M4CH THYRISTOR POWER SYSTEMS

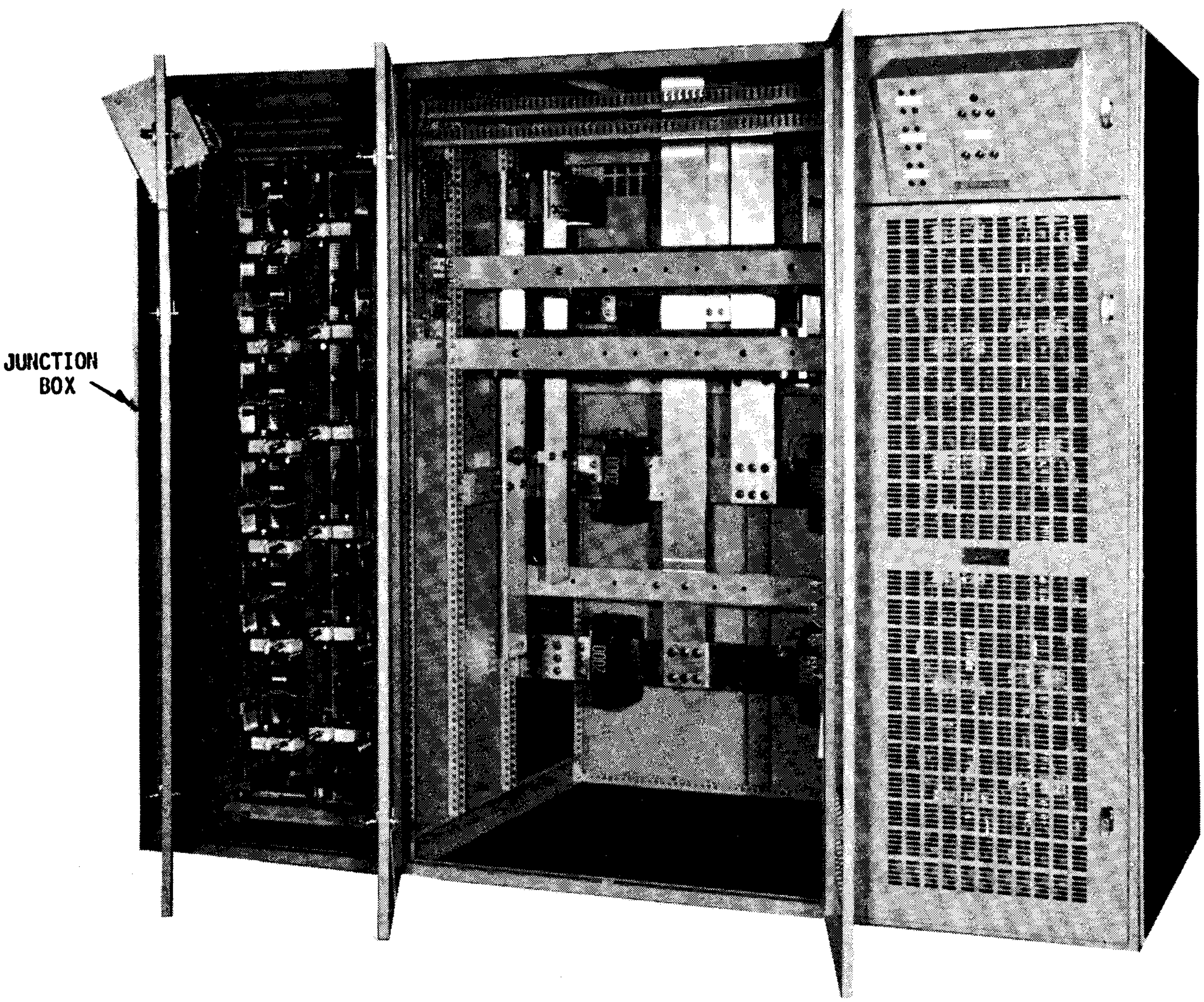

FIGURE I-1
M4CH THYRISTOR POWER CONVERTER

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I. INTRODUCTION

M4CH Thyristor power systems (TPS) are large (high power) systems designed primarily to provide adjustable-voltage power for armatures of dc machines. These systems may be broken into two main parts:

(1) Thyristor power converter consisting of, a combination of 1 to 6 thyristor cabinets, an incoming cabinet, a junction box, one or more gate pulse amplifier (GPA), and protective elements.

