A REPEATED-TRANSIENT, PARALLEL TYPE THYRATRON

INVERTER WITH SELF EXCITATION

by

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176259

ABSTRACT

The basis of the high voltage direct current trans-
mission system will be static rectifiers and inverters, the
basic part of which will be some form of grid controlled
vapor tube. In this report the development of a simple type
of single phase inverter is described and as far as is
possible an analysis of the circuit made. Its character-
istics, possibilities and limitations are discussed. The
problem is of interest because it represents in their sim-
plest form the problems that will be encountered in the
design of the apparatus for the load end of the high vol-
tage d.-c. transmission line.

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CONTENTS.
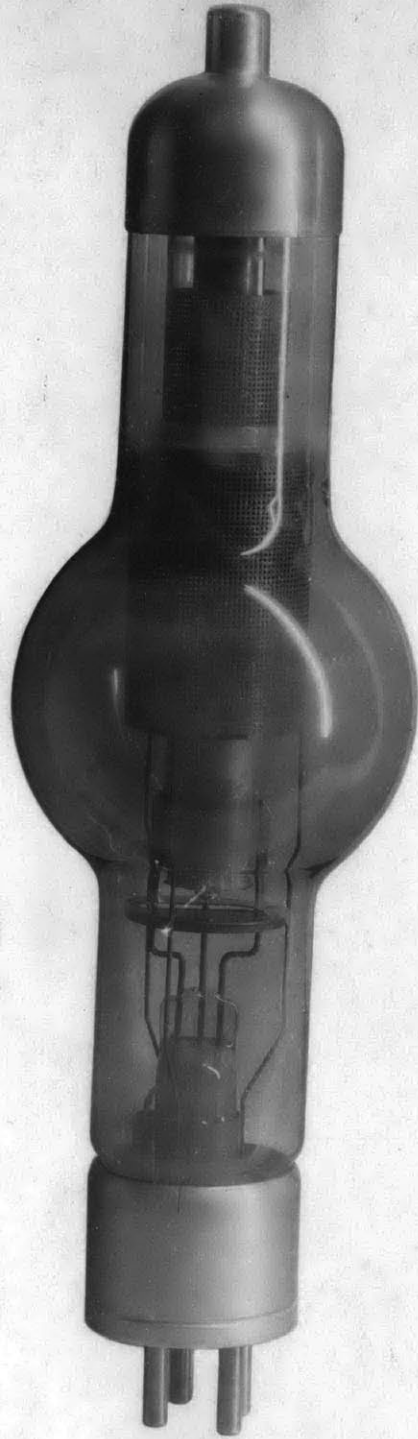
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I. THE THYRATRON TUBE

Mechanically, the Thyratron tube is nothing more
or less than a three-electrode vacuum tube in which a small amount
of inert gas or vapor has been placed. The name also applies to
tubes having a mercury pool as cathode, in fact, in its
original form it was an ordinary pool type rectifier tube
with grids surrounding the anodes.

Physically, the Thyratron combines the low-voltage
drop and consequent high efficiency of the mercury pool recti-
fier tube with some of the control characteristics of the
three-electrode hard vacuum tube. With direct current applied
to the anode the grid, however, has "one-way" control only.
When made positive, it can start current flow from anode to
cathode, but once the conduction process has started no
amount of negative grid potential will stop current flow.
This is because the whole space surrounding the electrodes
is ionized. However, with alternating current applied between
anode and cathode the grid has an opportunity to regain control
during the negative half-cycle. In this manner, the average
plate current can be controlled by a phase displacement between
grid and anode voltages.

The high efficiency of the Thyratron is due to the

small and practically constant (i.e. independent of anode
current) voltage drop between anode and cathode, which re-
sults from the fact that the negative space charge at the
cathode is neutralized by positive mercury ions.

In the tubes used in this investigation the
emission is obtained from an enclosed tungsten filament,
having a high heat capacity. From figures 1, 2, and 3,
some idea can be had of the external appearance and phy-
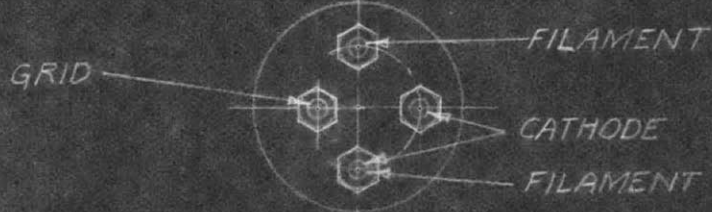sical dimensions of the tubes used.

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475349 **Fig.1.** G-E TYPE FG-41 THYRATRON.

E351.32 1-2-31

BASE #1902

2 1/2" DIA. APPROX.

18" APPROX.

5 1/16" DIA. MAX

2 5/8" DIA APPROX.

BASE #3601

FILAMENT

GRID

CATHODE

FILAMENT
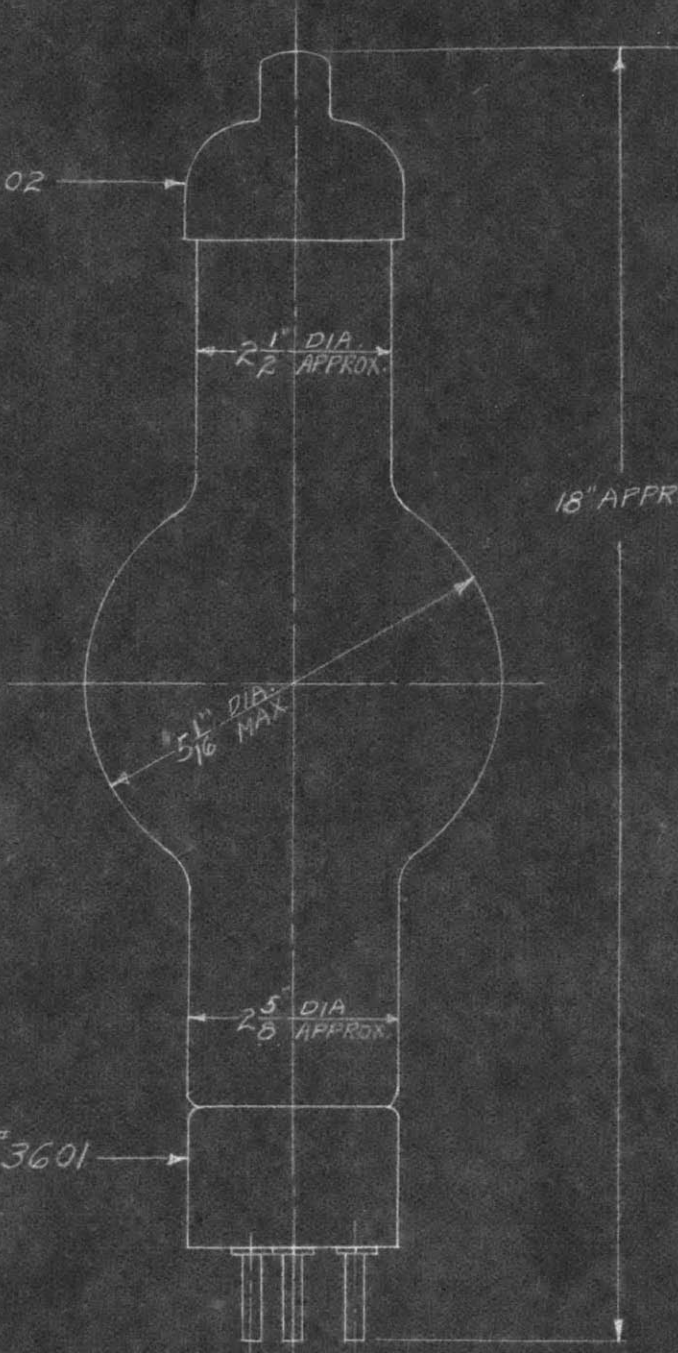
VIEW LOOKING AT BOTTOM OF BASE

Fig.2 OUTLINE

THYRATRON FG-41

DRAWN BY H. Corr Oct. 6, 1930   INSPECTED BY Oct. 6, 1930

K-4373353

GENERAL ELECTRIC COMPANY SCHENECTADY WORKS

FF-440-A 20m 4-29-29

V.T.

SINGLE-PHASE, SELF-EXCITED THYRATRON INVERTER, UTILIZING
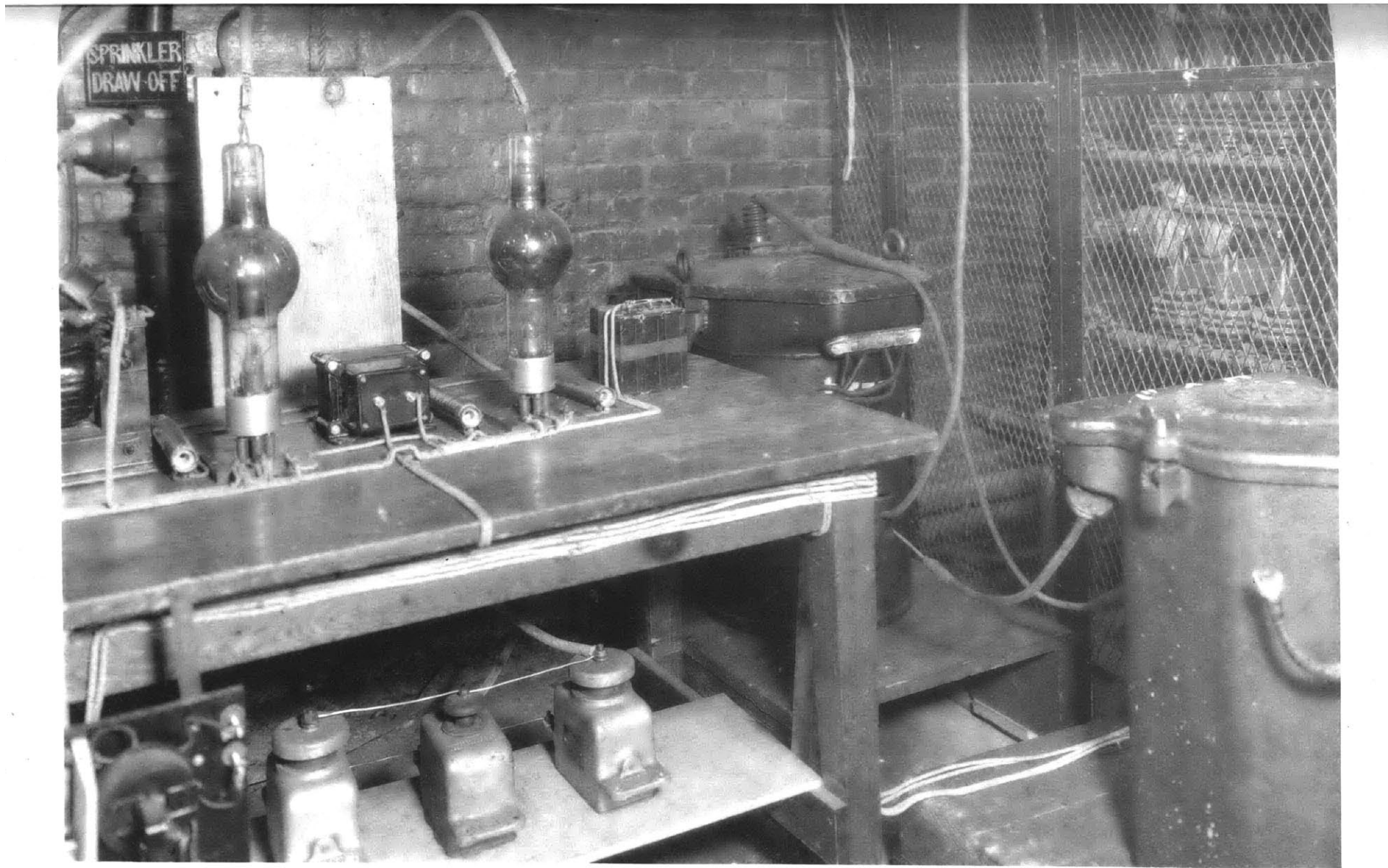TYPE FG-41 TUBES.

473354

E331.9   9-25-30

II. BRIEF HISTORY OF THE STATIC INVERTER.

Definition.

The name "inverter" implies any apparatus for the conversion of d.-c. power into a.-c. power. Lately, however, it has been applied to static circuits which are essentially the same as rectifier circuits and containing transformers, condensers, etc., and thermionic tubes, the function of which is the inverse of that of rectifier circuits; viz., to convert direct current into alternating current.

a. The Hard Vacuum Tube Inverter.

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In 1925 D. C. Prince described the principle of operation of a hard-vacuum tube inverter (See Ref. 2(a)). The function of this circuit was the conversion of direct-current into three phase alternating current. Power was "pumped back" into an a.-c. system and the grids of the tubes were controlled and the frequency determined by the latter.

The successful performance of this circuit was perhaps in no small measure due to the positive "two-way" control of the hard-vacuum tubes used. The grids could not only start the current through the tubes but could also shut it off.

Due to the limitations inherent in the use of hard-vacuum tubes in power circuits, their use in inverter circuits has not developed. With the advent of the grid controlled mercury arc tube the inverter idea gathered momentum and although not yet extensively applied, holds considerable promise for the future.

b. The Direct Current Transformer.

An inverter circuit, utilizing thyratron tubes, was described by D. C. Prince in 1928*(See Reference 2(b)). Mercury pool type grid-controlled tubes were used in a single phase circuit. Since the inverted d.-c. power was again rectified at a different d.-c. voltage, the whole assemblage of apparatus was called a "direct current transformer."

In the same article the ideal single phase inverter circuit was also described. This was essentially the same as the circuit utilizing hard-vacuum tubes with the latter replaced by mercury pool type tubes. The voltage wave form was supplied by a synchronous load.

In the "d.-c. transformer" the a.-c. wave-form was supplied by an oscillatory combination of a condenser, connected between anodes, and a low exciting reactance trans-

* Alexanderson Patent 1,800,002 filed 7/15/23 and operated prior to this date.

former, which combination acted as a flywheel. The cathodes
of the two tubes were connected together and the line reac-
tors of both circuits were placed on the same core. Thus
a back e.m.f. was provided for the inverter and the balance
between input and output resulted in very little energy
storage action.

The circuit of this investigation corresponds to
that of the inverter part of the d.-c. transformer, with, how-
ever, no special provision made for a "flywheel effect " to
maintain approximately sine waves of voltage. All voltages
and currents are transients. Every half-cycle a new transient
is started. Hence, the name "repeated transient" type inver-
ter.

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III. THE EXPERIMANTAL INVESTIGATION

The specific purpose.

With the economies possible in the replacement of
rotating machinery by static circuits for supplying high
voltage direct current realized, this investigation was
concerned with the possibilities of accomplishing the op-
posite; i. e., the inversion of high direct current vol-
tages to obtain power in the form of low a.-c. voltages.
More specifically, the requirements of the circuit were:

(1) That it should be self-starting and self-excited,
both as regards grid and filament power.

(2) That power supplied at 3000 volts d.-c. should be
converted into single phase 110 volts a.c.

(3) That it should have a convenient regulation character-
istic on a variable pure resistance load up to 5 kw.
maximum.

(4) That it should have a frequency of 60 cycles.

(5) That the cost should be low. This involved the use
of standard apparatus.

The output wave-shape was not required to be approx-
imately sinusoidal, but as will be seen the circuit had to all
intents and purposes to perform the duties of a motor-generator
set.

Method of Attack.

An investigation of this type at the present stage of development resolves itself into three parts:

(1) Determination of the tubes to be used. This involves the investigation of characteristics and secondary power requirements for filament and grid excitation.

(2) Development of the circuit and the investigation of its operation, by studying its wave-shapes.

(3) The development of modifications for the sake of meeting special requirements.

Determination of the most suitable tube.

The types of Thyratrons manufactured at the present time fall into two general classes according to the purpose for which they are to be used. The essential difference between the two classes is that those types used as "Controlled Rectifiers" need a minimum of 1000 micro-seconds for de-ionization while those used in "Inverter" circuits require approximately 100 micro-seconds.

The types differ as far as constructional details affecting filament supply voltage and tube voltage and current rating are concerned.

