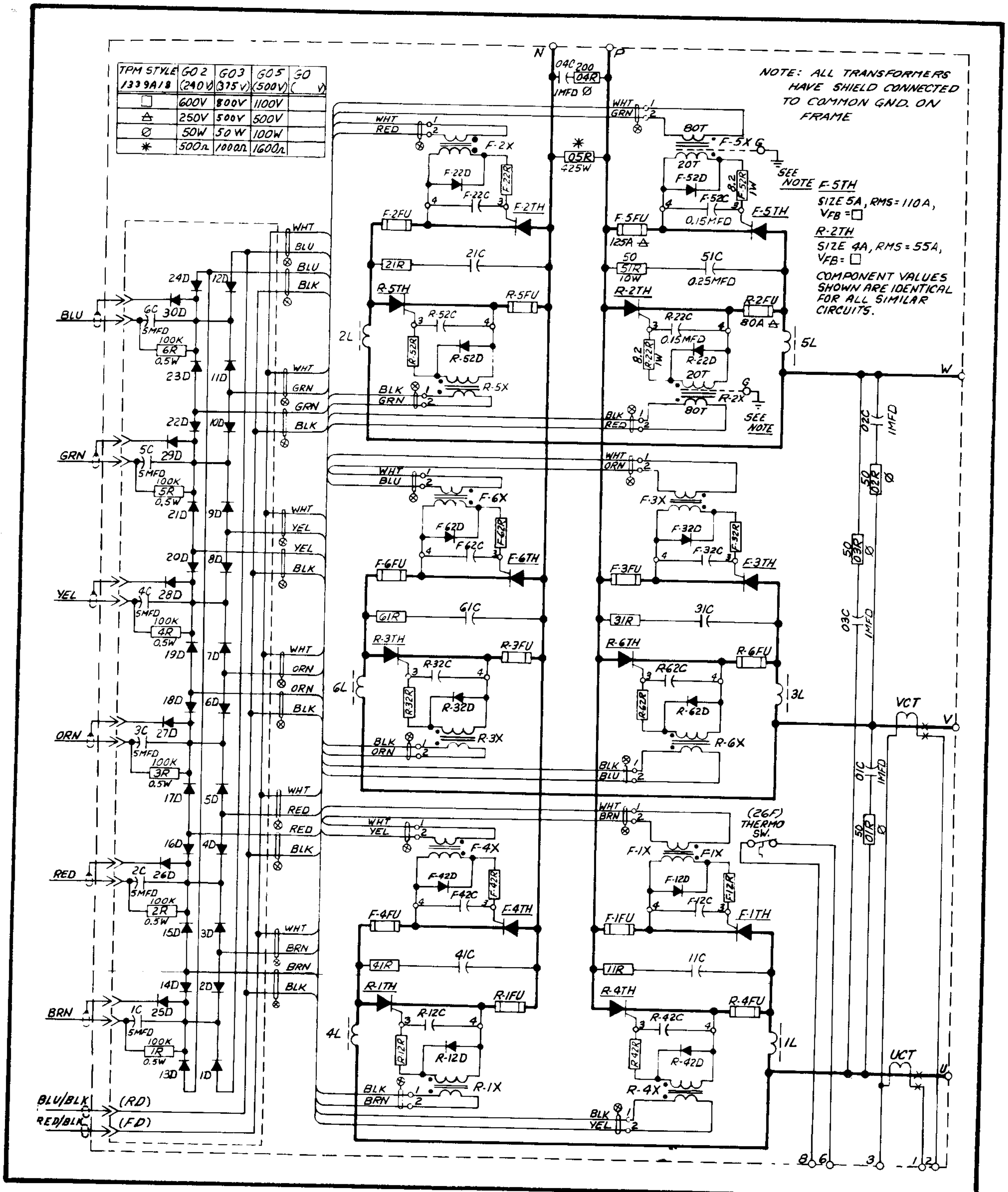


FIGURE III-8

THYRISTOR POWER MODULATOR - ASYMMETRICAL DUAL CONVERTER

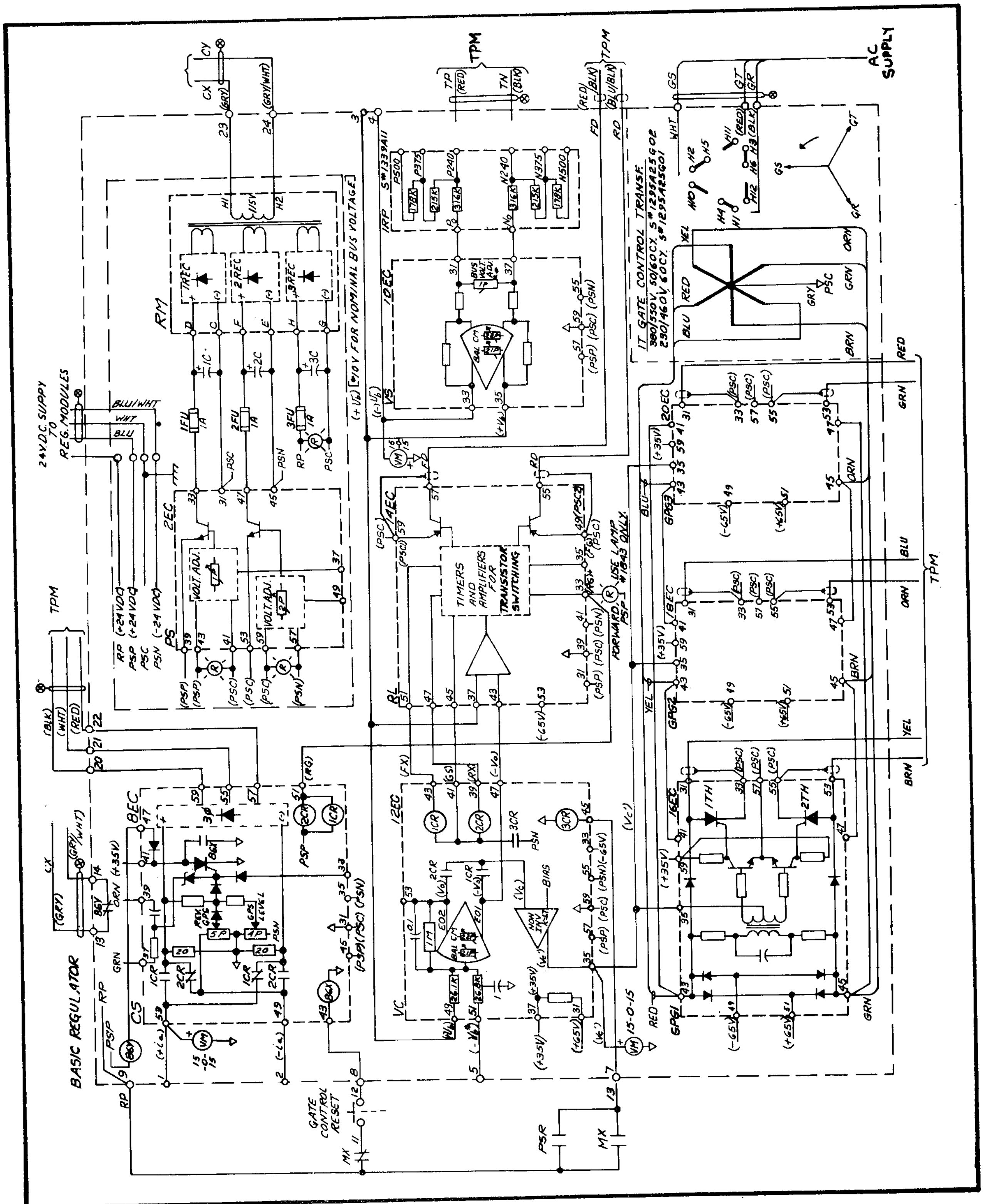


FIGURE III-9
BASIC REGULATOR SIGNAL DISTRIBUTION

1. Gate Pulse Generating System

This subsystem consists of three gate pulse generator pc boards (GPG1---3), a gate control transformer 1T, and a pulse distributor module (PD), which is mounted on the TPM. It meets the following requirements:

a. The GPG provides a linear relationship between the input dc control signal and the internal voltage of the power converter. Since the internal voltage varies as the cosine of the gating angle, the phase position of the output pulses of the GPG must vary as the inverse cosine of the dc control signal.