(2) Regulator section consisting of a basic regulator, a variable regulator, basic controls, and referencing and director logic elements.

There are several types of converters made up of six-phase converter sections:

(a) Six-phase single converter. The output voltage is reversible in this type, but the current is restricted to one direction.

(b) Twelve-phase single converter made up of two six-phase sections. Each section is supplied from separate thyristor transformers. The two sections are electrically displaced by 30 degrees to obtain the twelve-phase system from two six-phase sections.

(c) Six-phase double converter made up of two converter sections (F1, R1). The two sections may be supplied from the same thyristor transformer since only one section supplies power at any time. Double converters 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 double converter.

(d) Twelve-phase double converter made up of two six-phase double converters. As in the six-phase double converter it may be symmetrical or assymmetrical.

(e) Twelve-phase/six-phase double converter consisting of a twelve-phase system (two six-phase sections) in the forward channel, and a six-phase section reverse. This type is always asymmetrical.

M4CH Thyristor power converters are normally supplied from three-phase mill power or a large substation, and the thyristor transformers are individually designed for the station voltage. The rated output voltage of the converters is 500V, 600V, 700V or 800V. The rated output current range varies from about 1000A to 12000A and the variation is accomplished by paralleling thyristor bridges. The variable regulator portion is needed to complete a system for such functions as bus voltage regulation, current regulation, speed regulation, or combinations thereof.

The M4CH system is contained in several cabinets which include a regulator cabinet, one or more thyristor cabinets depending on the size of the system, an incoming cabinet, and on some systems a control cabinet containing additional control equipment not housed in the regulator cabinet. Large transformers and circuit breakers are mounted externally. The regulator cabinet houses the basic regulator(s), the variable regulator, small transformers for control purposes, and a number of relays. The thyristor cabinet houses one or two thyristor bridges, thyristor fuse lights, a GPA, an air fan to cool the thyristors and load sharing reactors, and R-C networks. The incoming cabinet contains power distribution bus work, current sensing transformers, the differential current sensors (A140's), and the optional DC fault current sensors (50 device).

II. SCOPE OF APPLICATIONS

M4CH TPS are used to provide adjustable-voltage power for armatures of large dc machines (greater than 500 HP) such as used on metal mill main drives. The type of system used depends on the application. A double converter would be used rather than a single converter where current reversal is necessary. A twelve-phase system would be used rather than a six-phase system to:

a) Extend the power capability beyond what is available in a six phase system.
b) Reduce ripple to the motor.
c) Reduce harmonics on the main ac line.
d) To increase the ratio of impedance of converter sections to the feeder system.

Types of converters other than those listed in the introduction can be built up of converter sections where the application warrants.

The basic building block for M4CH power systems is a thyristor cabinet containing either a single bridge or 2 parallel bridges of the six-phase double-way, circuit configuration. All six legs are controlled (thyristor) and six pulses per cycle are produced. From 1 to 6 bridges in parallel can be controlled from a single GPA to form a converter section.

Two six-phase converter sections are connected antiparallel to make a six-phase double converter. Both converter sections are essentially controlled from the same basic regulator although separate current sensing, gate amplifiers and distribution circuitry is employed. Usually both converters are supplied from the same transformer. Reactors to limit circulating current between sections under certain fault conditions may be used. These two converter sections are identified as F1, R1.

Twelve-phase systems are essentially two six-phase systems, F1, R1 and F2, R2.
The two converter sections are displaced by 30 degrees so that the summation of the two outputs yield twelve pulses per cycle (the output shows a ripple on the dc twelve times the fundamental frequency of 50 or 60 hertz). Load sharing reactors are used between the two sections. Maximum capability of a twelve-phase double converter would be 12 thyristor power bridges forward and 12 reverse.