Table I

Technical Information on Thyratrons Used

Code No.	F. G. 67	F. G. 41*
Type	"Inverter"	"Inverter"
Cathode		
Volts	5.0	5.0
Amps.	4.5	12.0
Type	Indirect Heat	Indirect Heat
Heating time	5 min.	5 min.
Anode Peak Volts (Max..)	1,000	15,000
Anode Current (Max..)		
Instantaneous	15	75
Average	2.5	12.5
Max. Tube Voltage Drop	24	24
Min. Tube Voltage Drop	10	10
Temp. Limits (^oC)	20-50	10-50
Deionization time (micro-seconds)	100	100

    * This tube was the one actually used. The information contained in Table II applies to the shielded grid type that superseded it.

THYRATRON FG-41

TECHNICAL INFORMATION

Designed as	Inverter Tube
Number of Electrodes	3
Cathode	
Volts	5.0
Amperes	12.5
Type	Indirectly heated
Typical Heating Time(min.)	5
Maximum Peak Inverse Voltage	15000
Maximum Peak Forward Voltage	15000
Maximum Instantaneous Plate Current(Amps.)	75
Maximum Average Plate Current(Amps.)	12.5
Maximum Time of Averaging Plate Current(sec.)	30
Maximum Instantaneous Grid Current(Amps.)	5.0
Maximum Average Grid Current(Amps.)	1.0
Maximum Tube Voltage Drop	24
Minimum Tube Voltage Drop	10

Approximate Starting Characteristic

Plate Voltage	Grid Voltage
1000	+4.0
15000	-5.0
Approx. 3000	0

Overall Dimensions	
Maximum Length	18"(approx.)
Maximum Diameter	5 1/16"
Base Type Numbers	3601 and 1902
Temperature Limits - Ambient(°C.)	10° - 50°
Type of Cooling	Air
Deionization Time(micro-seconds)	100(approx.)

December 17, 1930.   H-4359290

Of the tubes available at the time of this investigation
the F. G. 67 type seemed to fill the bill in all requirements
except in as far as anode voltage rating was concerned. It
had been found very successful in low voltage inverter cir-
cuits and its characteristics were well-known. Since in a
previous investigation it had been found that this tube would
stand up under anode voltages of 1500 volts; i. e., 150% of
the rated value, it was decided to find its limitation.
Another factor that affected this decision was that the fil-
ament heating power of this tube was small and its cost a
fraction of that of the next and considerably larger type.

The circuit shown by figure 4 was set up and
these tubes tried out. With the grids separately excited
from an a.-c. source it is a comparatively easy matter to
make this circuit function, provided that the grid voltage
is high enough for cleaning up the positive ions in the
limited time available with a rectangular wave-shape. The
limiting voltage on the tubes was found to be 2400 volts
d.-c. At this voltage they failed after operation for half
an hour.

The symptoms of breakdown were small sparks on the
upper side of the anode and a "corona effect" on the glass
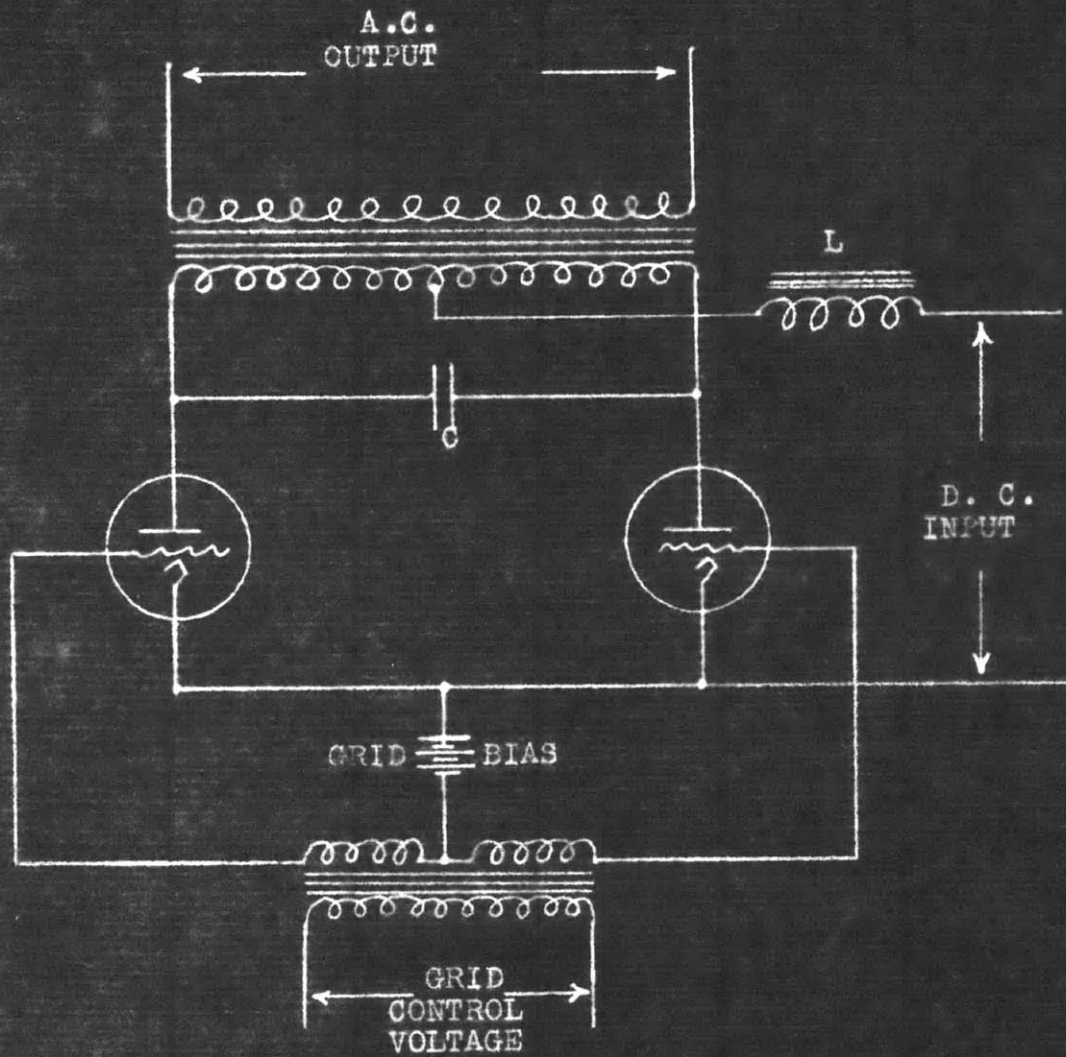where the anode lead was brought out with consequent breaking

FIG. 4. Separately Excited Parallel Inverter Circuit
in which Preliminary Tests on the Tubes were Made. The
Grids are contro lled from a Separate a-c. source.

of the glass bulb. As a result of these tests it was concluded that the spacing of the elements of the tube was inadequate for their use at high voltages.

Experimentation with Special "Bent-Arm Tube.

There was at this time available some specially constructed tubes, the rating of which were the same as that of the F. G. 41 type. Mechanically, they differed to a very great extent from the latter. Two anodes were placed in the same bulb in bent arms, similar to those in pool type tubes used for high voltages. The cathode had twice the capacity of that of the F. G. 41. In effect the tube was two of the latter combined into one, with the addition of a "holding anode" for maintaining ionization.

With separate excitation on the grids this tube functioned very well, however, not when the holding anode circuit was opened. The latter seemed essential, and the explanation lies in the fact that the tube elements (cathode and anodes) were a comparatively long distance apart, so that the anode voltage (which also is the applied d.-c. voltage) employed was not adequate.

First self-excited Grid Circuit.

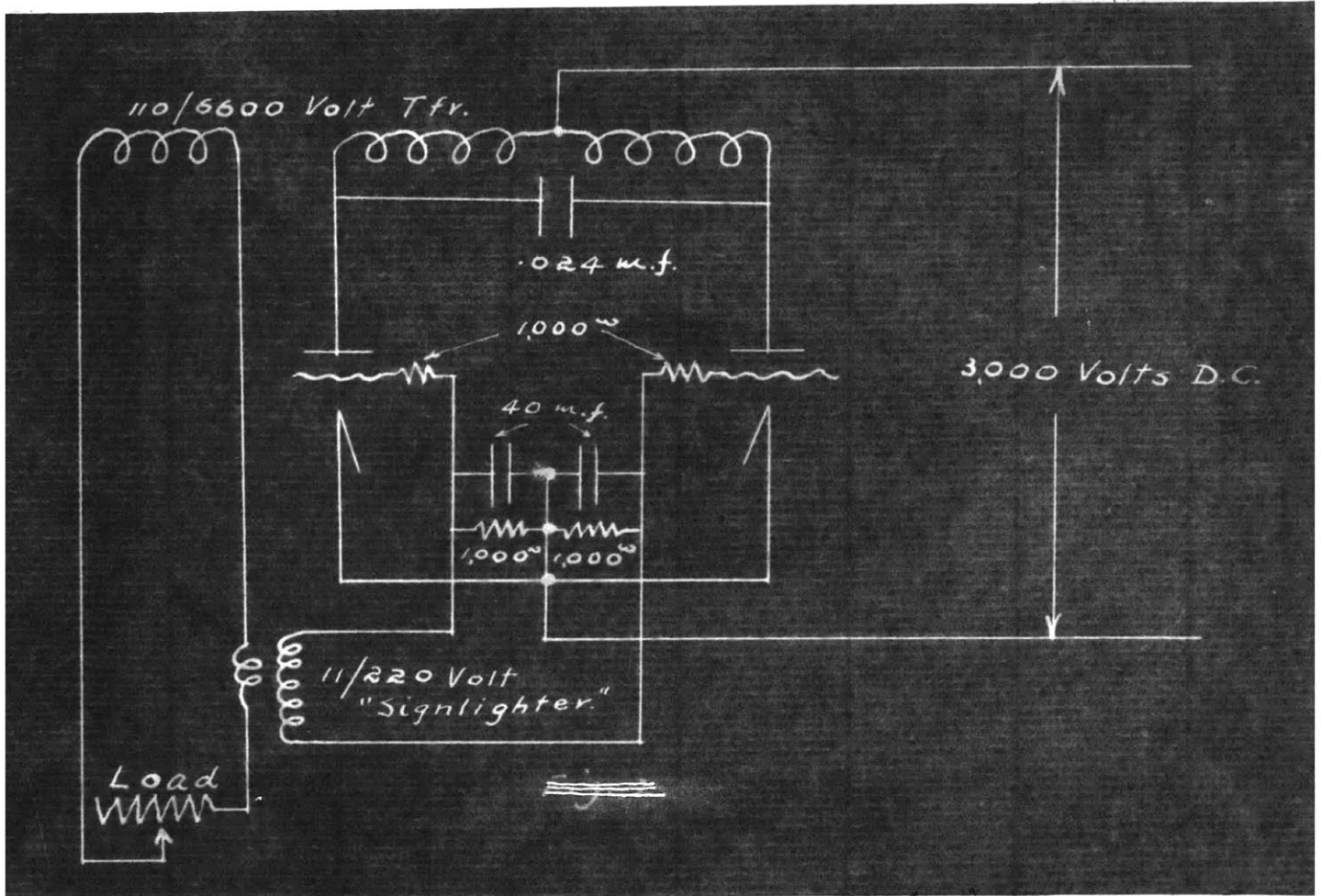The problems of self-starting and grid circuit design

Fig. 5. First Scheme Used to Obtain Self Excitation
of the Grids. For the Waveshapes of this Cir-
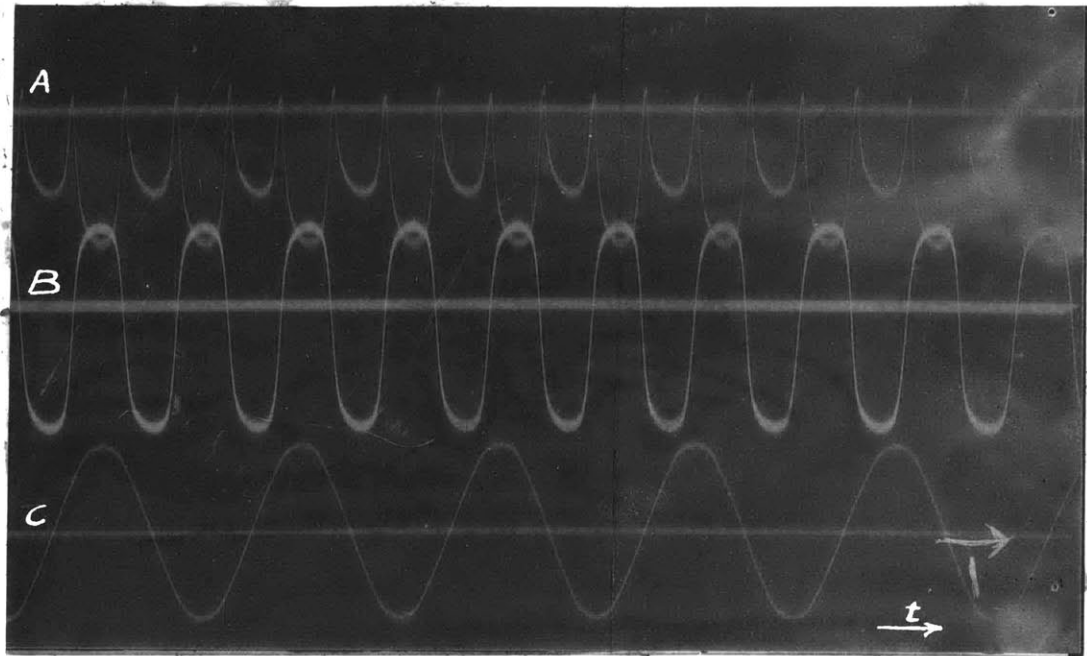cuit see Figs. 6 & 7.
(H-4359129)

Fig. 6. Waveshapes of the Circuit of Fig. 5. Load 1.70 kw.
Trace A: Grid Current
Trace B: Grid Condenser Current
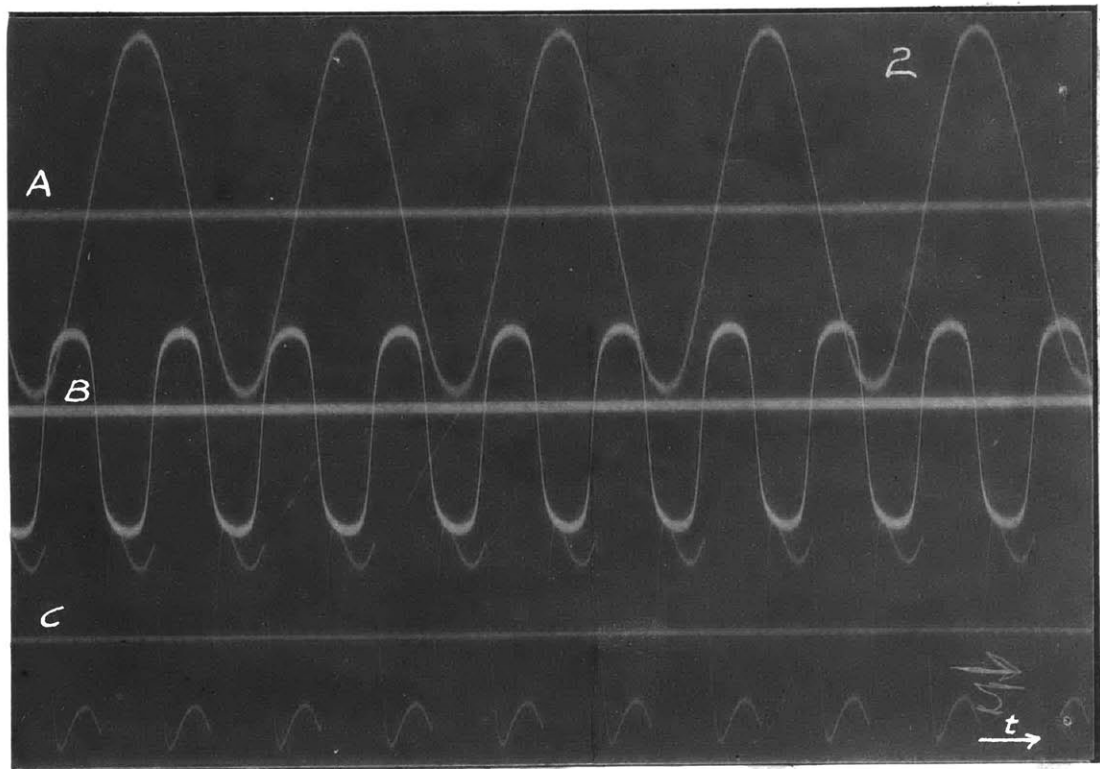Trace C: Timing Wave ⚓ 60 Cycles.
(C. D. 193080)

Fig. 7. Waveshapes of the Circuit of Fig. 5. Load 1.70 kw.
Trace A: Timing Wave ⚓ 60 Cycles
Trace B: Grid Condenser Current
Trace C: Output Voltage
(CD 193081)

are considered later in greater detail. Many of the facts

in connection with these were not realized when self-excita-

tion was first tried with the bent arm tube. For the sake of

completeness the first grid circuit found to do the trick is

included. The circuit is shown by figure 5 and its wave-

shapes by figures 6 and 7. It never was seriously considered

for this inverter on account of its inherent disadvantages,

viz.:

(1) The grid excitation was not derived in such a way

as to be unaffected by the amount of load current.