b. When the input dc control signal demands a phase delay exceeding 170 degrees, pulse generation is inhibited.

c. When the input dc control signal demands a phase advance ahead of 10 degrees, pulse generation will continue; the gating angle will remain at 10 degrees.

d. The gating angle responds instantly to the input dc control signal within the gating cycle to provide precise pulse timing, to allow for instantaneous pulse suppression for fault protection, and to avoid the insertion of time delays in the feedback control loops.

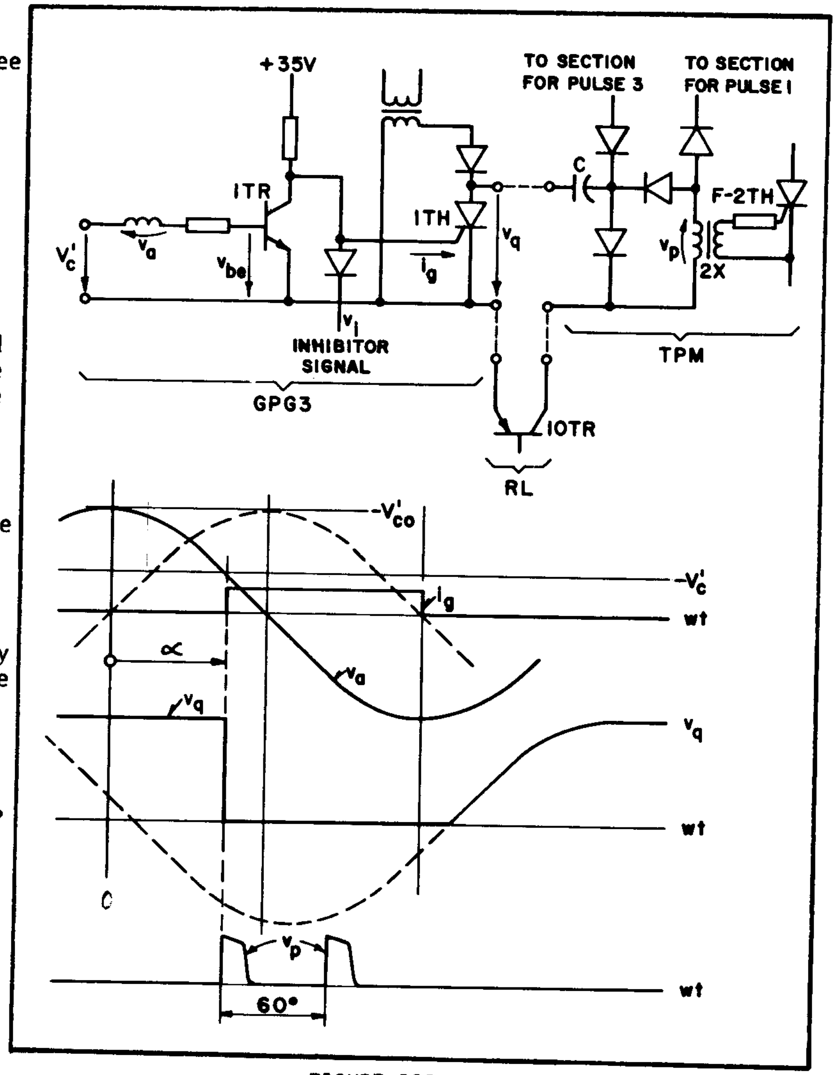


FIGURE III-10
GATE PULSE GENERATION

e. The gate pulse generator provides six output pulses per cycle that remain precisely spaced 60 degrees apart over the entire phase shift range under steady-state conditions.

f. The output pulses have a rise time of less than one microsec and a shape and energy content as required by the thyristors in the TPM.

A simplified schematic diagram of the GPG which has been developed to provide these characteristics is shown in Figure III-10. A control method known as vertical control lends itself ideally to generate the desired inverse cosine function. A cosine wave v_a is intersected by the control voltage V_c'. As long as $v_a > -V_c'$, the transistor 1TR is turned on. At $\omega t = \alpha$, the transistor turns off, and the collector current commutates into the gate of signal thyristor 1TH. The latter turns on and produces a pulse through the output transformer.

The operating range must be restricted as shown in Figure III-10. This is done by feeding an inhibitor signal v_i into the circuit which prevents pulsing at times when the anode voltage of the corresponding power thyristor is negative.

As v_a is taken from the same ac line as the feeder voltage R-S-T of the power circuit, the system becomes self-compensating for line voltage dips.

Each circuit can produce one pulse per cycle. However, six pulses at 60^{0} spacing are required to control the six-phase, double-way converter. The gate pulse generator module contains the components necessary to produce these six pulses. However, part of the pulsing system is incorporated in the TPM. The capacitor C is charged at time $t < 0$. Then, at $\omega t = \alpha$, a pulse i_g is applied to thyristor 1TH. Capacitor C discharges through the output transformer 2X, which has its secondary windings connected to the thyristors in the thyristor power modulator. Transistor 10TR in the reversing logic (RL) module has to be turned on for this purpose (a similar circuit path exists to gate the reverse thyristor R-2TH if the reverse distribution switch 7TR is closed).

In a six-phase, double-way converter circuit, it is necessary that two legs are conducting simultaneously to complete a current path through the load. Gating pulses occur every 60^{0} and are channeled sequentially to each of the six legs of the converter circuit. To ensure a conduction path, a pulse applied to a leg on the positive side of the circuit (e.g., leg 1) must overlap with the following pulse applied to a leg on the negative side (e.g., leg 2). Therefore, the pulses must either be larger than 60^{o} in width, or a second pulse must be applied 60^{o} after the first one to ensure a conduction path under any condition of operation. The second, so-called, double-pulse method allows the use of narrow pulses having fast rise time and high peak energy content, both necessities for reliable gating of high-power thyristors. This method has, therefore, been chosen. Figure III-10 illustrates how the second pulse is fed into the circuit from the similar section producing the following pulse, and how a pulse is fed on to the preceding section. Figure III-2 shows how the pulses are distribued in the TPM.

For a detailed description of the GPG, as well as for its ratings and characteristics, see I.L. 16-800-127.

2. <u>Voltage Sensor (VS)</u>

This module is used to sense the dc bus voltage and to transduce it to a regulator signal for use in the basic as well as the variable regulator. A transistorized differential amplifier with excellent common-mode rejection is utilized in an op-amp manner. The output voltages are essentially independent of the bus potential to ground, but reflect only the difference of the potentials at P and N. The input attenuator is adjusted to yield output voltages of ±9.6V for nominal bus voltage. This voltage sensor is not used in single converters for motor field excitation because no inner-voltage loop is utilized there. For a detailed description as well as ratings and characteristics, refer to I.L. 16-800-130.