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 for a six-phase system. The transformer is shown delta-wye connected, but the inverse may be used. It is desirable to use the delta connection for at least one winding to eliminate 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 (as well as added reactors associated with each converter bridge) 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 wt = 15° a pulse train of 120° duration is applied to thyristor No. 6. Since there is no other thyristor gated at this time a current path is not available to carry current. Sixty degrees later at wt = 75°, a pulse train of 120° duration is applied to thyristor No. 1. Now with thyristors No. 6 and No. 1 receiving synchronized pulses a current path is available from U tp P through the load to N and then to V. Thus the line voltage euv is applied to the load. Sixty degrees later at wt = 135° a pulse train is applied to No. 2; current is flowing in No. 6 and No. 1 at this time, however, the current in No. 6 will commutate to No. 2 because the voltage e_{uw} is greater than e_{uv}. Pulse trains are applied to successive thyristors each 60° and commutations will take place each 60° (on the negative side of the bridge when even numbered pulses are applied and on the positive side of the bridge when odd numbered thyristor gates are applied).

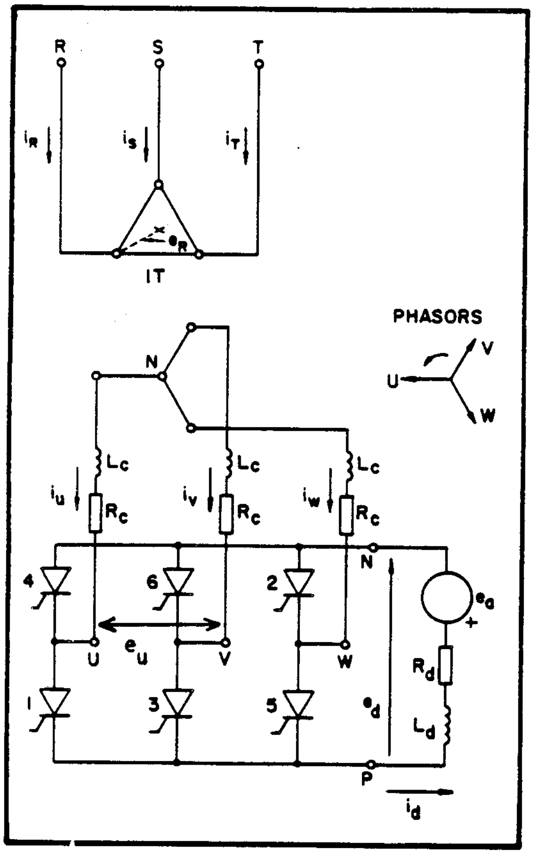


FIGURE III-1

SIX-PHASE, DOUBLE-WAY CIRCUIT

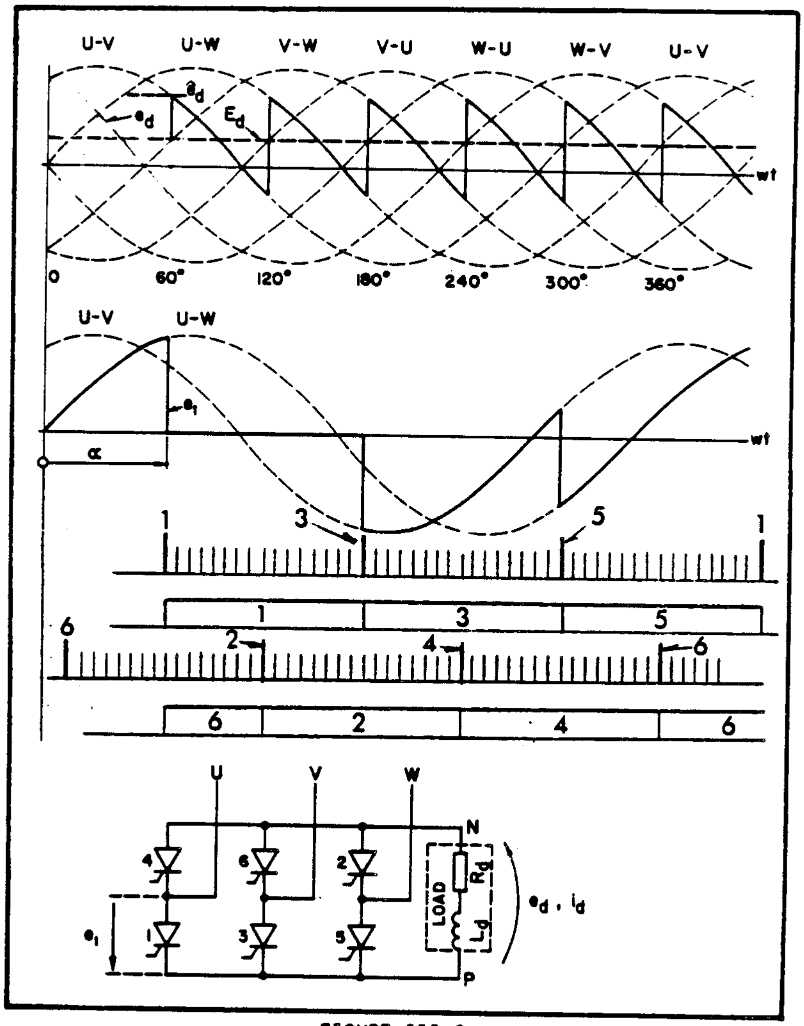


FIGURE III-2

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

Assuming that the load is highly inductive, the dc current will reach a steady value after a number of cycles, and each tyyristor 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.

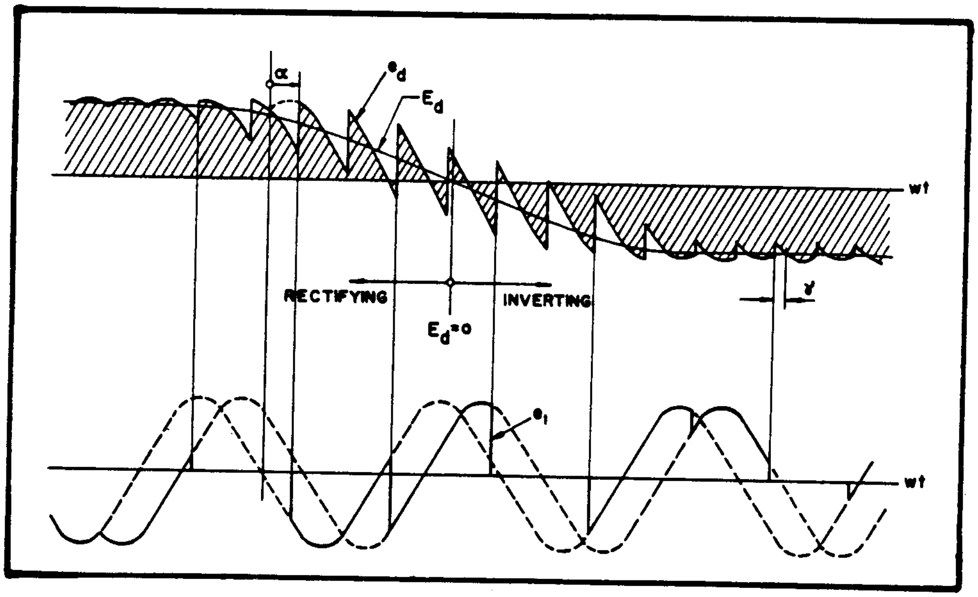


FIGURE III-3

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, reactors in the ac line and the power line have been neglected. This so-called commutating reactance, however, is significant. Instead of instantaneously commutaing 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, ac reactors and line (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 double converter.