(2) Selfstarting could not be obtained. It was found

necessary to reduce the d.-c. voltage to less than

1500 and then to touch the grids off with a separate

source of a.-c. There is a possibility that this

characteristic was more due to the characteristic of

the tube used than to any feature of the circuit.

(3) As a matter of experimental observation, the fre-

quency lacked all control and seemed proportional

to load current. Very wide variations with load

were observed.

Second Selfexcited Grid Circuit.

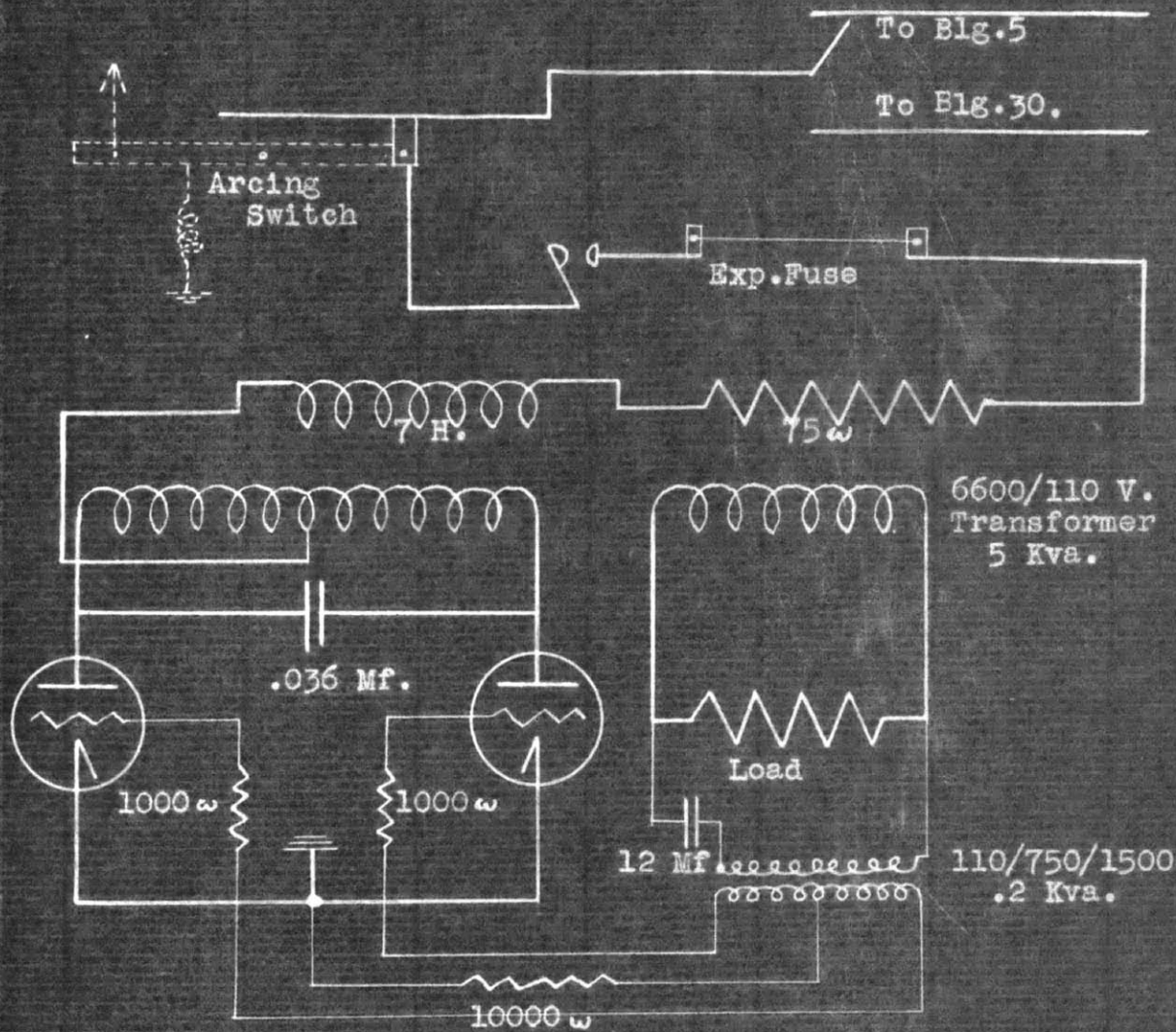With continued experimentation the grid circuit shown

by figure 8 was evolved. It had none of the disadvantages
of its predecessor. Frequency regulation was almost flat
above 1.5 kw. load and starting was readily obtained when
the line switch was closed on full d-.c. voltage. The vol-
tage and current waveshapes are shown by figures 9 to
17.

The Performance of F. G. 41 Tubes.

The circuit that resulted from continuous experimentation
is shown by figure 8. Its waveshapes are shown by figures
9 to 17. Its performance was considered highly satisfactory.
The use of a standard tube, however, was an essential
requirement and although the rating of the F. G. 41 was far
in excess of requirements, it seemed to be the only one
available.

Satisfactory operation with these tubes was not
obtained until they had been modified to the extent of apply-
ing a conducting coat of lampblack-aluminum paint to the bulb
and connecting this to the grid lead. This procedure in-
sured good grid control at all times and prevented any charge
on the glass from creating a secondary, and uncontrolled, grid
effect.

SINGLE PHASE, SELF-EXCITED INVERTER CIRCUIT WITH F.G.41

TYPE THYRATRONS.

To Blg.5

To Blg.30.

Arcing
Switch

Exp.Fuse

7 H.

75 ω

6600/110 V.
Transformer
5 Kva.

.036 Mf.

Load

1000 ω   1000 ω

12 Mf.

110/750/1500
.2 Kva.

10000 ω

D.C. Supply Voltage = 3,000.
Tube Filaments Supplied from 125 V. A.C. through Transformer
at 5 Volts.

Fig.5.

C.D.C. 9/30/30.

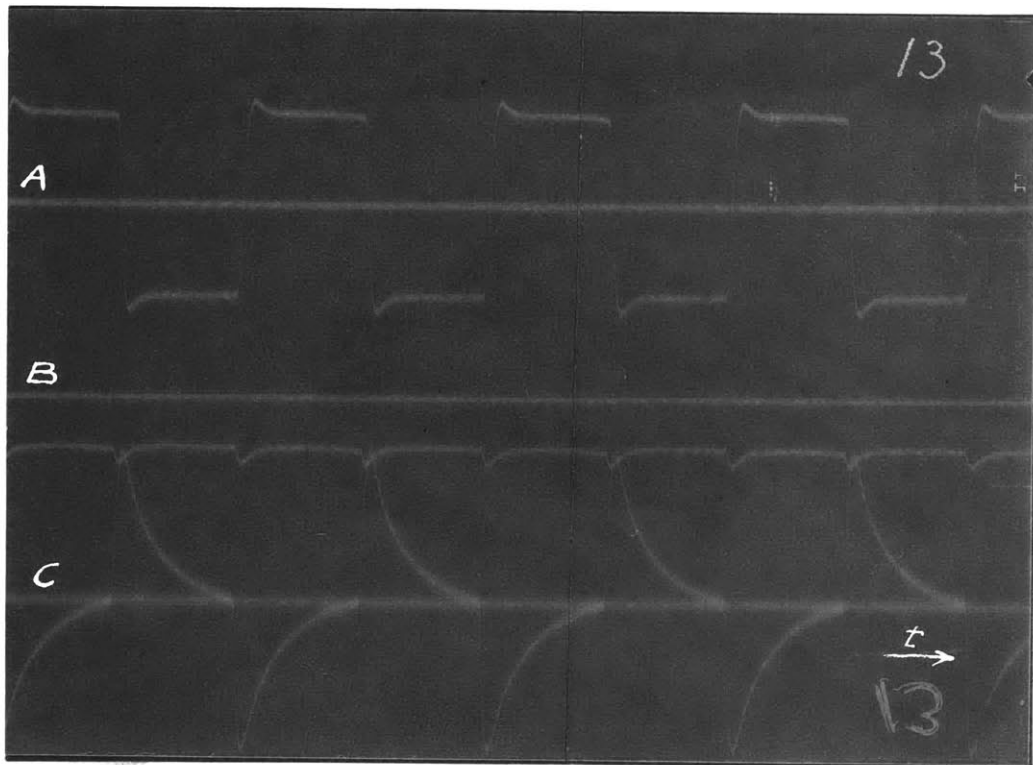H-4359149.

Fig. 9.   Waveshapes of the Circuit of Fig. 8 at 4.80 kw.
          Load and 75 Cycles.
          Trace A: Output Voltage
          Trace B: Input Current
          Trace C: Grid Voltage   (CD 191853)
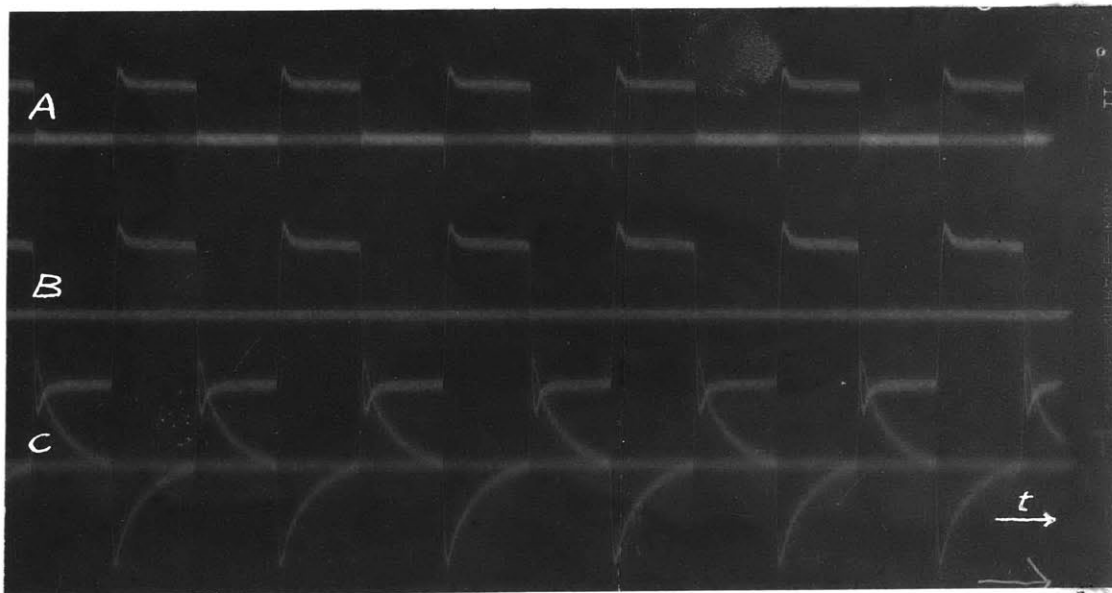

Fig.19.   Waveshapes of the Circuit of Fig. 8 at 3.70 kw.
          Trace A: Anode to Cathode Voltage on one Tube
          Trace B: Output Voltage
          Trace C: Grid Voltage   (CD 191853)