3. <u>Current Sensor (CS)</u>

There is a design each for dual converters and single converters. The CS module is used to sense the dc output current. It accomplishes this with the help of a set of current transformers metering the ac current flowing into the TPM. The output signals from these CTs are rectified and brought to two burden resistors, where both polarities of current signals become available. These signals are true reflections of the waveform and magnitude of the TPM dc output current.

The proper polarity of these signals are selected by the relays 1CR and 2CR, which are energized by the reversing logic module.

The burden voltage is also supplied thru resistors to the gate of a thyristor. If its magnitude exceeds a preset bias level, this thyristor is triggered. It will then short out the 35V supply to the GPG, which will suppress any further gate pulses. The sensitivity level for reverse current can be recalibrated by an additional potentiometer.

After such gate pulse suppression has occurred, the thyristor can be reset to its blocking state by temporarily energizing relay 86X.

A phase sequence and single-phase detector circuit is also incorporated in this module. Two 120^{o} displaced ac voltages are supplied to an R-C network; and depending on the sequence, its output voltage magnitude may or may not be sufficient to overcome the breakover level of the zener diode to the gate of the thyristor. In the first case (improper sequence or single phasing), gate suppression occurs.

The current sensor for single converters differs from the dual converter model only slightly. There are no reversing relays. Instead, the normally-open contacts are replaced by jumpers. There is also no recalibration potentiometer for reverse gate pulse suppression. For a detailed description, as well as ratings and characteristics, refer to I.L. 16-800-132.

4. Voltage Controller (VC)

This module serves as comparator for the voltage feedback and reference signal. It amplifies the difference in a transistorized differential amplifier utilized as an op-amp. The time delay at the reference input is required to modify step inputs to signals of acceptable rate for the converter system. The time delay across the amplifier itself is required to stabilize the "inner" voltage loop of the converter. Depending on the direction of the output current, either one or the opposite amplifier is selected by relays 1CR or 2CR, and brought to a low-gain driver amplifier which also incorporates bias means for the GPG.

Relay 3CR is used to stop gate pulsing when sequencing the converter into and out of service. When the input to the low-gain driver amplifier is opened up, its output assumes a voltage value which causes the GPG to phase out. Further, opening 3CR causes the pulse distributing transistors in the reversing logic to turn off.

For single-converter applications for motor armature supplies, this module is somewhat modified. The selecting relays 1CR and 2CR are not required. Instead, a clamp is added to reduce the gain when the output voltage swings to values which indicate that current conduction has stopped. At the same time, a signal is produced to simulate reverse current flow, which is utilized to clamp the current controller in cascaded (variable) regulators. For a full description, ratings and characteristics, refer to I.L. 16-800-129.

5. GPG Driver (GD)

This module is only used in power converters for motor fields. In this application, no inner-voltage loop is closed. The sole purpose of the module is to adapt the signal of an input device (such as a flux controller) to the GPG, and to serve the function of pulse suppression when sequencing the converter into and out of service. The circuit is essentially similar to the low-gain amplifier portion of the voltage controller. Biasing levels are chosen such that the converter is pulsed at about 95° for zero input volts to this module. For a full description, ratings and characteristics, refer to I.L. 16-800-131.

6. Reversing Logic (RL)

The function of the reversing logic module has been described in the chapter "phase-controlled converter principles". Depending on the values of the signals $-V_0$ and v_b, either the forward or reverse distribution switch is turned on, and appropriate reversing relays are operated.

There are three sets of outputs. RG and FG change states as soon as the input comparator switches. FX and RX operate conditionally with time delay. For instance, if the initial state is "forward conduction", and a reversal is demanded, FX will immediately swing from 0 to -24V. However, RX will only switch from -24V to 0V in approximately 3ms. The same principle holds for the outputs FD and RD, which are serving the function of pulse distribution to the forward and reverse converter respectively. A low-energy bulb (28V - 22mA) is driven by output RG. It lights up if the state of the logic is for forward current conduction. A more detailed description, ratings, and characteristics are given in I.L. 16-800-134.

7. DC Power Supply

The power supply consists of the following essential parts:

rectifier transformer
bridge rectifiers
filter capacitors
±24 V power supply regulator module.

115 vac is reduced to a suitable level by a transformer with three secondary windings. Two of these windings are used together with the rectifiers 1REC and 2REC, and the capacitors 1C and 2C to produce two independent 40 vdc nonregulated power sources. They are applied to a power supply regulator module (PS). At its output, a highly-regulated, ±24 vdc power source for feeding transistor circuits is available.

The third winding together with 3REC and 3C produces 24V nonregulated power for small control and reed relays.

The outputs of the power supply are monitored with incandescent bulbs. Fuses provide short circuit protection. For a full description, characteristics, and ratings, see I.L. 16-800-128.

D. Converter Sequencing and Protection

The sequencing elements and their deployment required to turn the converter on or off depend on the application. The same is true to some extent for the protective element. There is a main difference between the schemes employed for armature supplies and field supplies. They shall therefore be discussed separately.

1. Armature Supplies

Figure III-11 shows a single line diagram of a dual-converter armature supply. The ac voltage is brought from the customer feeder to an ac breaker (device 52), which depending on the short-circuit capacity may be followed by current limiting ac fuses. This breaker is feeding both the thyristor transformer as well as the gate control and regulating system. It may therefore, as an option, be located in the customer distribution center. This common supply without interlocking of the TPM and gate control is made possible by a design feature of the GPG which eliminates any spurious pulsing during the ac turn-on transient.

The molded-case, type-AB, ac breakers employed in C-56 systems have magnetic trip only, set high enough that no tripping occurs due to the transformer inrush current.

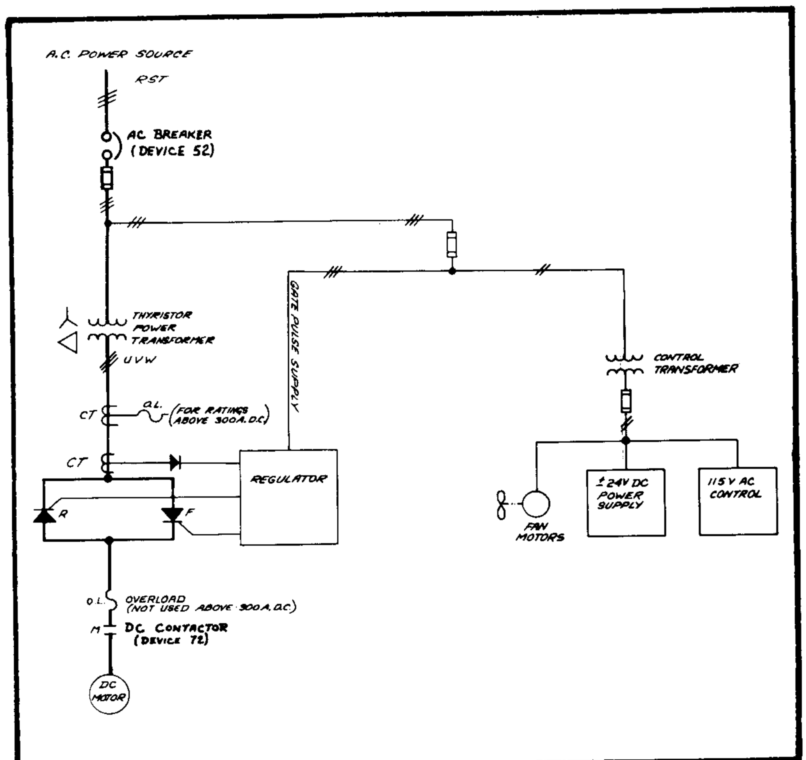


FIGURE III-11

THYRISTOR POWER SYSTEM
(Dual Converter, Armature Supply)

The transformer secondary current is metered with current transformers. In the current sensor, the dc current is synthesized (see III.C.3). If this current exceeds a certain preset value, gate pulse suppression is initiated, which prevents any further commutations. This stops the dc current flow during rectifying service. Gate pulse suppression is normally set to about 120% of the maximum current (current limit setting) demanded during normal operation.