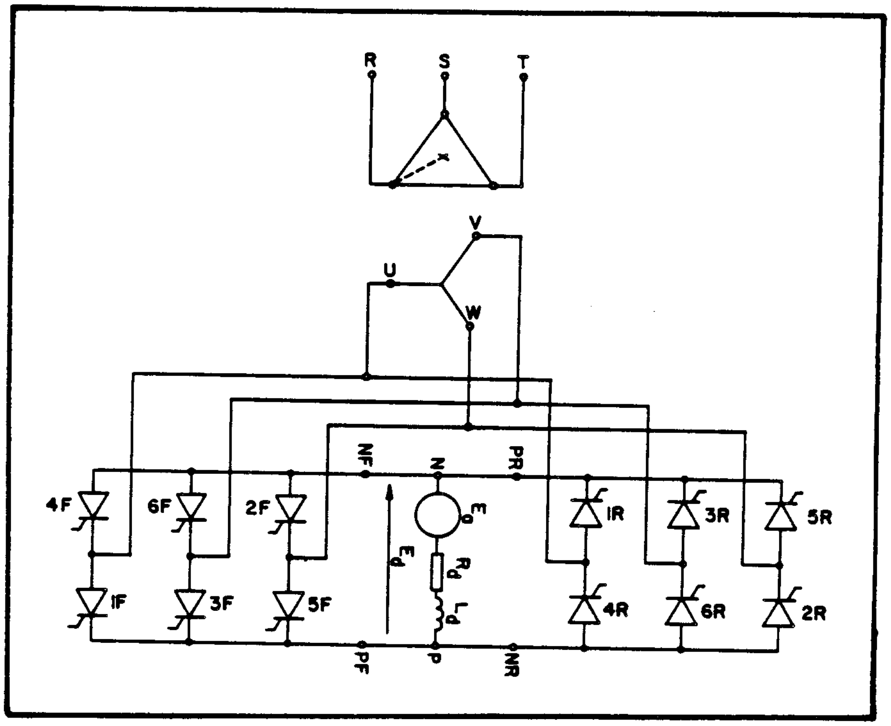
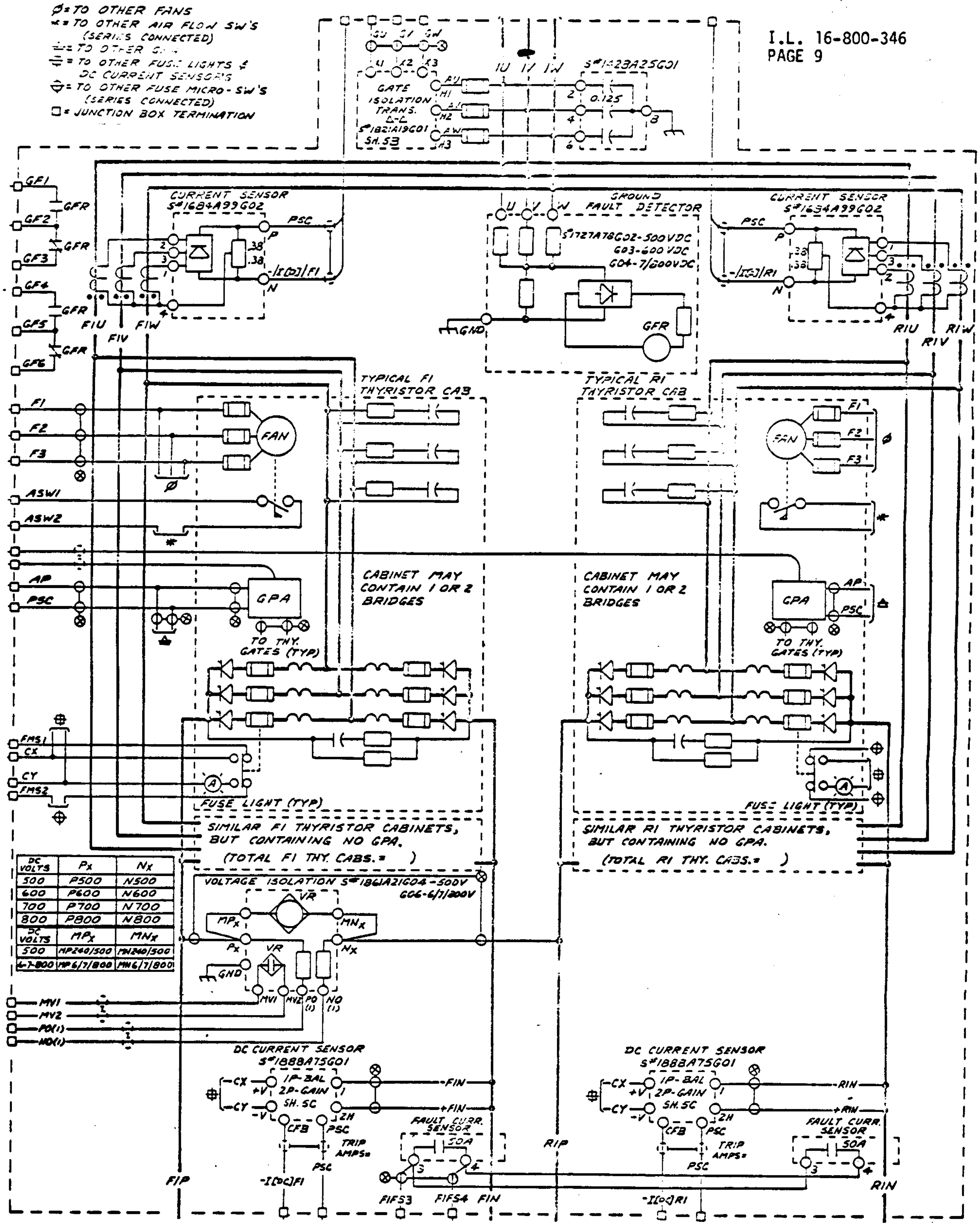