Fig. 11.   Waveshapes of the Circuit of Fig. 8 at .85
           kw. Load.
           Trace A: Anode to Cathode Voltage on
                      one Tube.
           Trace B: Output Voltage
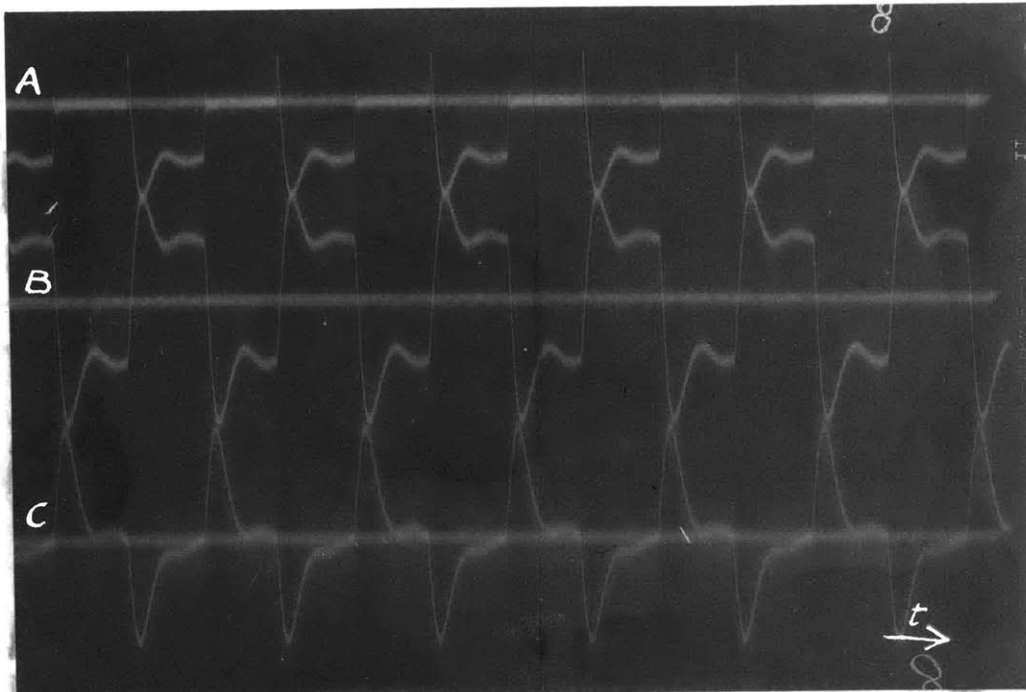   Trace C: Grid Voltage   (CD 193087)
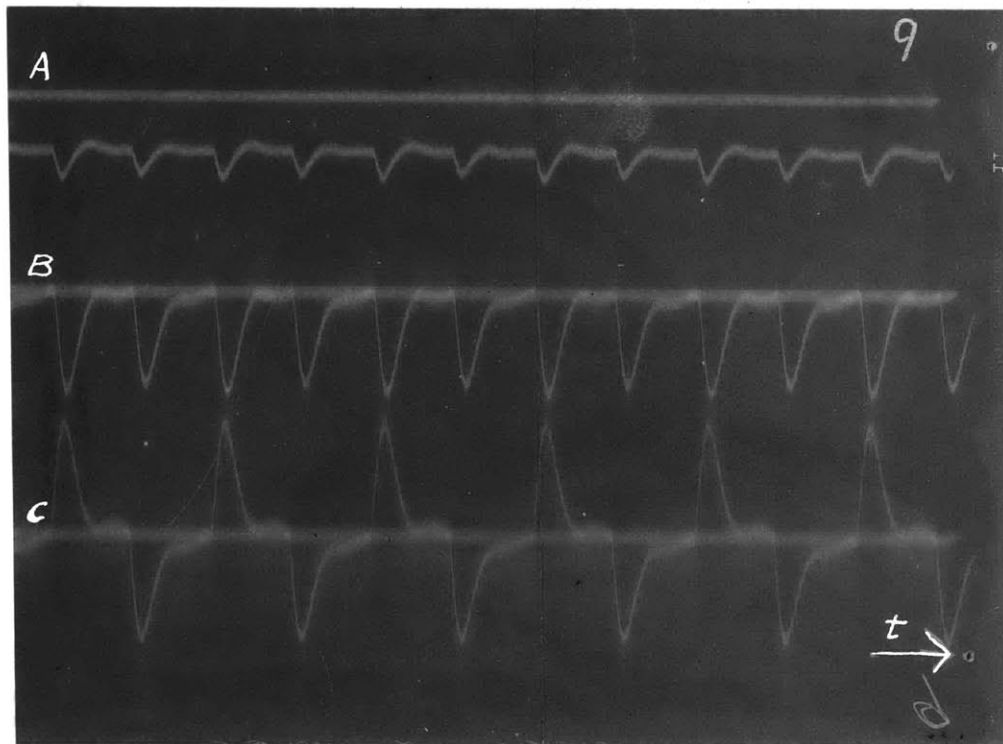
Fig. 12.   Waveshapes of the Circuit of Fig. 8 at .85
           kw. Load.
           Trace A: Input Current
           Trace B: Grid Current
           Trace C: Grid Voltage   (CD 193088)
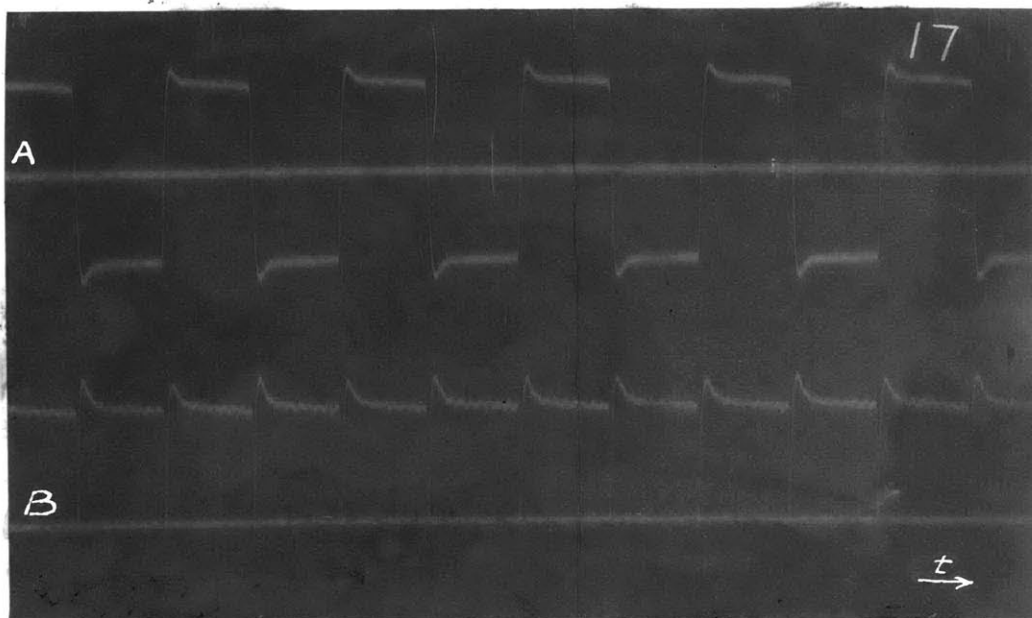
Fig. 13. Waveshapes of the Circuit of Fig. 8 at
4.8 kw. Load and 75 Cycles.
Trace A: Output Voltage
Trace B: Voltage from Transformer Mid-
tap to Ground. (CD 191855)
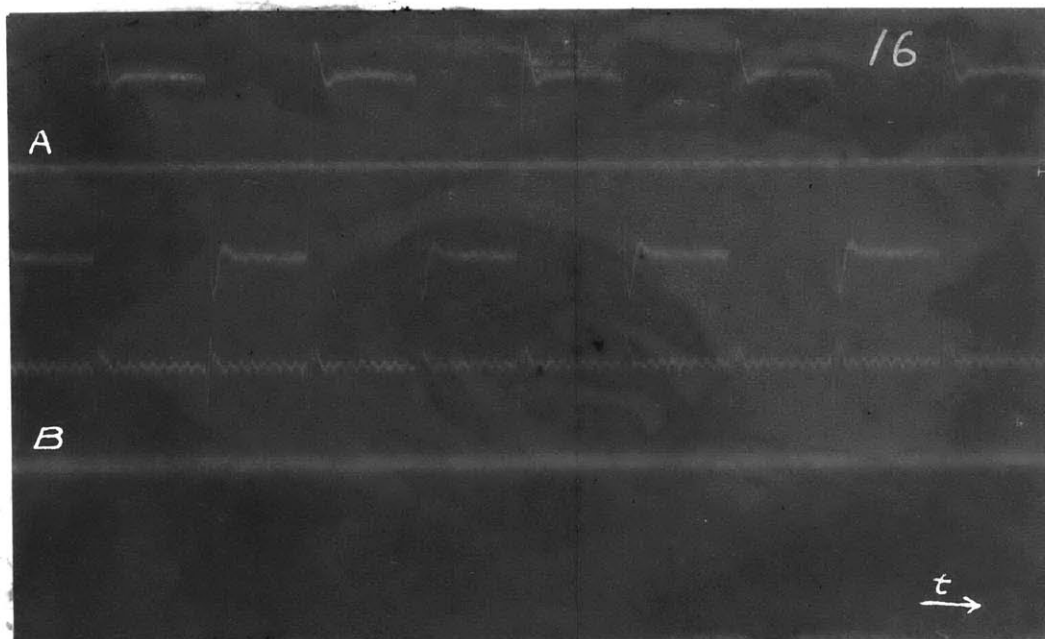
Fig. 14. Waveshapes of the Circuit of Fig. 8, but with
very small Inductance in the d-c. Line. 4.8
kw. Load and Frequency of 73 Cycles.
Trace A: Output Voltage
Trace B: Voltage from Transformer Mid-tap
to Ground.   (CD 191854)
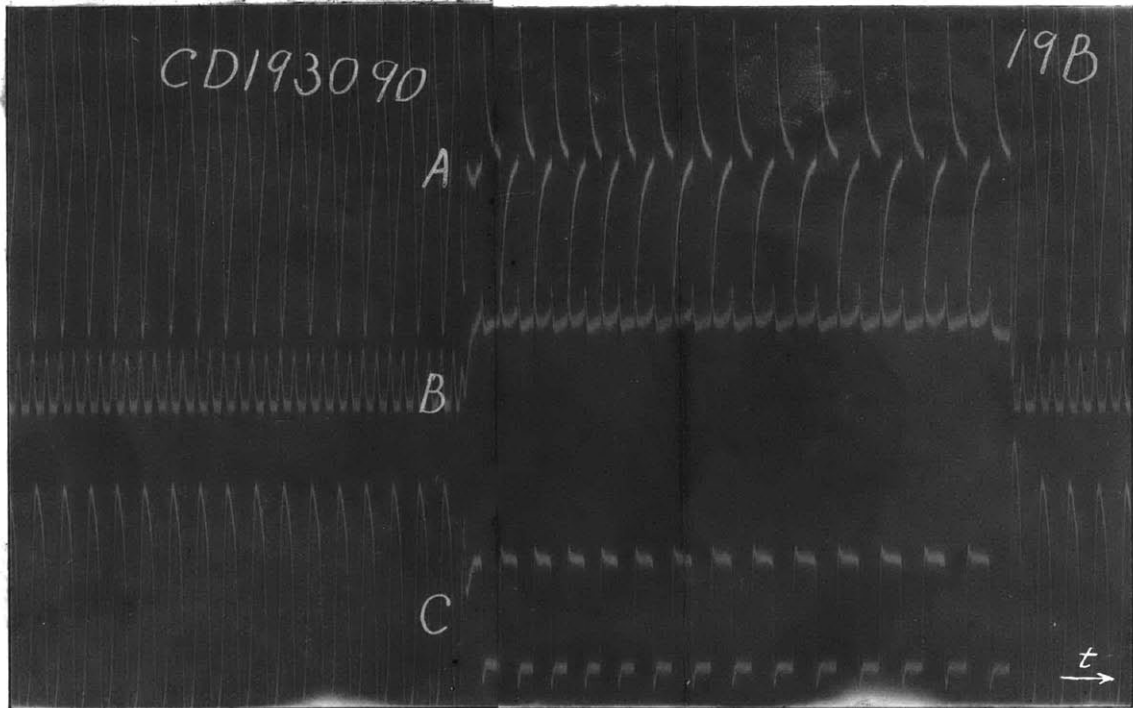
Fig. 15. Waveshapes of the Circuit of Fig. 8, but with very small inductance in the d-c. Line, Switching .27 to 4.8 kw. Load and back to .27 kw. Load.
Trace A: Grid Voltage
Trace B: D-c. Line Current
Trace C: Output Voltage   (CD 193090)
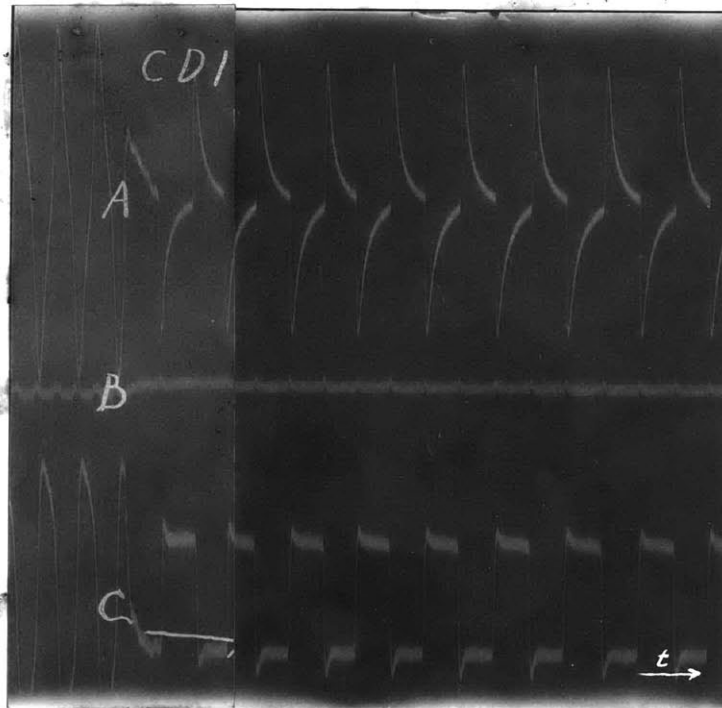
Fig. 16. Waveshapes of the Circuit of Fig. 8, switching from .27 kw. Load to 4.8 kw.
Trace A: Grid Voltage
Trace B: D-c. Line Current
Trace C: Output Voltage   (CD 193089)
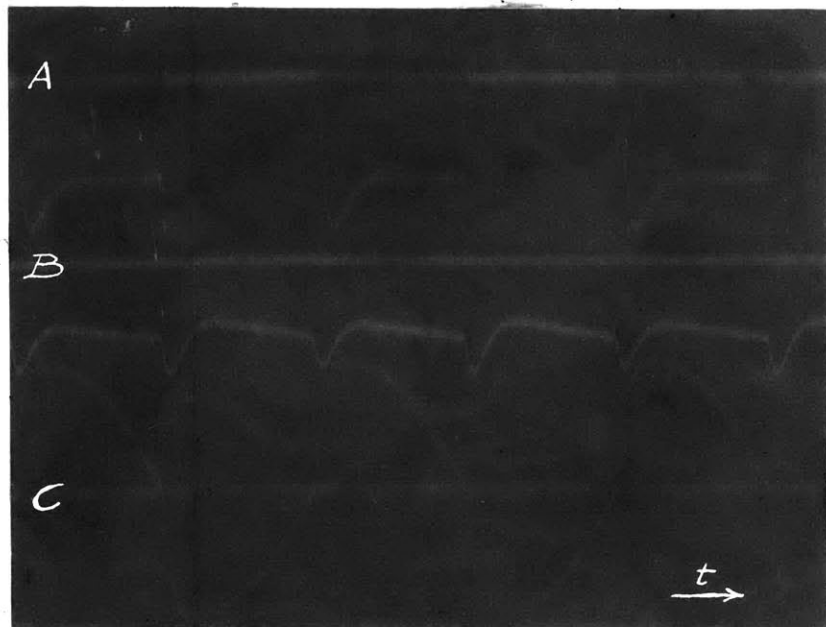
Fig. 17. Waveshapes of the Circuit of Fig. 8 at
5.0 kw. Load, and with the Oscillatory
Grid Circuit of Fig. 25.
Trace A: Anode to Cathode Voltage on
one Tube.
Trace B: D-c. Line Current
Trace C: Grid Voltage   (CD 191983)

Physical Explanation of the Operation of the Inverter.

The type of inverter with which this investigation
is concerned does not represent the ideal case, which has
been described by D. C. Prince. Mechanically, its operation
can best be visualized by considering the action of a common
duplex boiler feed pump. There is no flywheel; i. e., no
stored energy. The steam acts directly on the piston, which
sets the rod in motion, and, through the latter the water in the
water cylinder. At the end of the stroke of one rod the
latter acts on the steam valves of the other rod, which starts
its journey in the opposite direction, to trip the valves
of the first rod and start it on its way once more. The
action is discontinuous for each part of the pump during al-
ternate half-cycles of operation.

Electrically, the thyratrons perform the same
function as a synchronous switch, externally driven. When
the d.-c. line switch is closed, one tube or switch starts
conducting. Current flows through both halves of the main
transformer, the "power component" going through the tube,
and the other going into the condenser to charge it up to the
d.-c. line voltage. As soon as current starts flowing the
voltage applied to the grid of the non-starting tube is made

negative with respect to its cathode and it is preven-
ted from starting.

At the end of the first half-cycle the condenser in
the grid circuit becomes charged and the grid voltage of the
tube that was non-conducting approaches zero or becomes more
positive until the critical voltage is reached. At this point
the second tube becomes conducting, the current from the one
previously conducting is transferred to the condenser, with an
accompanying negative voltage "impulse" on its anode as shown
by figures 10, 11 and 17. At the same instant, the secondary
voltage reverses and its grid becomes negative so that by the
time the anode voltage passes through zero the de-ionization
is complete. The transfer of current from one tube to the
other takes place in about 1000 micro-seconds.

Due to the fact that a cathode ray oscillograph
was not available the exact de-ionization time was not measured.
From figure 11, it can be only guessed. It is very near
the rated value of that of the tubes. The successful oper-
ation of this circuit is in no small measure due to the
fact that the tubes could be de-ionized in about 100 micro-
seconds.

The Starting Operation.

It has been said that the inverter starts simply

by closing the d-c. line switch, with no special provisions
made that one tube only should start conducting. When both
tubes start conducting at the instant the line switch is
closed serious damage will result, especially in high vol-
tage circuits such as the one under consideration. It
is for this reason that in addition to a circuit breaker,
a current limiting resistor and a fuse were employed
as shown by figure 8.

An "average" grid voltage-striking voltage char-
acteristic of the F. G. 41 type tube is shown by figure
23. For individual tubes there are in many cases considerable
departures from this curve below 2500 volts. The critical
grid potential for 3000 volts for practically all tubes
used was 9 to 11 volts negative. From the symmetry of the
circuit it will be seen that if the two tubes do not have
identical characteristics or at least the same critical grid
voltage for 3,000 volts, one would conduct for a slightly
longer period of time than the other. The inevitable result
would be saturation of the main transformer, a condition tha t
would make operation cease in a few cycles.

For satisfactory steady state operation then, the
two tubes should have the same critical voltage. However,

for satisfactory starting they should be dissimilar; i. e.,
one should start conducting slightly before the other, be-
cause the instant before starting both have zero grid
potential. Tests showed that some pairs of tubes would
not start, while others would start but would cease oper-
ating in a very short length of time. The majority of
the tubes tested, however, did "cooperate" quite satisfac-
torily.

Regulation Characteristics and their Variation.

The voltage regulation, efficiency and frequency
characteristics with varying load of the circuit of figure
8 are shown by figure 19. The efficiency curve does not
include the 120 watts needed for cathode heating. It has
the same shape as that of a high voltage rectifier circuit
that employs mercury vapor tubes. The losses, in order
of importance, are: transformer losses, resistance losses
in the d.-c. line, grid power, and tube arc drop. Com-
pared with that of a rotating machine the efficiency is
remarkable.

The rise in frequency with decreasing load is
due to the change in out-put voltage wave-shape from that
of a rectangle at full load to a sinusoid at no load.

Fig.19. CHARACTERISTIC CURVES OF PARALLEL TYPE, SINGLE PHASE INVERTER.