The main sequencing device is the dc contactor (device 72) between the power converter and the dc motor armature. Its main function is to de-energize the motor positively in case of an emergency or if any work is required on the driven machinery. It is not providing any electrical isolation of the armature. This is accomplished by tripping the ac breaker.

Figure III-12 shows a typical sequencing control diagram for an armature supply. The power supply push buttons are located on the C-56 cubicle. Interlocks in zone A are of the type generally under the control of electricians, e.g., cooling fans, auxiliary motors, overloads etc. If all these interlocks are closed and gate pulse suppression is reset (86Y), then relay PSR can be picked up upon depressing the "ON" button. This will pick up relay 3CR in the voltage controller (see Figure III-9) which starts gate pulsing and makes the power converter ready for operation. A second set of pushbuttons may be located on the operators station, if required. Upon depressing the contactor "CLOSE" pushbutton, the MC relay will pick up if all interlocks in zone B are closed and the motor is stopped (VRX dropped out). The interlocks in zone B cover functions which are under the control of the operating personnel, e.g. lubricating pumps, limit switches, proximity switches, etc. This split into A and B interlocks is intended to clarify the responsibilities in case of problems. It also allows the operator to restart the drive after correcting B interlock state, without an electricians help.

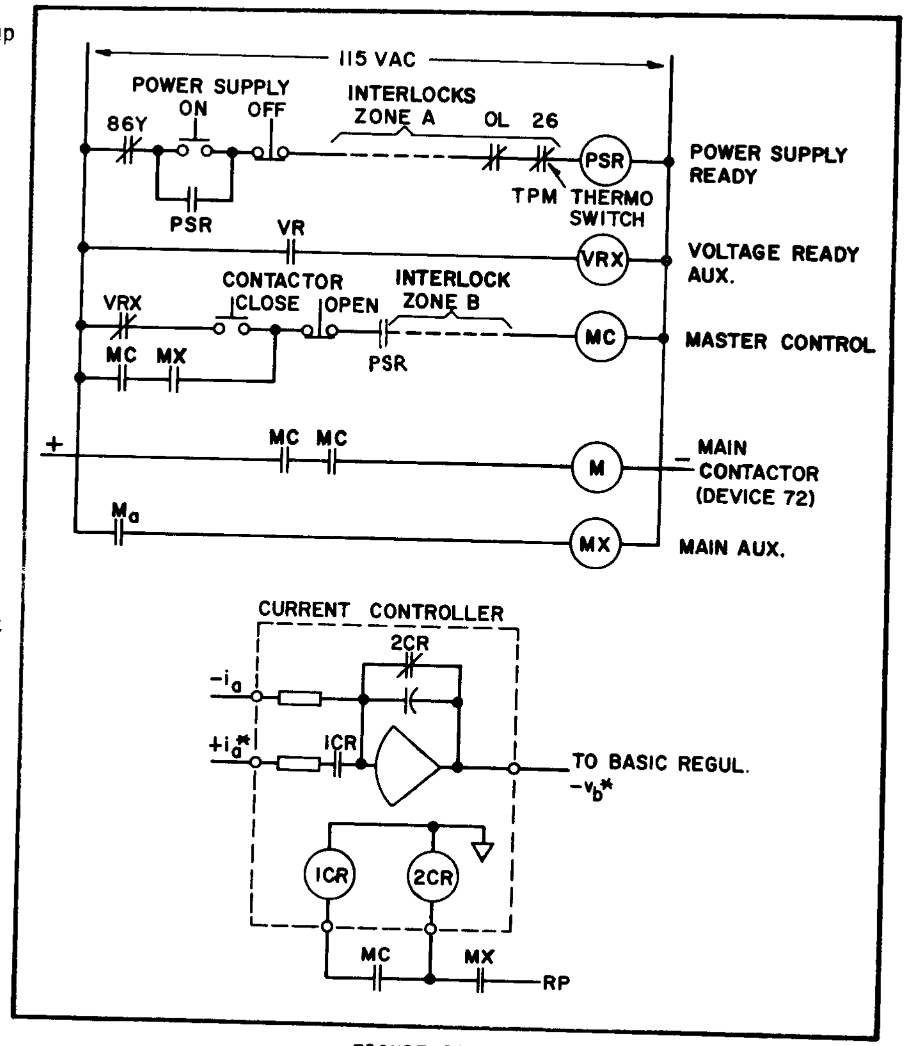


FIGURE III-12

SEQUENCING CONTROL FOR ARMATURE SUPPLY

After MC picks up, the contactor coil is energized, which leads to connecting the armature to the converter thru the M contactor. Finally, MX picks up, which in turn energizes 2CR and 1CR in the current controller. This last step closes the armature current regulating loop. If the MC relay is de-energized by an interlock or pushbutton, the current reference is first removed from the current controller. This reduces the current (if any current is flowing at this time) to a low value before the main contactor opens. This reduces its duty and prevents windup in the regulator. Finally, when MX drops out, the current controller is reset.

A master control switch could be used in lieu of the contactor pushbuttons. It would be wired to allow closing of the contactor only in the neutral position. In any case, interlocks in zone B must be used in combination with some kind of lockout method to prevent any accidental startup.

As mentioned earlier, fault currents while rectifying are normally turned off by gate pulse suppression. In case of inverting service, gate pulse suppression stops only the fault current contribution from the ac line. The contribution from the dc motor must be interrupted by the fuses on the TPM, if it is not self-clearing (as is generally the case at lower-voltage operating levels).

Gate pulse suppression can be initiated by either a fault current or an interlock. In the first case, a thyristor in the current sensor is triggered, which in turn, shorts out the +35 vdc supply line to the GPG (see III.C.3.). It can be reset by picking up relay 86X (Figure III-9) thru the gate control reset pushbutton.

Gate pulse suppression thru interlocking works thru relay 3CR in the voltage controller (see III.C.4.).

2. Field Supplies

The sequencing scheme for field supplies differ from the ones for armature supplies mainly by the absence of the main contactor (device 72). Figure III-13 shows a typical example.

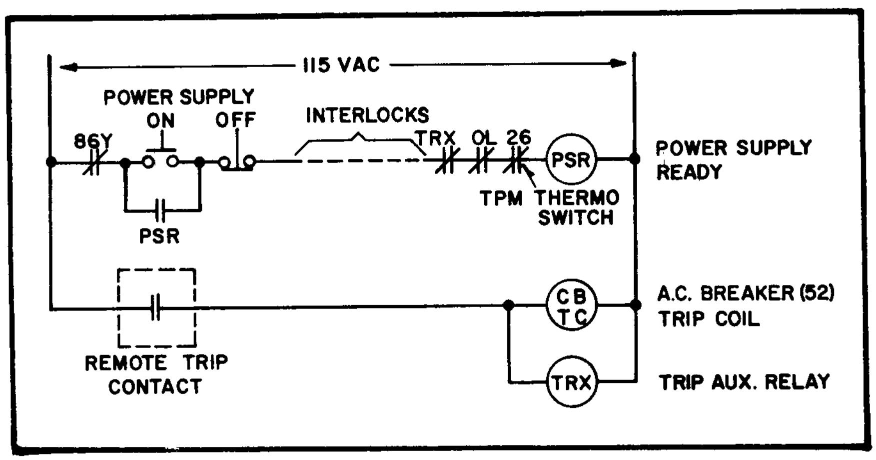


FIGURE III-13

SEQUENCING CONTROL FOR FIELD SUPPLY

As soon as the PSR relay is picked up, the power converter is gated and connected to the field. Thus, any reset interlocks in the variable regulator are taken from relay PSR.