FIGURE III-4

DOUBLE CONVERTER, ANTIPARALLEL CIRCUIT

Figure III-5 shows the schematic diagram for a 6∅ double converter (F1,R1). The square terminals on the dotted line represent terminal blocks or groupings of terminal blocks (GPA inputs) within the junction box. The maximum no of thyristor cabinets per converter section is 3. This limitation is due to the limitation of the gate pulse amplifier. Each of the 6 channels within the GPA is capable of driving 6 thyristor pulse transformers 2 in each of the 3 thyristor cabinets possible within a converter section. The theory or operation for the gating system is covered in I.L. 16-800-289. In the case of a single converter the R1 converter section and its associated sensing devices disappear. In the case of 12 ∅ systems a second power converter scheme would be included duplicate of that shown in Figure III-5 except the converter sections would be identified as F2, R2.



DC VOLTS	Px	Nx
500	P500	N500
600	P600	N600
700	P700	N700
800	P800	N800
DC VOLTS	MPx	MNx
500	MP240/500	MN240/500
6-7-800	MP6/7/800	MN6/7/800

FIGURE III-5

SCHEMATIC DIAGRAM 6 Ø DOUBLE CONVERTER

B. Thyristor Cabinet

This power modulator assembly includes the thyristor mounted on integral heat sinks. Figure III-6 shows the schematic diagram. Current limiting fuses are used to protect the thyristors under most fault conditions, and to disconnect defective cells in multiple branch circuits. RC networks across the cells serve in conjunction with the series reactor for each cell, to attenuate excessive rates of voltage, which otherwise may lead to undesired turn-on of thyristor. There are externally mounted RC networks across the ac phases and the dc output to damp the oscillations that would otherwise be produced by the commutation process.

Pulse transformers in conjunction with diodes, resistors and capacitors in the gate-cathode circuit, provide isolation and shaping for the gate pulses.

The thyristor power module is easily removed for servicing. The complete procedure for the replacement of thyristors and fuses is covered in I.L. 16-800-263.

Ventilation

Thyristor cabinet - air intake is through the large bottom front door and is exhausted through the ventilation fan located in the rear of the cabinet in the roof or in the floor. The cabinet is a negative pressure enclosure.

C. Incoming Cabinet

This a NEMA 1 convection cooled cabinet that contains the current transformers, the a-c and d-c current sensor(s), the voltage isolation board, transient capacitor panel, ground fault detector, and the customers a-c power terminations in any combination of top or bottom entry. The negative leg of each converter section (F1,R1,F2,R2) is designed to accept a fault current sensor (50 device). Refer to Figure III-5 for schematic representation of above items.

D. Junction Box

The junction box provides a standard interface between the power converter and the regulator cabinet which allows each standard STYLED power converter to be preterminated and in the case of a 12 Ø system it allows the customer to connect all the F2, R2 section gate and sensor leads into the F1, R1 junction box with out the regulator cabinet being present.