[CIRCUIT OF H-4359149]
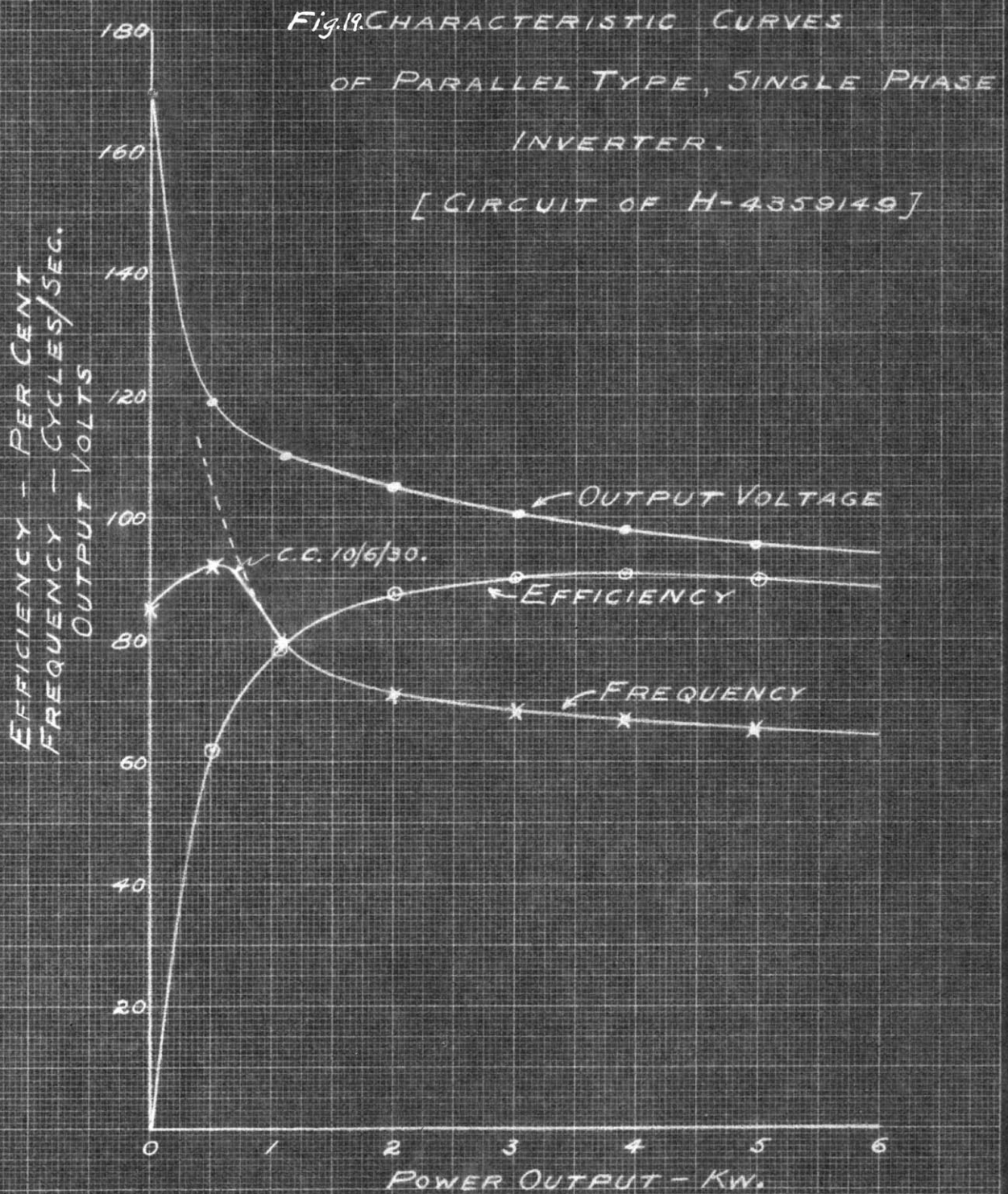
The cause of the rise and drop in frequency at loads bet-
ween 1 kw. and zero has not been ascertained but it is not
of very great importance as due to the rise in output vol-
tabe the inverter should always be connected to a minimum
load of, say, 500 watts.

The load-output voltage curve reaches a critical
region, between 500 watts and 1 kw., beyond which a de-
creased load results in a somewhat excessive voltage rise.
An explanation of this is not far to seek. Although the
anode condenser is small, it stores energy during each
half-cycle, that must be dissipated during the time trans-
fer of the current from one tube to the other takes place.
The transformer losses are small and neglecting them the
rate of energy dissipation is equal to the square of the
output voltage divided by the load resistance. At load
resistances less than the critical, therefore, the out-
put voltage must rise because a point has been reached
where the rate of energy storage is a minimum and re-
mains substantially at this value up to the open circuit
condition.

An analogous condition would arise in electrical machinery if it were not for the fact that a back emf. exists. To make the actual analogy between inverter and rotating machine complete we can rectify the inverter output at light loads and connect the rectifier output back to the d.-c. line. Obviously, however, this would not be economical. If the need for suppressing the light load output voltage does arise, a minimum load left on the inverter will prevent the inconvenience.

Figure 22 shows the variation of regulation characteristic with circuit constants. The most convenient regulation curve, it will be seen, is obtained with maximum line inductance and a minimum capacitance between anodes. The lower the capacitance and the higher the line inductance the lower will the rate of energy storage and dissipation be and hence the lower the output voltage at light loads. If it were not for losses in the circuit the output voltage on open circuit would be infinite, somewhat analogous to the high speed of a d.-c. motor when its field circuit is opened.
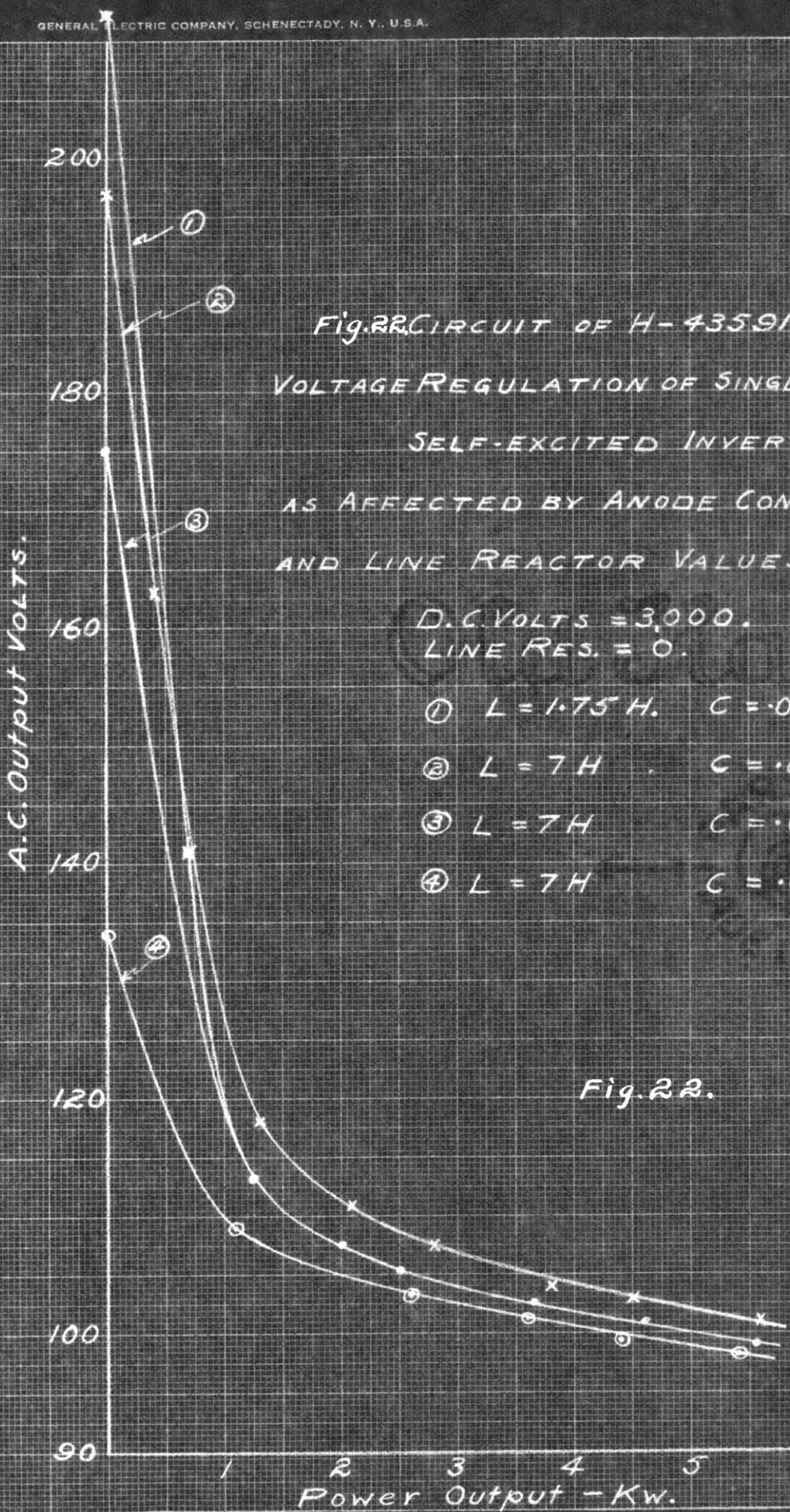
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Fig. 22. Circuit of H-4359149.

Voltage Regulation of Single Phase,
Self-Excited Inverter
as Affected by Anode Condenser
and Line Reactor Values.

D.C. Volts = 3,000.
Line Res. = 0.

① L = 1·75 H.   C = ·036 Mf.
② L = 7 H   .   C = ·056 Mf.
③ L = 7 H   C = ·036 Mf.
④ L = 7 H   C = ·024 Mf.

Fig. 22.

Fig. 22. Circuit of H-4359149. Voltage Regulation of Single Phase, Self-Excited Inverter as Affected by Anode Condenser and Line Reactor Values.

IV.   ANALYSIS OF THE INVERTER CIRCUIT.

Assumptions.

The main difficulty in the analysis of circuits containing vacuum tubes (or vapor tubes for that matter) lies in the fact that these devices are variable circuit parameters and a convenient method for handling such analyses, without simplifying assumptions, does not yet exist.   In analyzing the circuit under consideration the action of the two tubes can be assumed to be that of a synchronous switch.   That is, imagine that some mechanism external to the circuit periodically opens and closes the two switches A and B of figure 18.   When A is closed B is opened and vice versa.   The current through, say A, the instant B is closed is then assumed to be abruptly transferred to the condenser.

Furthermore, the circuit parameters will be assumed linear.   The circuit is symmetrical so that one set of differential equations set up in terms of the three loop currents will completely specify its behavior.

The Symbols Used (See figure 18)

Let E = Direct Voltage

L = d.-c. line inductance

R = d.-c. line resistance

$L_1 = L_2$ = Self-inductance of one-half
the transformer primary

$L_{12} = L_{21}$ = Mutual Inductance between the
two primary windings of the main
transformer.

$R_1 = R_2$ = Resistance of one-half of the
transformer primary winding.

L_3 = Self-inductance of transformer
secondary winding.

$L_{13} = L_{23}$ = Mutual inductance between one-
half the transformer primary
winding and the secondary winding.

i_1, i_2 and i_3 = Loop currents for the respective
loops.

R_3 = Combined resistance of load and
transformer secondary winding
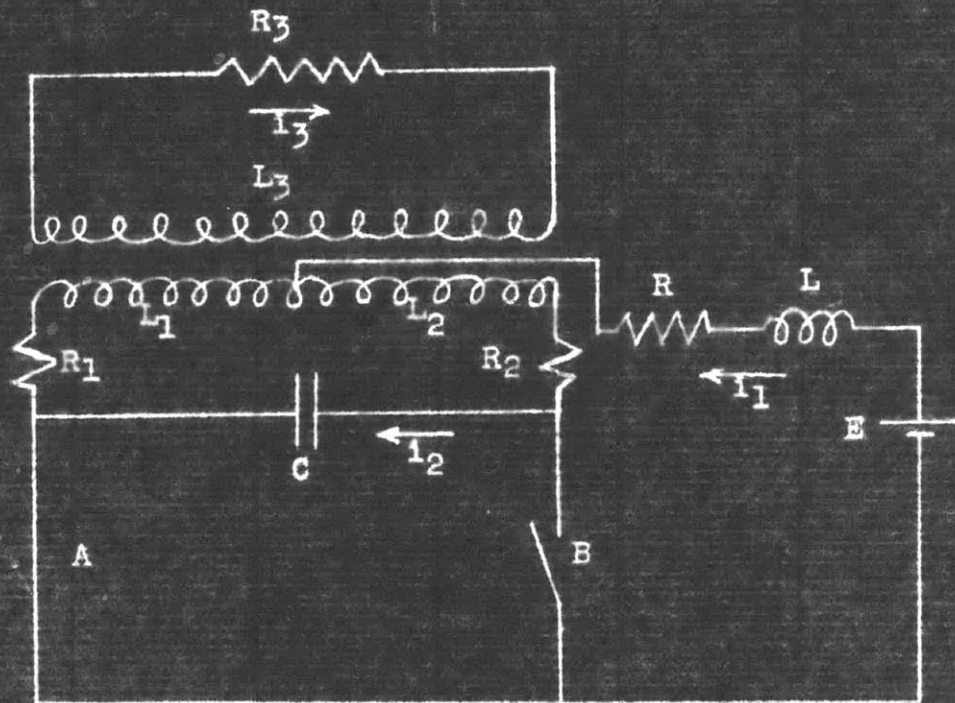
E = 3,000 Volts
L = 10 Henries
R = 100 Ohms
$L_1 = L_2 = 57.8$ Henries
(This corresponds to 10% Mag. Cur.)
$R_1 = R_2 = 48$ Ohms
C = .63 Microfarad
$R_3 = 2.45$ Ohms

The mutual inductances are:-
$L_{12}, L_{13} \& L_{23}$

Fig. 18. The Circuit for which the Differential Equations
were set up and Solved. The Currents are plotted in
Figures 20 and 21.

The Differential Equations of the Circuit

For the first loop:

$$L\frac{di_1}{dt} + R i_1 + L_1\frac{di_1}{dt} + R_1 i_1 - L_2\frac{di_2}{dt} - L_{12}\frac{di_2}{dt} - R_2 i_2 + L_{13}\frac{di_3}{dt} = E$$

$$\dots\dots\dots\dots(1)$$

For the second loop:

$$R_1 i_2 + L_1\frac{di_2}{dt} + R_2 i_2 + L_2\frac{di_2}{dt} + 2L_{12}\frac{di_2}{dt} + \frac{1}{c}\int i_2 dt$$

$$- L_1\frac{di_1}{dt} - R_1 i_1 - L_{12}\frac{di_1}{dt} - L_{23}\frac{di_3}{dt} - L_{13}\frac{di_3}{dt} = 0 \quad \dots\dots\dots(2)$$

For the third loop:

$$R_3 i_3 + L_3\frac{di_3}{dt} + L_{13}\frac{di_1}{dt} - L_{23}\frac{di_2}{dt} - L_{13}\frac{di_2}{dt} = 0 \quad \dots\dots\dots\dots(3)$$

Replacing the derivative operator by p and noting that $L_1 = L_2$, $L_{13} = L_{23}$, and $R_1 = R_2$, these three equations can be put into determinantal form as follows:

$$D(p)= \begin{vmatrix} (Lp + R + L_1 p + R_1) & -(L_1 p + L_{12}p + R_1) & + L_{13}p \\ -(L_1 p + L_{12}p + R_1) & (2R_1 + 2L_1 p + 2L_{12}p + \frac{1}{cp}) & - 2L_{13}p \\ L_{13}p & - 2L_{13}p & + (R_3 + L_3 p) \end{vmatrix} = 0 \quad ..(4)$$

For the sake of not making the determinantal equation too cumbersome the assumption will be made that the linkage reactance of the transformer is negligible. The effects and justification of this will be considered later.