The ac breaker (device 52) serves in field supplies an additional protective function. The overvoltage relay contact or a similar vital protective device trips the breaker directly, which in turn, will also lead to gate pulse suppression thru relay PSR. Other interlocks are inserted directly into the PSR path.

E. Rating

1. AC Feeder

Standard power system incoming voltages and frequencies are 460V and 550V - 60 Hz - 3 phase or 380V - 50 Hz - 3 phase. Tolerance: ±10% on voltage, ±5% on frequency.

2. DC Voltages

Standard dc voltages are 240V, 375V and 500V. These thyristor power systems are able to produce the rated dc voltage at 200% current, 95% line voltage, with 5% phase back.

3. DC Current

The continuous dc current rating of a TPS depends on several factors:

Thyristor Transformer
TPM Size
Ambient Temperature
Elevation.

Standard ambient temperature range: 0 to 40°C.
Standard elevation limit: 3300 feet above sea level.
Standard continuous current ratings: 28A, 40A, 80A, 120A, 160A, 230A, 300A, 360A, 420A, 510A.
The overload heaters are selected to protect the load. The heater rating should not exceed the respective TPS rating by more than 20%.

The transient current rating is usually limited by the TPM, although the overload relay may be another limiting factor. The allowable overcurrent duration depends on the previous load current and the overcurrent duration.

IV. AUXILIARY FIELD EXCITER

Constant potential and variable voltage field exciters can be added to feed the fields of the dc machines which have the armature powered by the main C-56 power converter.

A. Constant Potential Exciters

They consist of a transformer feeding a single-phase, bridge rectifier. The dc output of this rectifier is connected thru a fuse to the constant potential bus. Voltraps across the ac and dc side of the bridge as well as an R-C network are provided to protect the diodes against voltage transients.

This type of exciter is also used to supply such loads as dc contactor and relay coils in the C-56 TPS. It is usually employed where a customer CP feeder is not available. Standard voltage is 250 vdc and the standard dc current ratings are 5, 10, 15 and 20A.

B. Adjustable-Voltage Field Exciter

The C-56F auxiliary field exciter system consists essentially of a transformed supplied single-phase thyristor power modulator (TPM), a corresponding gate pulse generator (GPGF) and a field current controller (FC). The two pc cards GPGF and FC are housed in the basic regulator cage. Figure IV-1 shows a simplified diagram of these additions to the basic regulator and Figure IV-2 shows the converter in a similar form.

The single-phase bridge TPM employs two diodes and two thyristors in the well-known semiconverter circuit. The gate pulse generator feeds phase-adjustable pulses to the TPM thyristors. This allows control of the TPM output voltage over a range of about ten to 190 vdc as a linear function of the input voltage (+0.6 to -9V) to the GPG. The TPM and the GPGF modules are described in more detail in I.L. 16-800-117 and in I.L. 16-800-111, respectively.

A field current regulating loop is closed by picking up the feedback signal from a field current droping resistor and feeding it to the FC module. This module contains an operational amplifier with integral-proportional characteristics. It is further described in I.L. 16-800-133.

The reference may come from an external source thru terminal 10 or thru jumper 1J from PSP. Relay 1CR allows for selecting a "weak field" reference from potentiometer 5P.

This field control system can be used in speed regulator systems with bus voltage control in the weak field range. In this case, the bus voltage signals v_b and $-v_b$ are connected to terminals 11 and 12. When the absolute value of the bus voltage signal reaches a level higher than the current feedback signal, commutation from diode 4D to 3D takes place. The field current will then be controlled to yield a constant bus voltage.

External programming of the field current is possible thru terminal 10 for CEMF regulators, etc.