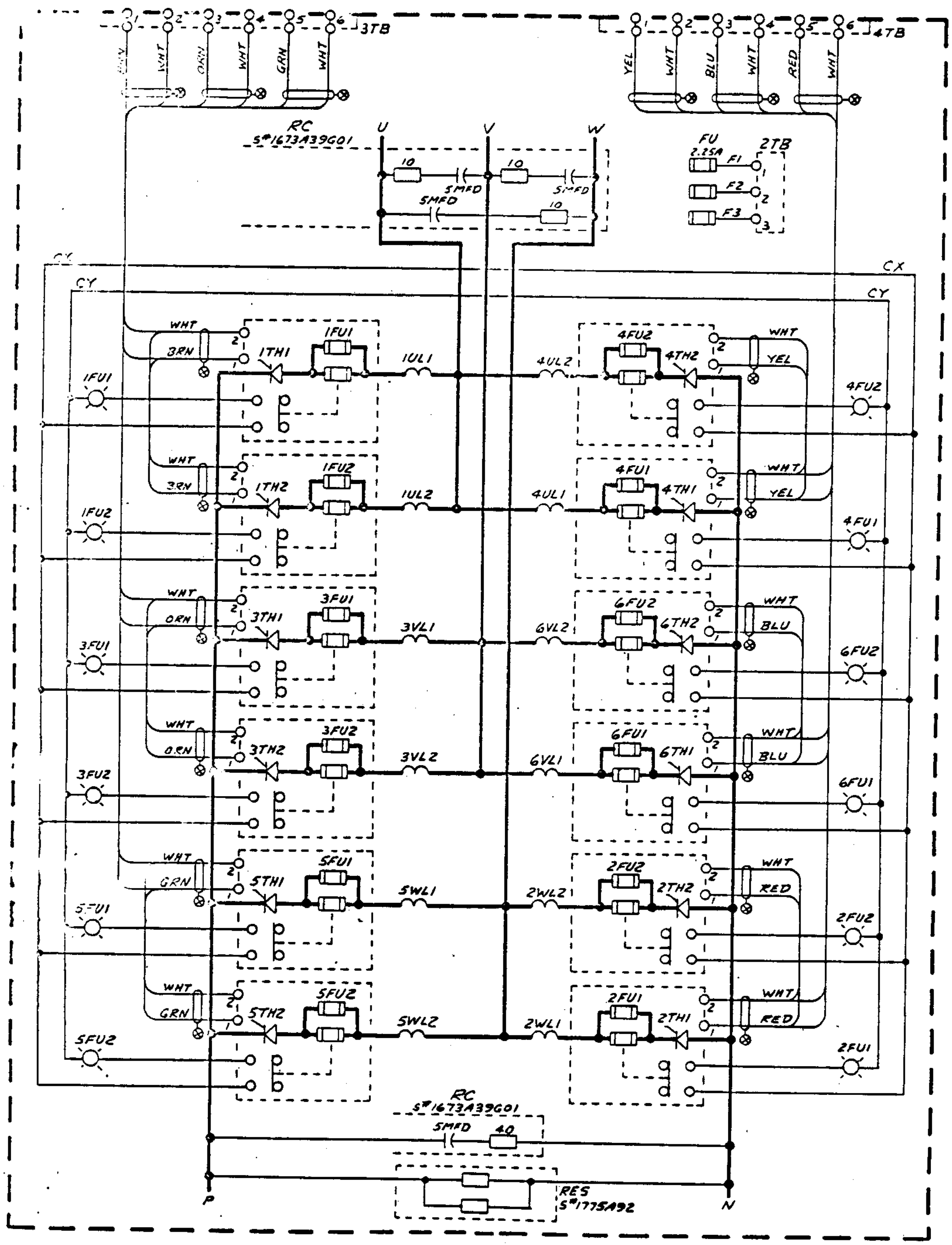


FIGURE III-6

THYRISTOR CABINET SCHEMATIC

V. REFERENCES

The following is a listing of supporting M4CH instruction leaflets

M4CH Regulating System	Later
M4CH Field Start-up	Later
Procedure for the Replacement of Thyristor and Fuses	16-800-263