Noting that under the above assumption $L_{12} = L_1$, the determinantal equation will be as follows:

$$2(R_1LL_3 + R_3LL_1 + 2R_3L_1^2) \, p^3$$

$$+ \, (2R_1R_3L + \frac{LL_3}{C} + 2R_1R_3L_1 + R_1^2L_3 + 2RR_1L_3 + 4RR_3L_1) \, p^2$$

$$+ \, (\frac{LR_3}{C} + \frac{L_1R_3}{C} + R_1^2R_3 + \frac{R_1L_3}{C} + 2RR_1R_3 + \frac{RL_3}{C}) \, p$$

$$+ \frac{R_1R_3}{C} + \frac{RR_3}{C} = 0 \quad \dots\dots\dots\dots\dots\dots\dots(\, 5 \,)$$

For any given set of circuit constants the three roots of this equation can be found. They will have the usual form:

(1) Non-oscillatory case:

$$p_1 = -a \quad$$
$$p_2 = -b \quad \Big\} \quad \text{all real}$$
$$p_3 = -c \quad$$

The solution for any current in the circuit will be:

$$i = I_{ss} + K_1 e^{-at} + K_2 e^{-bt} + K_3 e^{-ct} \quad \ldots \ldots \ldots \ldots \quad (6)$$

(2) Critically damped case:

$$p_1 = -d \quad \Big\}$$
$$p_2 = p_3 = -f \quad \Big\} \quad \text{both real}$$

The general form of solution for any current will be:

$$i = I_{ss} + K_4 e^{-dt} + K_5 e^{-ft} + K_6 t e^{-ft} \quad \ldots \ldots \ldots \ldots \quad (7)$$

(3) Oscillatory case:

$$p_1 = -r \qquad \text{(real)}$$
$$p_2 = -u + jw \quad \Big\}$$
$$p_3 = -u - jw \quad \Big\} \text{(Conjugate complex)}$$

and the current will be of the form:

$$i = I_{ss} + K_7 e^{-rt} + K_8 e^{-ut} \sin (wt + \theta)$$

where I_{ss} in all three cases is the value of the current

at t $=\infty$, or the steady state value, and K_1 to K_8 are

constants.

For any set of circuit constants the values
of the K's in equations (6), (7) and (8) can be found if
the initial conditions are known.

In order to calculate the currents two solutions
must be made; viz., one for the starting half-cycle and
the other for the "steady-state" or all subsequent half-
cycles; i. e.,assuming that the steady state is reached
in one half-cycle, as the oscillograms indicate.

The Starting Half-cycle.

When tube A starts, at $t = 0$, we know that i is
zero and all the applied d.-c. voltage appears across the
line inductance so that $\left(\frac{di_1}{dt}\right)_o$ will be $\frac{E}{L}$. For

finding the third condition; viz., the value of $\left(\frac{d^2 i_1}{dt^2}\right)_o$ we
must go back to the differential equations. Multiplying
equation (1) by 2 and adding (2) we have

$$2Lpi_1 + 2Ri_1 + R_1i_1 + \frac{1}{Cp} i_2 = E \quad \ldots\ldots\ldots(9)$$

Differentiating (9) with respect to t, we have

$$2L \frac{d^2 i_1}{dt^2} + (2R + R_1)\frac{di_1}{dt} + \frac{i_2}{c} = 0 \quad \dots\dots\dots (10)$$

so that

$$\frac{d^2 i_1}{dt^2} = -\frac{\left[(2R + R)\frac{di_1}{dt^2} + \frac{i_2}{c}\right]}{2L} \quad \dots\dots(11)$$

Already having the value of $(\frac{di_2}{dt})_0$ and noting that

$i_2 = 0$, when $t = 0$, $\frac{d^2 i_1}{dt^2}$ can be found.

For finding $\frac{di_2}{dt}$ we know that the rise in line current at $t = 0$ divides equally between the two parts of the transformer primary so that $\frac{di_2}{dt} = \frac{1}{2}\frac{di_1}{dt}$. The third condition for the solution of i_2 is gathered from the fact that the charge on the condenser initially is zero and hence

$$q_c = \int i_2 dt = 0 \quad \dots\dots\dots\dots (12)$$

In the integration of (12) a constant will appear which is simply the ultimate charge on the condenser. Neglecting resistance drops this will be CE, and, being in opposition

to the direct supply voltage it will be positive in sign

so that

$$\int i_2 dt = -CE$$

To sum up:

When $t = 0,$ $\qquad i_1 = 0$

$$\frac{di_1}{dt} = \frac{E}{L}$$

$$d^2 i_1 = \frac{-\left[(2R + R_1)\frac{E}{L}\right]}{2L}$$

$$i_2 = 0$$

$$\frac{di_2}{dt} = \frac{E}{2L}$$

$$\int i_2 \, dt = -CE$$

$$I_{ss} \ (\ i_1 \ ) = \frac{E}{R+R_1}$$

For the circuit constants shown in Figure 18 the two

sets of simultaneous equations are:

$$K_1 + K_2 \sin \theta = -20.25 \quad \dots\dots\dots(14)$$

$$-2.06 K_1 - 552 K_2 \sin \theta + 55.0 K_2 \cos \theta = 300 \dots(15)$$

$$4.24 K_1 + 301,500 K_2 \sin \theta - 60,600 K_2 \cos \theta = -3720 \dots(16)$$

$$K_1 + K_2 \sin \theta = 0 \quad \dots\dots\dots\dots\dots\dots\dots\dots(17)$$

$$-2.06 K_1 - 552 K_2 \sin \theta + 55.0 K_2 \cos \theta = 150 \quad \dots\dots\dots\dots(18)$$

$$\frac{-K_1}{2.06} - \frac{K_2 (-552 \sin \theta -55.0 \cos \theta)}{552^2 + 55.0^2} = .00009 \quad \dots\dots\dots(19)$$

Solving the above we have:

$$i_1 = 20.25 - 19.33 e^{-2.06t} 4.59 e^{-552t} \sin(55t + 11.5°) \dots(20)$$

$$i_2 = 2.73 e^{-552t} \sin 55t \quad \dots\dots\dots\dots\dots\dots\dots(21)$$

These are plotted in figures 20, and 21, where the output frequency is arbitrarily taken as 62.5 cycles/sec. so that one-half cycle takes .008 seconds.

Calculation of the Currents during the Second Half-Cycle.

When the second half-cycle starts conditions are different from those of the first half-cycle. The instant tube B starts the condenser voltage adds to that of the d.-c. supply and full line voltage again appears across the line inductance (see figure 13).

i_1, however, does not start from zero. Its magnitude is 1.2 amperes; i.e., the current that is flowing through tube A when tube B starts to conduct at $t = .008$ seconds for the first half cycle and $t = 0$ for the second half cycle.

For the third condition; i. e., the value of $\frac{di_1}{dt}$ we find the initial conditions contradictory and not in accordance with the fundamental differential equations. These were set up on the basis of one tube only being conducting. Hence, with the condenser fully charged, either aiding or bucking the direct voltage, i_2 must be nero at $t = 0$. Conversely, if i_2 has some value the condenser cannot possibly be fully charged.

The third initial condition for finding i_1 then, based on the initial value of i_2 (see equation (11)) is useless. Similarly, the initial conditions for finding i_2 are useless.

The key to the situation is of course the
fact that all the current through tube A at $t = .008$
seconds is not abruptly transferred to the condenser.
Some of the current is transferred at once but until some
time before the positive ion cleanup is complete there
is a current flow in tube A. At the instant de-ionization
is complete and the voltage across the condenser passes
through zero, the condenser only carries current. For
purposes of analysis then, we cannot assume the action
of the tubes to correspond to that of a synchronous
switch and what happens during the de-ionization period
cannot be calculated on this basis.

Calculation of d.-c. Line Current during the Second
Half Cycle.

The fact that the initial conditions for finding
i_1 are contradictory does not preclude its calculation.
i_1 can be calculated accurately. The oscillograms show
that after the starting half-cycle all others are alike,
so that the initial conditions, as far as i_1 is concerned,
for the second half-cycle must be the same as for the
third. Since at the end of the starting half-cycle, only

one component of i_1 ; viz., $(20.25 - 19.33e^{-2.06t})$ still

has a value we conclude that this component of i   is the

same for __all__ half-cycles. Knowing i_1 and $\dfrac{di_1}{dt}$ at   t =   0,

the other component of the form $Ke^{-552t}\sin(55t + \theta$ can

be found. For the circuit under consideration we have:

$$\text{At}\quad t = 0$$

$$K\sin\theta \qquad = .28 \qquad \dots\dots\dots\dots(22)$$

$$-552\,K\sin\theta + 55.0\,K\cos\theta = 300 \quad \dots\dots\dots (23)$$

Solution of (22) and (23) gives

$$i_1 = 8.26\,e^{-552t}\sin(55t + 1.9^{\circ}) \quad \dots\dots\dots\dots(24)$$

(as a component of i_1)

and the complete form of i_1 hence is:

$$20.25 - 19.33\,e^{-2.06t} + 8.26e^{-552t}\sin(55t + \theta)\dots(25)$$

This is plotted in figures 20 and 21.

Calculation of other currents during Second Half-Cycle.

In order to form a picture of the current com-

ponents in the circuit during the second half-cycle two
calculations were made. They are shown by figures 20 and
21.

In figure 21, the assumption was made that
i_2 (the condenser current) starts from zero. It will
of course have the same form as it had during the first
half-cycle with twice the amplitude since the condenser
is initially charged, aiding the direct voltage. It
was further assumed that the current in tube A dies down
rapidly and becomes zero at the instant the charge on the
condenser is zero.

In figure 20, the assumption was made that the
condenser at the end of the first half cycle takes over
all the current that has been flowing in tube A, that
is, that the current through tube A stops abruptly and
that it has the form $K \epsilon^{-552t} \sin(55t+\theta)$ and for our
two initial conditions we have that i_2 = 1.20 amperes
and $\int i_2 dt = -CE$.

We hence solve

$$K \sin \theta = 1.2 \quad \dots \dots \dots \dots (26)$$

$$-552 \ K \sin\theta + 55.0 \ K \cos \theta = -55.3 \quad \dots \dots (27)$$

and find $i_2 = -11.2 \ e^{-552t} \sin(55t - 6.2^\circ) \quad \dots \dots (28)$
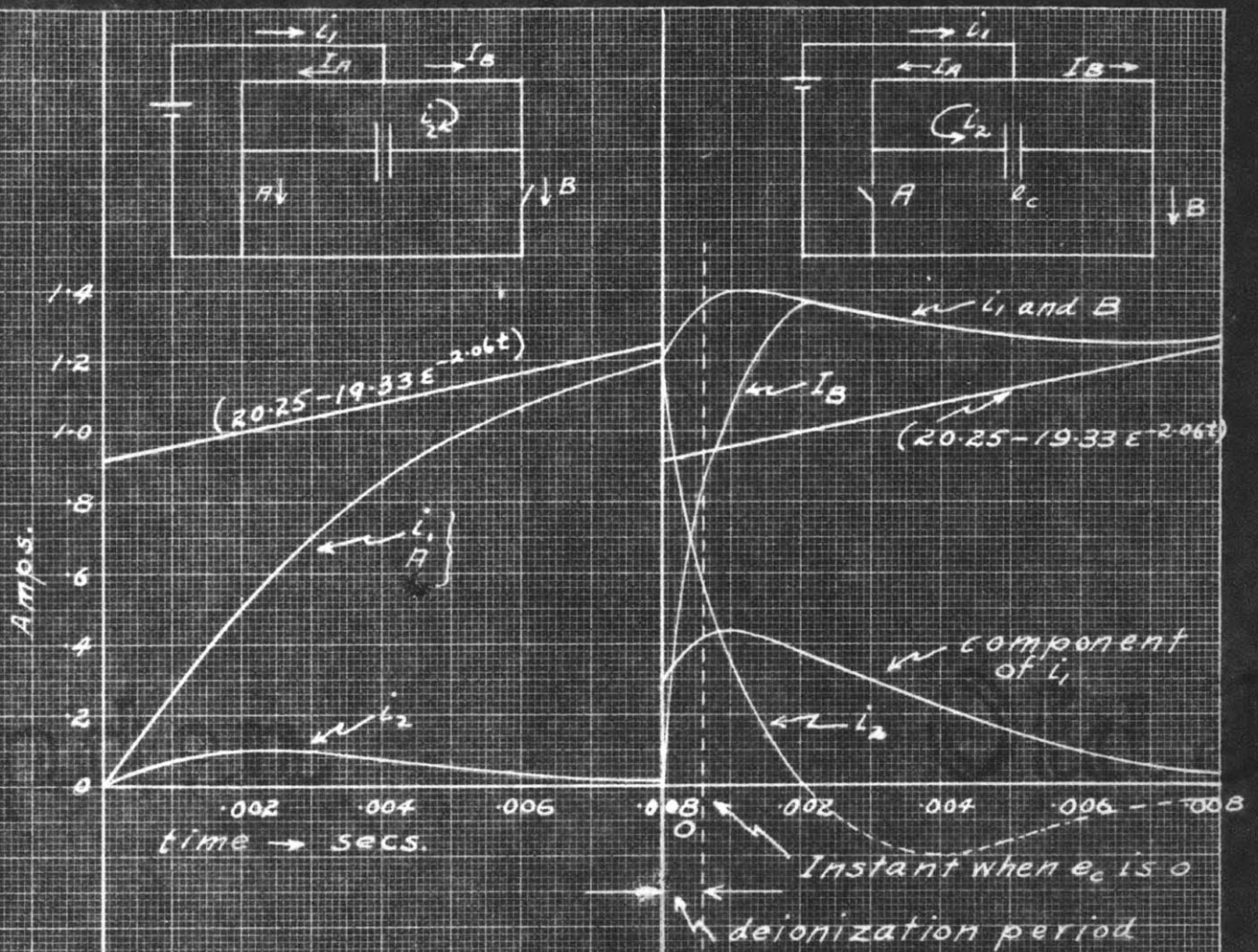
We find that i_2 decreases sharply, comes to
zero at .002 seconds and becomes negative, as shown by
the dotted line (figure 20). The negative portion of
course does not actually exist to the extent shown,
because it means that during the rest of the second
half-cycle the condenser discharges and charges again,
which we know is not the case. The physical interpreta-
tion of the negative loop of i_2 seems to be that the cur-
rent was brought in initially from some outside source
(in this case tube A), and, after the condenser is
charged at t = .002 seconds, it will tend to discharge
again. Since tube A has stopped conducting some time prior
to t = .002 seconds, i_2 must be discontinuous at this
point.

Results of Analysis.

It has already been shown that the current
                                    abruptly
through the outgoing tube cannot cease/with the condenser
capacity assumed. At the beginning of the second half-
cycle it has some value and it takes a short time to come
to zero. Since in the circuit under consideration no
oscillograms were taken of the components calculated, there

$(20.25 - 19.33 \varepsilon^{-2.06t})$

i_1 and B

I_B

$(20.25 - 19.33 \varepsilon^{-2.06t})$

i_1 A

component of i_1

i_2

i_2

i_2

Amps.

$\cdot 002$ $\cdot 004$ $\cdot 006$ $\cdot 008$ O $\cdot 002$ $\cdot 004$ $\cdot 006$ — $\cdot 008$

time → secs.

Instant when e_c is 0

deionization period

Procedure :—

1. Calculate i_1
2. Calculate i_2
   Use equations (14) to (19)

Procedure :—

1. Insert $(20.25 - 19.33 \varepsilon^{-2.06t})$
2. Calculate component of i_1 from eq^{ns} (22) & (23) & add
3. Calculate i_2 from (26) & (27)
4. Subtract i_2 from i_1 to obtain I_B.

Fig. 20. Showing Current Components in Inverter Circuit under assumption that Current of the Outgoing Tube is Instantaneously Transferred to the Condenser at Beginning of the Second Half Cycle of Operation. Circuit of Fig. 18.

Metric Divisions

Amps.