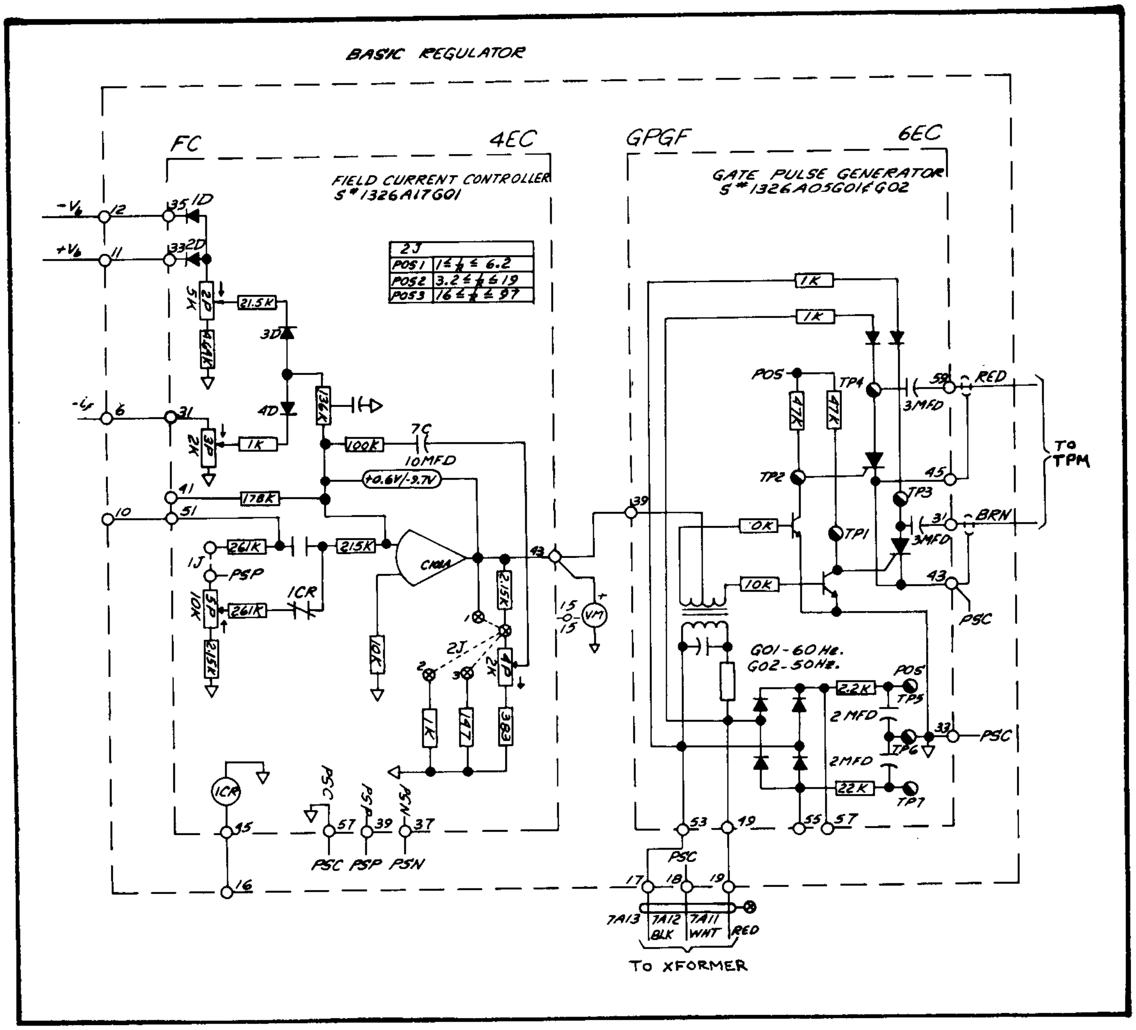


FIGURE IV-1

MOTOR FIELD REGULATOR

V. VARIABLE REGULATORS

A. Introduction

This portion of the C-56 thyristor drive system comprises the modules required to regulate the process variables, such as the armature or field current, bus voltage, speed and/or position of the machine. The word "variable" regulator refers to the fact that a great variety of combinations of modules is possible. No attempt is made in the following to give a comprehensive description; rather the principles involved are highlighted. Detailed descriptions of common regulator modules are given in the respective module Instruction Leaflets. These also contain startup and regulator optimizing procedures. A listing of these instruction leaflets is given in section VI.

Modern applications of regulated drives require not only the accurate control of the primary variable (for instance, speed), but also the control has to fulfill one or more of the following requirements:

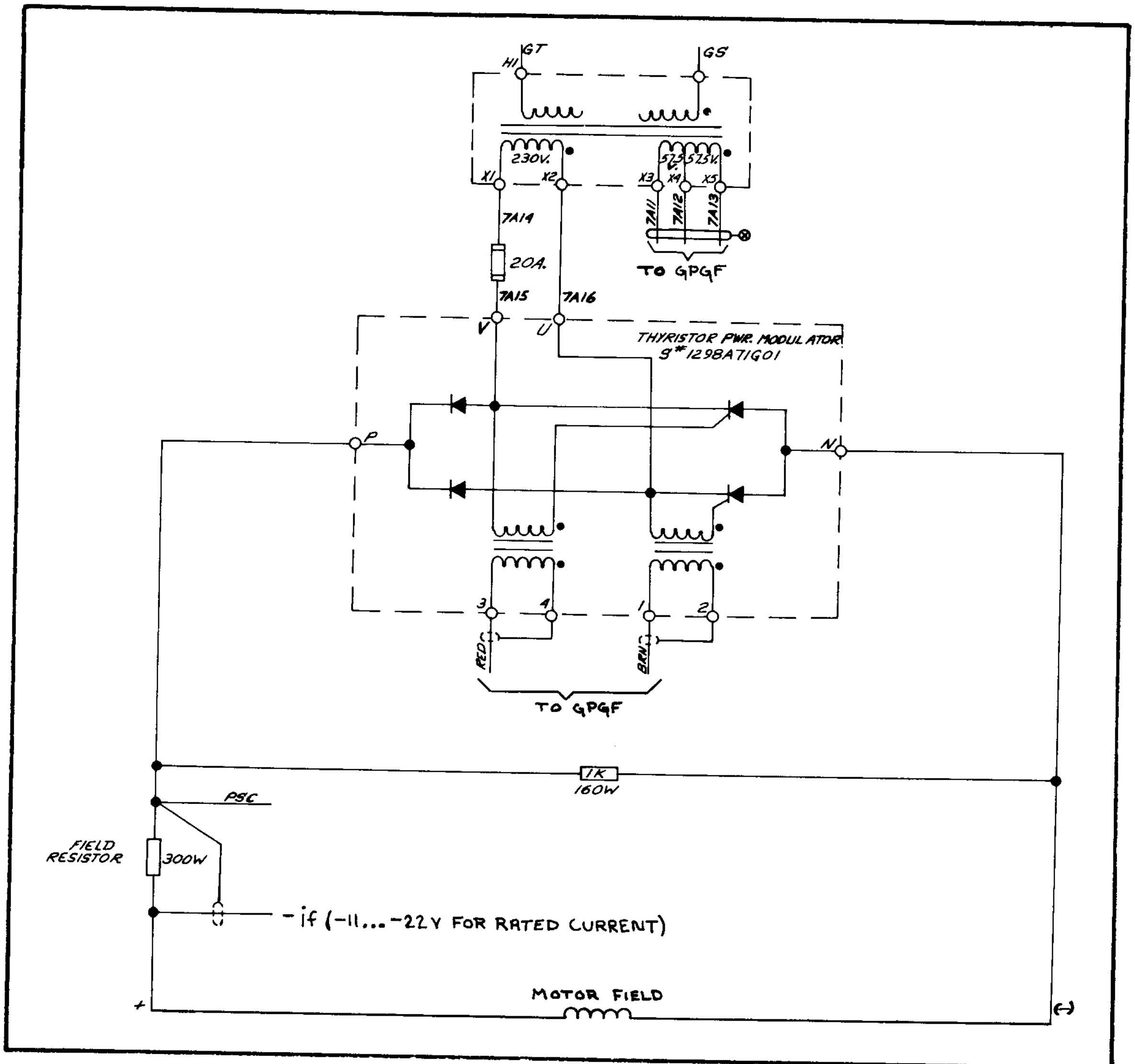


FIGURE IV-2
FIELD EXCITER CONVERTER

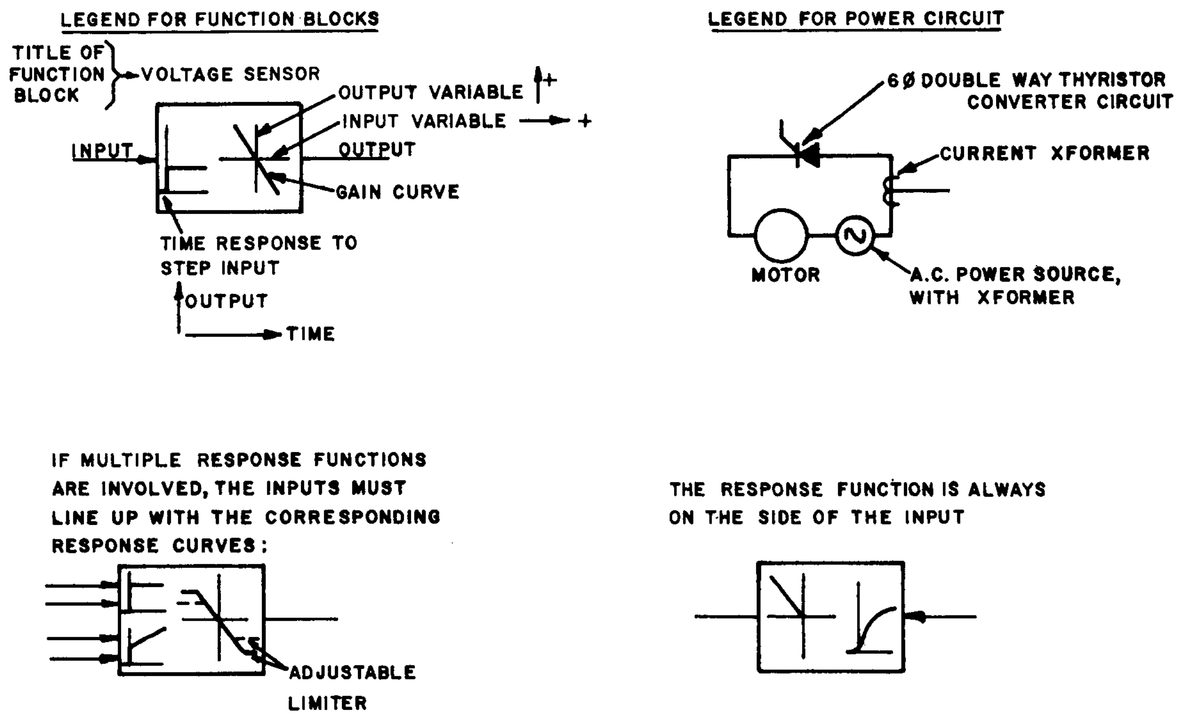
(a) Limitation of critical variables of the drive such as armature current or voltage in order to protect the system.