$(20.25 - 19.33 \varepsilon^{-2.06t})$

i_1

I_B

$(20.25 - 19.33 \varepsilon^{-2.06t})$

i_1

I_A

component of i_1

i_2

i_2

.002   .004   .006   .008   .002   .004   .006   .008
time → secs.   0
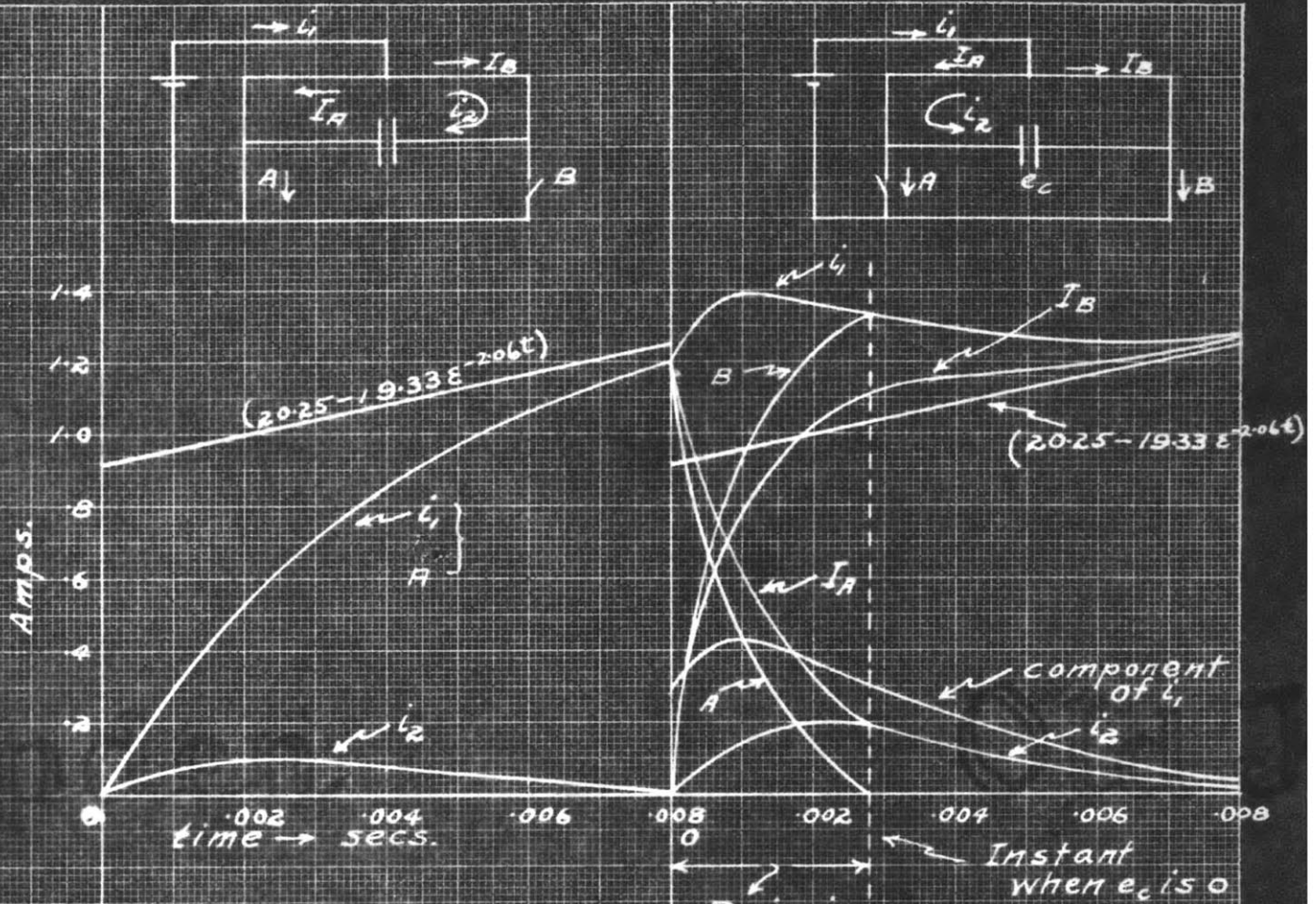
Instant when e_c is 0

Deioniz-
ation
period

Procedure:–

1. Calculate i_1
2. Calculate i_2

Use equations (14) to (19)

Procedure:–

1. Insert $(20.25 - 19.33 \varepsilon^{-2.06t})$
2. Calculate component
   of i_1 from eq^ns (22) & (23) & add.
3. Plot $i_2 = 2 \times i_2$ in first
   half cycle
4. Assume decreasing cur-
   rent thru' A & plot
5. Add A + i_2 to obtain I_A
6. Subtract I_A from i_1 to ob-
   tain I_B.
7. Add $i_2 + I_B$ to obtain B.

Fig. 21.   Showing Current Components in Inverter
Circuit under assumption that Current thru'
the Condenser Starts from Zero at Beginning
of the Second Half Cycle of Operation.
Circuit of Fig. 18.

are no means of checking the calculations. The actual

case will be somewhere between the components shown by

figure 20 and those shown by figure 21 with a tendency

more towards those of the ~~latter~~ *former*. Since this is the

extreme case; i. e., the shortest possible de-ionization

period available, the analysis provides a means of check-

ing up on probable tube performance.

That the actual oscillograms of the line cur-

rent merely resemble the calculated current is no doubt

due to the non-linearity of the circuit parameters and

is to be expected in work of this nature.

The Effect of Leakage Reactance in the Transformer.

The transformer used was an ordinary distribu-

tion transformer with small leakage reactance. If

leakage reactance is taken into consideration in the anal-

ysis it would merely result in the addition of small high

frequency currents corresponding to the oscillating fre-

quency of the leakage reactance and the condenser capacity.

These currents and their induced voltages are noticeable

in all oscillograms, where the lines are thick. Figures

13 and 14, however, show the high frequency voltage across

the transformer primary very clearly. The amplitude

of the high frequency voltage is small and no harm is

done. If an ordinary small leakage reactance transformer

is used, leakage reactance can be neglected both as far as

calculations and as far/its effects on operation and con-

cerned.

*****

V. DESImN OF THE MAIN CIRCUIT.

The Inverter not an Oscillator.

Although the inverter supplies alternating cur-
rent, it is not comparable to an oscillator. The name
Repeated Transient Inverter implies that sine waves do not
exist and hence the analysis, that has barely been started
in this report, is a new game. It is not played according
to the rules applying to oscillators. In the design of
an oscillator the first step is to see that the circula-
ting energy is large enough, the required minimum ratio
of volt-amperes to watts being 4   . The mechanical
problem of determining the correct flywheel size for an
engine is analogous. After this has been assured the cal-
culations of the proper voltages and proper phase relations
of grid and anode voltages must be undertaken.

An inverter can be made to oscillate either by
designing the circuit on an oscillatory basis or by sup-
plying a synchronous load. The latter method is by far
the more practical and economical and represents the
ideal case.

The design of the circuit under consideration

can be started directly by the calculation of proper voltages, phase angles do not exist, and the grid circuit can be considered as a separate problem.

Voltage and Current Relations.

The relation between the d.-c. supply voltage and the a.-c. output voltage determines the ratio of transformation of the transformer, which is simply $\dfrac{2\,E_{D.c.}}{E_{a.c}}$ Provisions must be made for a mid tap in the primary side. Since each half of the primary carries all the load current for one-half the time its rating must be for

$$\frac{\text{secondary amps.(full load)}}{\text{Transformation Ratio}}\sqrt{2}$$

For the inverter, then, similar to the case of the full wave rectifier the transformer must be of special design. The current rating of its primary must be 2 times that of the secondary.

VOLtage Regulation.

From the standpoint of most convenient voltage

regulation, which involves the suppression of the out-

put voltage at light load the ratio of line inductance to

condenser capacity must be a maximum. On the other hand,

most successful operation demands an adequate period for

de-ionization of the tubes. Maximum de-ionization time

is attained with sine waves of voltage which means a large

ratio of capacitance to transformer inductance. For an

inverter of the type considered here the transformer has

no less than ordinary inductance and the regulation

characteristic desired must be the most convenient so that

the line reactor size is determined by economical consider-

ations and the capacitance a function of the tube; i. e.,
characteristics

the condenser must be just large enough to provide sufficient

de-ionization time. More cannot be said as regards these

elements in the design of the circuit since the calcula-

tions of Chapter IV lack experimental check. There is no

doubt but that with adequately checked analyses along these

lines a firm basis for the design of the circuit can be

established.

Grid Voltage.

With the regulation characteristic the most con-

venient, the de-ionization time is a minimum. This posi-

tive ion cleanup process is accomplished not only by

means of a negative voltage on the anode but also by

a negative voltage on the grids. Hence the grid voltage

must be made the maximum allowable without jeopardizing

the life span of the tubes. However, here again there

is a limitation; viz., the fact that the voltage rise

at light load, especially with an oscillatory grid cir-
                     may
cuit,/be excessive. Hence the maximum grid voltage should

be based on the voltage at the minimum load.

Inductive Load and the Effects of Filters in Lines with the Load.

An inverter of this type cannot handle inductive

loads unless the condenser capacity is increased to com-

pensate for the load inductance. The tubes cannot supply

lagging current. The same applies to the insertion of a

filter in series with the load, except that in this case

the condenser must be increased only sufficiently to take

care of the harmonics. The effects of a filter in series

with the load can be analyzed as in Chapter IV with the

additional circuit constants added to the differential

equations.

*****

VI. GRID CIRCUIT DESIGN.

Introduction: Action Explained by Means of Analysis.

In the "ideal" inverter circuit, where sine waves
of voltage are maintained on the output side the excita-
tion of the grids does not represent a serious problem.
The grids are supplied by the load through a transformer
that has a condenser connedted in series with its primary
to cause the necessary phase shift of grid voltage with
respect to that of the anode. This case is analogous to
that of a steam engine, with a flywheel and a governor.
The valves move in synchronism with the piston and may
be advanced or retarded in phase.

The valves in our duplex boiler feed pump are
not permanently connected to the piston. They are merely
respectively tripped over at the end of each stroke of
"the other" piston; the valves of piston A are tripped
by rod B and vice versa. The analogy between the inver-
ter and the feed pump, however, holds only in as far as
the "main" circuit is concerned. In order to include
the grid circuit we must modify our pump. Let the valves
be controlled by a "gadget" that is "charged up" (a spring

is compressed or a pendulum is released, to start

swinging) when one of the pistons starts its motion.

Also imagine that by the time this piston reaches the end

end of the stroke the compressed spring is released by a

timing device or the pendulum reaches a point in its swing

where it acts on the valves of the other piston to start

it on its way. The analogy is crude, but the point we

are trying to make is that in our modified pump, as in

the inverter, the valves are not positively tripped at

the end of the stroke. They are acted upon or "set"

when one piston starts on its stroke, to trip automatical-

ly at the end of the stroke. Each piston rod at the start

of its motion "sets" the valves of the other.

When the inverter starts, the grid of the start-

ing tube is made positive and that of the non-starting

tube negative. Due to the charging up of the blocking

condenser in the grid circuit both waves die down, the

first becomes more negative and the second more positive.

As soon as the grid voltage of the incoming tube reaches

the critical grid potential, the tube starts. There is

thus no positive action that starts the tubes and no

oscillation in the main circuit that determines the fre-

quency. The latter simply depends on the constants of the grid circuit.

The Ideal Grid Voltage Wave-shape.

It has already been pointed out that in inverter experimentation separate excitation from an a.-c. source is frequently employed to excite the grids. In other words, the inverter is "driven". When the grid is made positive with respect to the cathode the tube conducts, while it is prevented from starting to conduct, when negative. At the beginning of the negative half-cycle of the grid voltage wave, conduction is stopped by transferring the tube current through a condenser and making the anode, for a brief space of time, negative with respect to the cathode.

If the critical grid potentials of both tubes have exactly the same value each tube will conduct for exactly the same length of time, provided the a.-c. voltage wave applied is symmetrical with respect to the time axis. If, however, the critical grid potentials are not the same (this has been stressed before) and the grid voltage does not have a high rate of change at the time

Fig.23. "Breakdown" Characteristic of FG41 Type Thyratron.

Grid Volts vs. Anode Volts, at Time Discharge Occurs.

Anode Volts

6000

5000

4000

3000

2000

1000

400

- 12   - 8   - 4   0   +4   +8   +12

Grid Volts
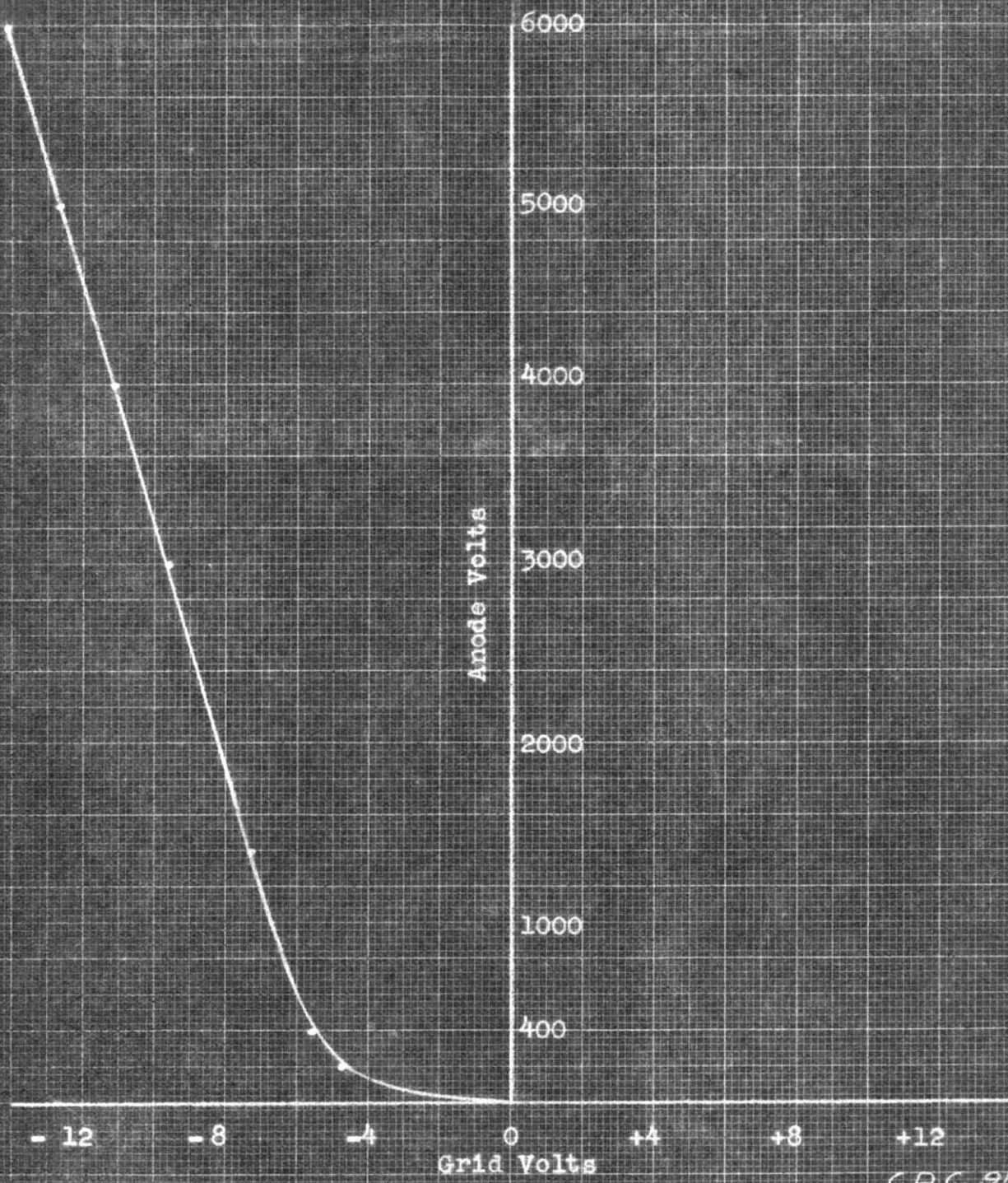
C.D.C. 9/29/30

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it passes through the critical value (getting more positive) one tube will conduct for a longer period than the other with the result that the main transformer will become saturated and operation will cease. In other words, with unequal conducting periods, the symmetry of the circuit will be upset.

The requirement for the grid voltage wave then is that, when it reverses, it must have a high rate of change. Grid characteristics sometimes differ and to eliminate any effects they may have on inverter stability, the ideal voltage wave should be rectangular (or square). Reversal would take place in zero time and no matter how far apart the critical grid potentials are, provided they do not exceed the amplitude of the applied rectangular wave, the control will be as good as can be desired.

Non-oscillatory and Oscillatory Grid Circuits.

The most convenient source of grid power (especially in high voltage applications) obviously is the output side of the main transformer. It is alterna-

Volts

A   B

Conducting
Periods Indi-
cated by t_A & t_B

V_A

+

0

V_B

t_A —— t_B

(a)

Inver-
ter Out-
put

C

R

To grid A   To
Cathode   To grid
B

Volts

A   B

+

0

V_B

V_A

t_A —— t_B

(b)

time →

Output

R   C

L

Critically Damped

Critical Grid Potentials
Indicated by V_A & V_B.