(b) Close control of variables to avoid excessive rates of change. For example, control of the rate of rise of current to assure good commutation of the machines.

(c) Smooth transfer from one mode of control to another. For example, smooth switchover from speed control with current limit to current control with speed limit.

(d) Simple and straightforward adjustment and optimization of a control loop. This requirement shows its importance during startup and later when a malfunctioning regulator has to be replaced.

There are 3 control concepts available--the spill-over control, the multi-loop (cascaded) control & the parallel control--which allow the control of the primary variable and the limitation of other secondary variables. Only the multi-loop and parallel control fulfill the requirements of modern applications, and are therefore used exclusively in the C-56 system. They shall be explained with the help of two examples. The sysmbols used in the following diagrams are explained in Figure V-1.



LETTER SYMBOLS

Upper-case letters denote power circuit quantities:

E: emf, V: voltage, I: current, ϕ: flux

Lower-case letters denote controller signals:

e: emf, v: voltage, i: current, ψ: flux

Subscripts:

a: armature, b: bus, f: field, n: angular speed,
m: motor

Superscripts:

*: reference signal

(NOTE: if additional reference signals for the same controlled variable are used, then second, third, etc. asterisks will be added.)

FIGURE V-1
REGULATOR SYMBOLS

B. Multi-Loop Control

A C-56 multi-loop (or cascaded) control system with single converter is illustrated in Figure V-2.

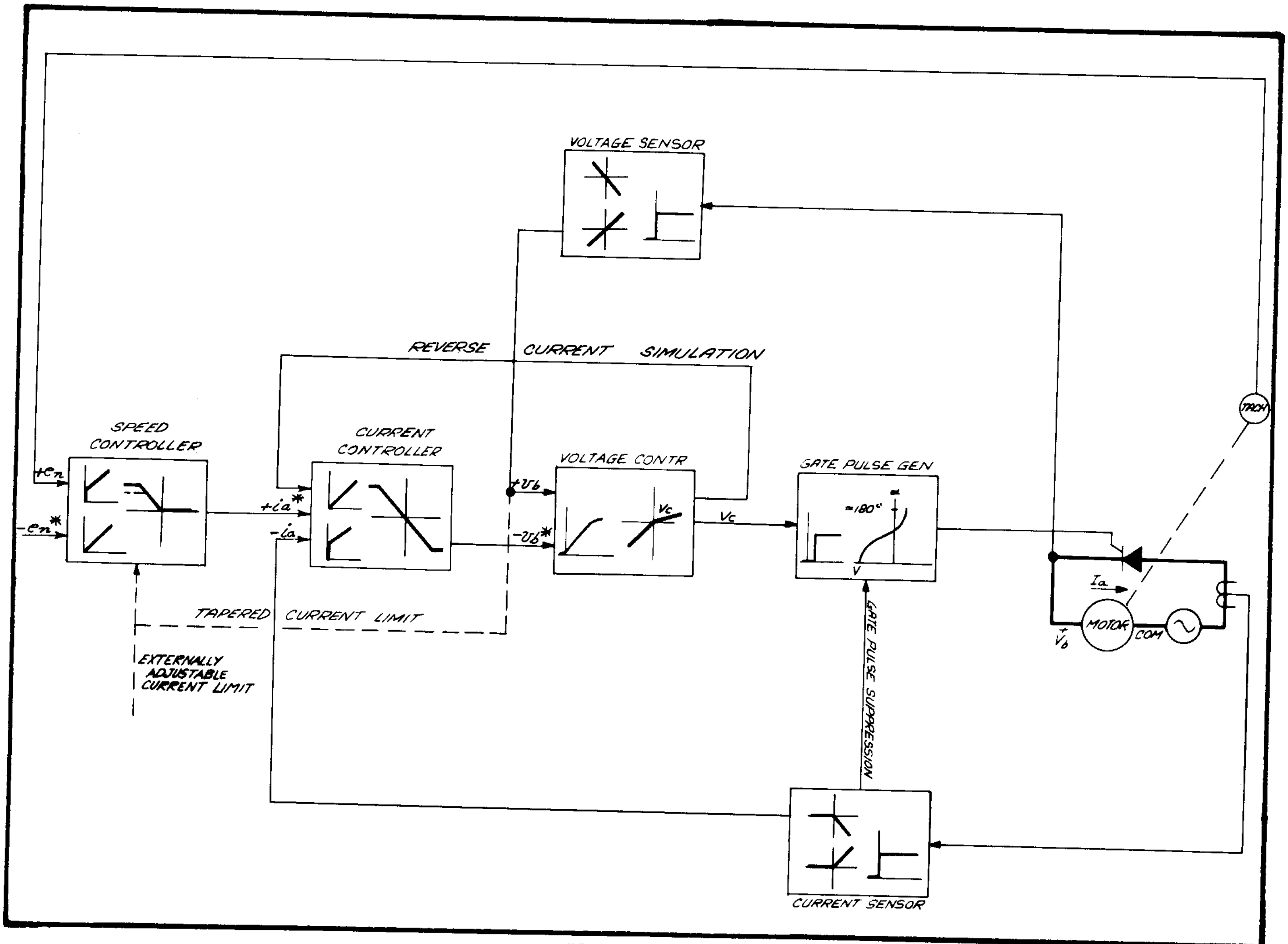


FIGURE V-2

MULTI-LOOP CONTROL
SPEED REGULATOR WITH SINGLE CONVERTER

The primary variable (speed) is controlled in the outer loop. The output of the outer (speed) controller represents the reference for the control of the secondary variable (current) in the inner loop. Therefore, it is possible by limiting of the output of the outer controller to obtain any desired current limit characteristics. A constant output limit results in a verticle current limit characteristic. By limiting the output dependent on armature voltage or drive speed, a tapered current limit can be obtained. The output of the current controller, in turn, represents the reference ($-v_b^*$) for the inner voltage loop, which with all remaining blocks has been described as part of the converter. The limits of the current controller are set to limit the range of bus voltage v_b produced by the converter. This range must be small enough to keep the power converter well in its linear operating range (no saturation). In practice, the output limiter in the current controller is in the range of 9.5-10.5 V, and the operating range is limited to 104% of rated bus voltage by adjusting the gain in the voltage sensor.

The outer loop is adjusted to be only about half as fast as the inner loop, providing a dynamic separation of the two loops. It is possible to add more loops around the outer speed loop (for instance, tension loop). In this case, the above adjustment rule applies and the next outer loop is again adjusted about half as fast as the next inner loop.

It is very easy in a multi-loop system to change the mode of control and to switch, for instance, from speed control to current control. In our example, it would require reducing the setting of the speed controller output limit to the desired current reference value and applying a small reference step into the speed controller to saturate the speed controller amplifier.

In the system shown in Figure V-2, a reverse current simulation loop is used. Its purpose is to keep the current controller from winding up if reverse current is demanded (which cannot be produced by the single converter). For this reason, the output of the voltage controller is fed back to the input of the current controller if V_C assumes positive values.

In general, multi-loop systems are designed such that there are only one or two major time delays in one loop which can be cancelled readily by the lead times of the respective controllers. The startup of a multi-loop system is straight forward since the steady-state and dynamic characteristics of the control are independent of each other. Starting out with the innermost loop, the outer loops are adjusted successively. The addition of outer loops sometimes increases the type of the control (the type of control is determined by the number of integrators in a control loop). For example, the speed control of a drive with inner current loop results in a type 2 speed control system.

The multi-loop control concept has proved to be very effective for the control of drives; and today, it is applied most frequently. A summary of the features of this control concept yields:

(a) Separate controllers are used for each controlled variable. This allows an optimum adjustment for each loop.

(b) The steady-state and dynamic characteristics of a control system are independently adjustable.

(c) Smooth transfer from one control mode to another can be easily accomplished.

(d) Design and calculation of the controllers and the startup of the control is straight forward.

C. Parallel Control

As in a multi-loop control, the parallel control scheme uses separate controllers for each controlled variable. However, the controllers are now in a parallel arrangement and the outputs are connected through a switching circuit to a common output terminal. Figure V-3 shows a typical application with a single converter. In a parallel control scheme, only one controller is in operation at any one time. This is a distinct difference from a multi-loop system, where all the controllers are continuously engaged. In our example, the outer voltage controller is in operation as long as the current limit is not reached. The current controller is switched off during this time. When current limit is reached, the current controller takes over the control of the drive and the voltage controller is switched off. This means that in this control, the current controller is working as a limit controller, and the voltage controller is in operation as long as no limit is reached.

The switching circuit consists of a few passive solid-state components. The controllers provide the intelligence for the correct switch-over point. Switching in and out of controllers is accomplished smoothly and quickly due to the characteristics of the operational amplifiers used.

The dynamic and steady-state characteristics of the control loops are independently adjustable as in a multi-loop control. Also, the transfer from one mode of control to another is accomplished in the same way as in a multi-loop system. The two control loops can be optimized and started up independently since only one controller is working at one time. Each control loop can be adjusted as if only this control loop would be employed in the system. Hence, a faster response can be obtained since the speed of response of each loop is independent of the other. This is an obvious advantage in comparison with the multi-loop system where the different loops have to be separated dynamically by a slower response of the outer loop.

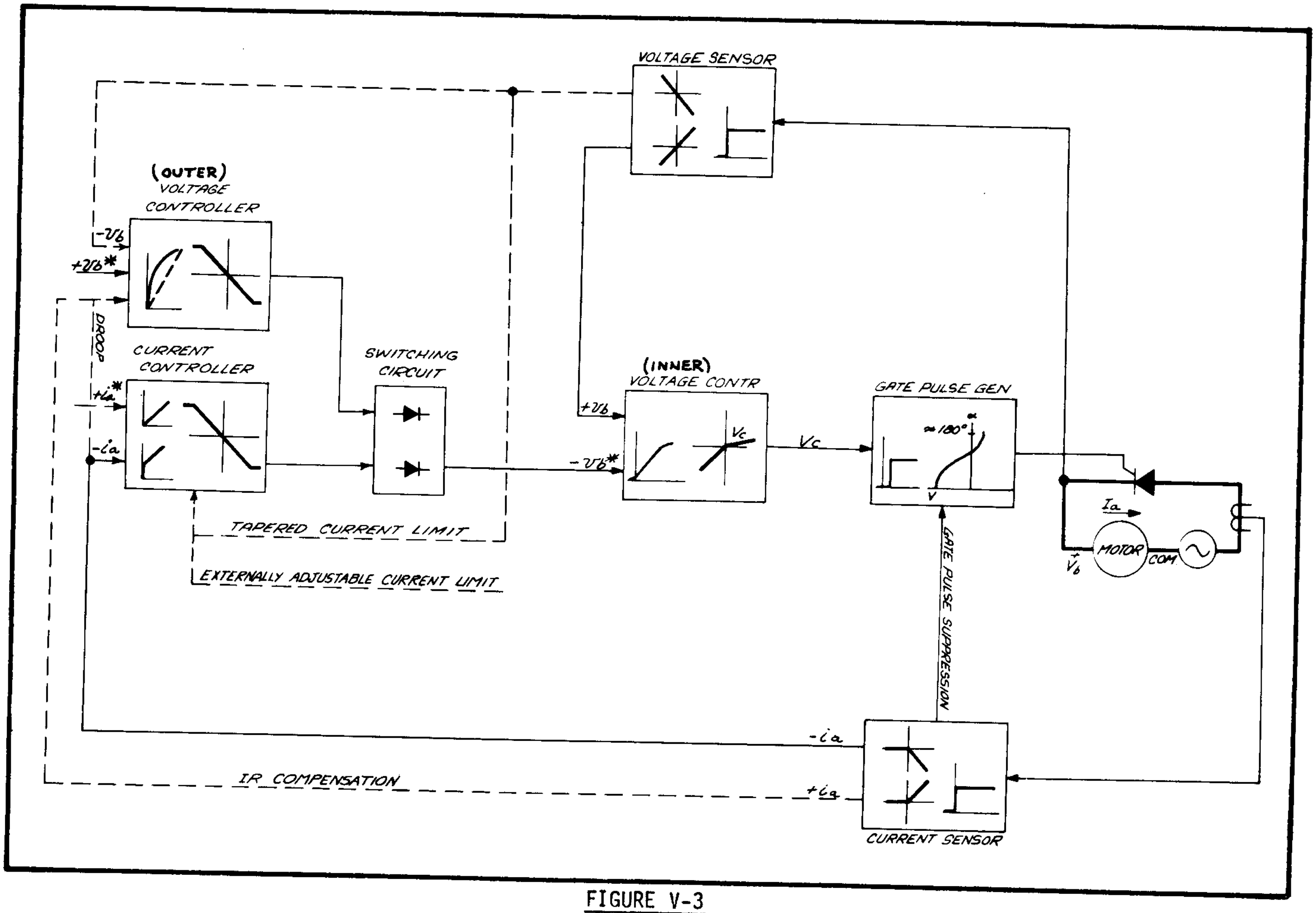


FIGURE V-3

PARALLEL CONTROL VOLTAGE/CURRENT REGULATOR
WITH SINGLE CONVERTER

In a parallel control system, the controllers have to be designed to compensate for all the major time delays which exist in the system. This is only practical for systems with two or less major time delays since a controller which could compensate three major delays is very noise sensitive and more difficult to design. Therefore, in more complicated systems with more than two time delays, a combination of multi-loop control and parallel control is applied. Inner loops are employed to compensate for some basic nonlinearities and time delays, and a parallel control system is closed around it. The C-56 system shown in Figure V-3 is an example of such a combination. The inner voltage loop compensates for the nonlinearities of the power converter; whereas, the outer parallel control for current and bus voltage is cascaded to it.

The following is a summary of the essential features of a parallel control system:

(a) Separate controllers are used for each controlled variable. This allows an optimum adjustment for each loop.

(b) The steady-state and dynamic characteristics of a control system are independently adjustable.

(c) Smooth transfer from one control mode to another one can be accomplished.

VI. REFERENCES

The following is a listing of supporting C-56 instruction leaflets.

A. Converter and Basic Regulator

B. Variable Regulator