Volts

A   B

+

0

V_B

V_A

t_A —— t_B →

(c)
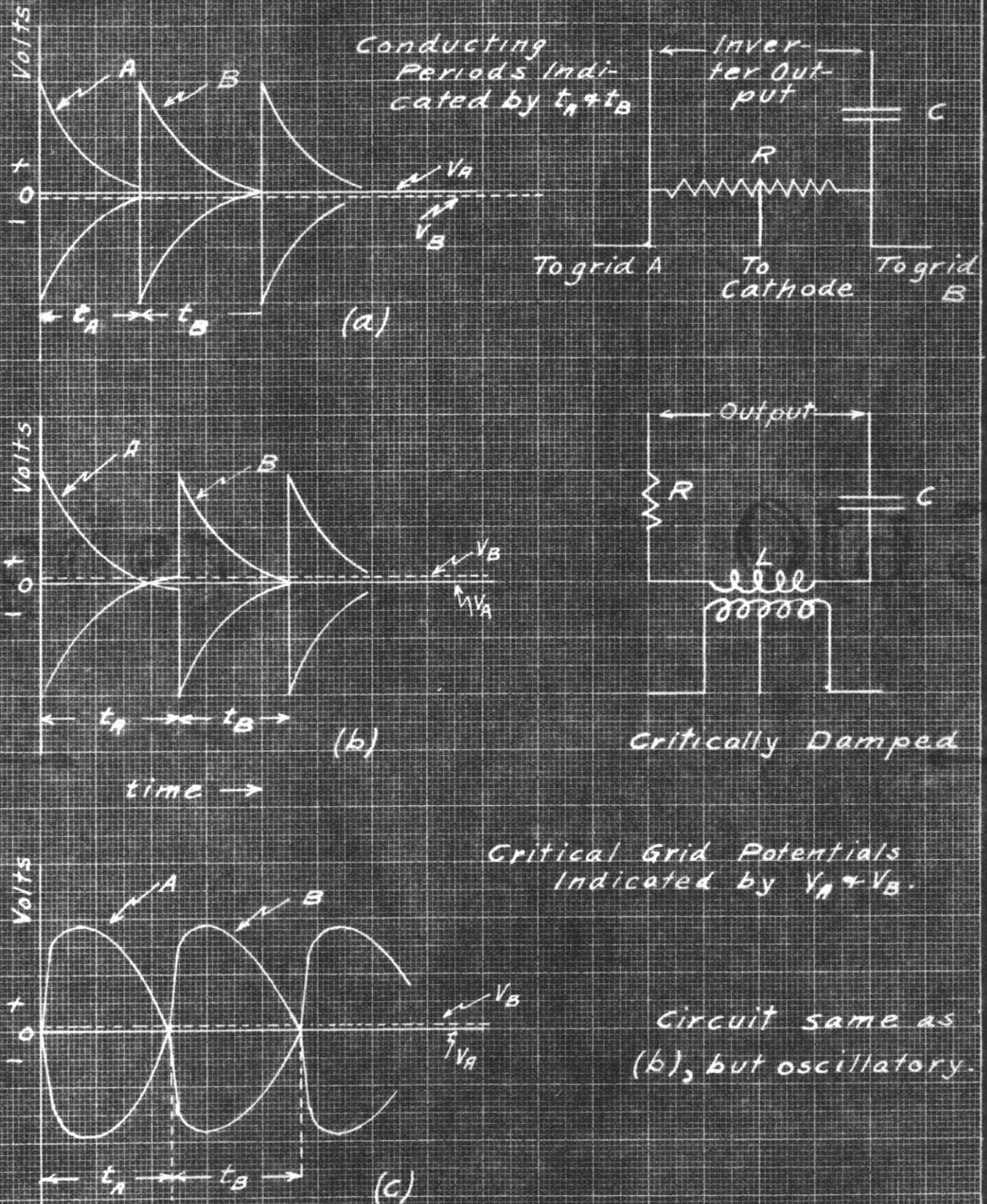
Circuit same as
(b), but oscillatory.

Fig. 24. Schematic Diagram Showing how
Conducting Periods of Tubes can be Equalized
by Employing an Oscillatory Grid Circuit.

ting and rectangular in shape. However, as far as the grids are concerned it must be regarded as a direct voltage, the polarity of which is reversed every half-cycle by the action of the grids on the main circuit.

We have now reached the point where we must design the "gadget" for our modified boiler feed pump. The simplest circuit possible is indicated by figure 24(a), which is simply a condenser and resistance in series. The drop across the latter is impressed on the grids through other, and much larger, resistances. The wave will be the familiar exponentially decreasing transient and the grid voltages will be one half-cycle out of phase with respect to the resistance mid-point; i. e., when one grid is positive the other is negative to the same extent.

As the condenser charges up the current through the resistance approaches zero and the grid voltage also approaches zero until the critical grid potential of the tube next to strike is reached. When it strikes the polarity of our d.-c. supply (inverter output) reverses and the process repeats.

In the light of what has been said before in
regard to the possible difference in critical grid poten-
tials of the two tubes figures 24(b) and (c) are self-
explanatory. They are developments of 24 (a) and show
how a difference in critical grid potentials with an
oscillatory circuit will tend to decrease instability
resulting from a longer period of conduction in one tube
than in the other.

Remarks in Connection with Grid Circuit Design.

In most of the experimental work in connection with
inverter under consideration a critically damped circuit
was used. In other words inductance played a minor part.
The step-up transformer was necessary to obtain an adequate
voltage. For obtaining an oscillatory wave, the capaci-
tance was increased and the inductance decreased. The
latter was accomplished simply by the addition of a reac-
tor in parallel with the grid transformer primary. For
purposes of calculation it is merely necessary to tune
the capacitance and the inductance in series to the desired

frequency and to make the damping small. The oscillatory
wave used is shown by figure 17 and the circuit constants
indicated in figure 25.

The advent of shielded grid thyratrons may
eliminate the necessity of using an oscillatory grid
circuit for this type of inverter. At the time this
investigation was carried on shielded grid tubes were
not available, and a conducting coat of paint was used
on the bulb of the tubes. With a shielded grid the tube
characteristics should be much more uniform, for then the
charge on the glass is prevented from having any influence
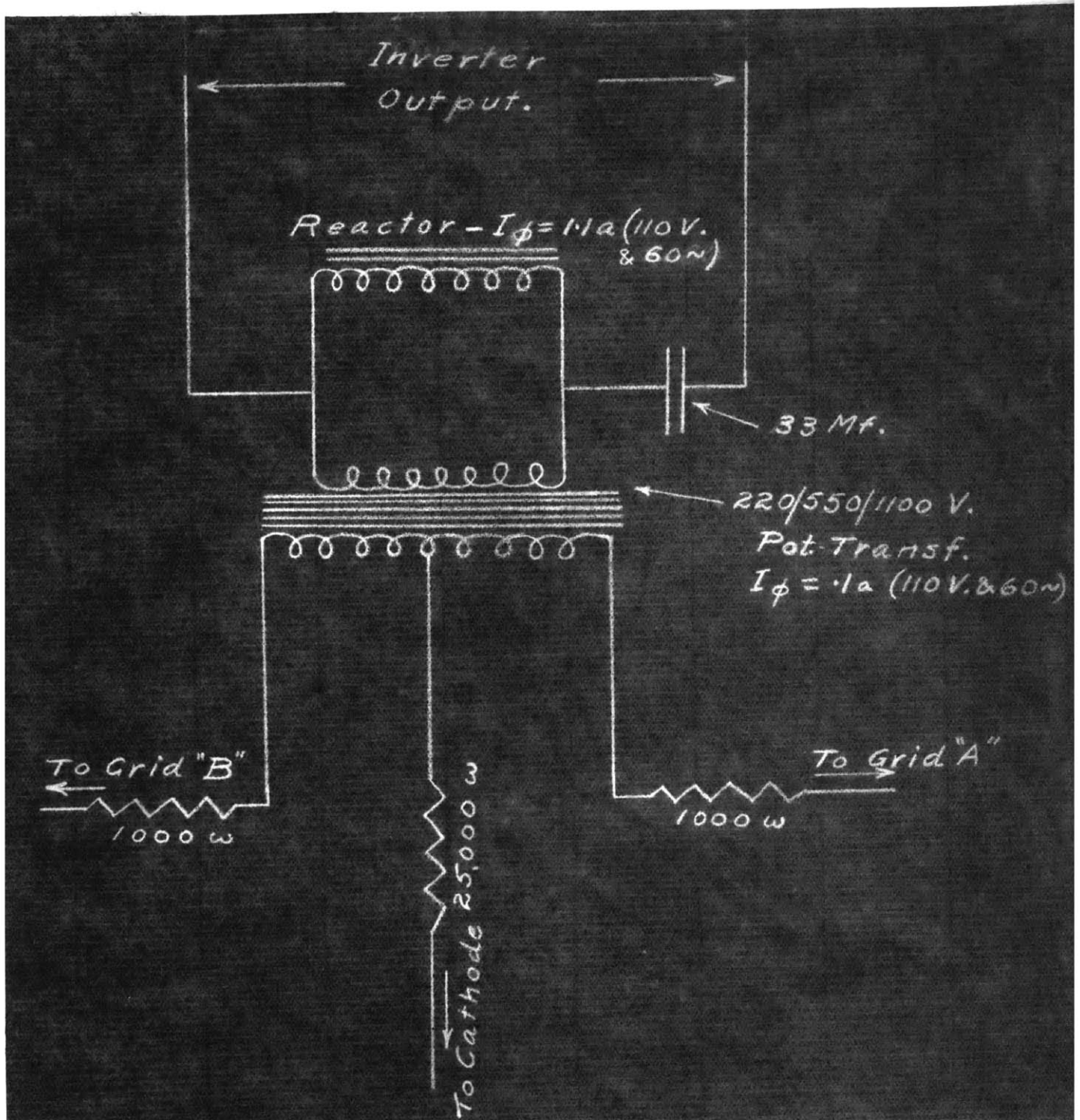on the action of the tube.

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Fig. 25. Oscillatory Grid Circuit Employed with
that of Fig. 8. For the Waveshapes of this
Circuit see Fig.17.
(H-4359151)

VII. DISCUSSION OF RESULTS AND CONCLUSIONS.

Discussion of Results:

In the foregoing the development of a static circuit, utilizing thyratrons, has been described and the way for analysis of the circuit pointed out.

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The success of the circuit is due to one important factor; viz., the fact that the latest type hot cathode thyratrons have a very short de-ionization period, much shorter than the former mercury pool type tubes.

The analysis shows some of the difficulties involved in analyzing circuits with vacuum tubes, difficulties that will have to be overcome with the advent of the high voltage direct current transmission line. Inverters of the type described will no doubt some day form an important adjunct to the much-talked-of new development.

As a result of experimentation a specific circuit is described and its performance characteristics

given, while as a result of analysis the probable wave-
shapes of currents in the circuit are calculated. Here
we say "probable", because the experimental data were
not adequate to provide a complete check.

The inverter serves the same purpose as a motor-
generator set over which it, however, has a number of ad-
vantages in the form of greater efficiency and much lower
first cost. These two factors are enhanced the higher the
direct voltage goes.

Conclusions:

(1) With present-day hot cathode tubes static
inversion of direct current is a feasible and economical

proposition, even with no alternating current available to drive the grids and the circuit not designed on an oscillatory basis.

(2) The mathematical analysis of power circuits containing vapor tubes cannot be accomplished successfully unless assisted by full physical pictures of actual conditions, but with the physics firmly in hand a rigorous analysis is possible.

Suggestions for Further Research.

The problem attacked in this investigation is an almost ideal one for the integraph. But before it is attacked it will be necessary to obtain more oscillograms of the currents in the main part of the circuit during the commutation period in order to ascertain physically the true state of affairs.

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Fig.26 WIRING DIAGRAM OF SINGLE PHASE
SELF EXCITED INVERTER

3000 V. D.C.

HIGH VOLTAGE
D.C. CONTACTOR

CURRENT LIMITING
RESISTOR

FUSE

REACTOR

LOAD

FILAMENT
HEATING SUPPLY

OVER LOAD
RELAY N. CLOSED

C.D.C. 9/30/30.

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CONTROL
CIRCUIT SUPPLY

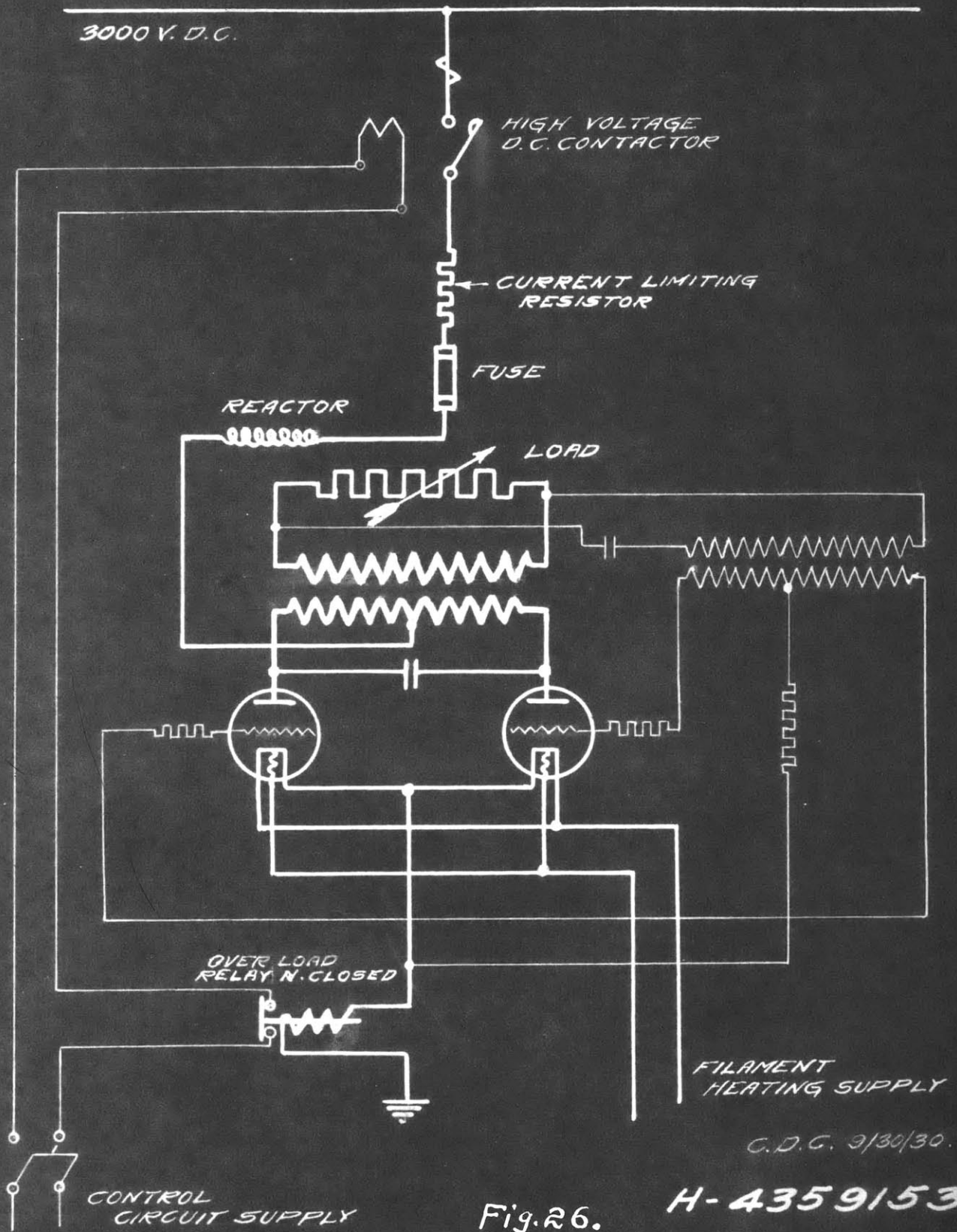Fig. 26.

REFERENCES

(1) Thyratron Tubes and Their Characteristics.

    (a) "Hot Cathode Thyratrons" , by A. W. Hull, Gen.
        Elec. Rev., 32, 213 and 390 (1929).

    (b) "Characteristics of Mercury Arcs" by W. B. Notting-
        ham, Journal of Frank. Inst., 211, 271 (1931)

(2) Inverters

    (a) "The Inverter" by D. C. Prince, Gen. Elec. Rev.,
        28, 676 (1925)

    (b) "The Direct-Current Transformer" by D. C. Prince,
        Gen. Elec. Rev. 31, 347 (1928).

(3) Analysis of Circuits Containing Mercury Vapor Rectifiers.

"The analysis of Polyphase Rectifier Circuits" by
Daniel Silverman, M. I. T. Doctor's Thesis, 1930.

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