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GRADIENT MAGNET POWER SUPPLY FOR THE FERMILAB 8-GeV PROTON SYNCHROTRON

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Jan Ryk

General

The booster synchrotron is a rapid cycling synchrotron used at the Fermi National Accelerator Laboratory near Batavia, Illinois for high energy physics studies.

The booster is used to accelerate protons from an injection energy of 200 MeV to an output energy of 8 GeV. The machine is of the alternating gradient type with both focusing and defocusing magnets located in a circular orbit with a 75.5 meter radius (ref. 12).

The magnets are excited with a 15 Hz biased sine wave. Capacitors are used to form a resonant network with the magnets. The resonant system is series excited by means of programmed solid state power supplies.

Design Considerations

The magnetic field needed in the booster magnets is of the form:

$$B_{(t)} = B_{dc} - B_{ac} \cos 2\pi \, ft$$

Ignoring saturation effects in the magnets, the flux density may be considered as a linear function of the magnet current. This means that the magnet power supply has to generate a current of the form:

$$I_{m(t)} = I_{dc} - I_{ac} \cos 2\pi \, ft$$

The most economic system is a resonant system, where energy can be exchanged between the magnets and capacitors, with the power supply providing the losses.

Large amounts of stored energy are associated with the required magnetic field in the booster synchrotron. Therefore, large capacitor banks are necessary. Also, chokes are necessary to bypass the dc current around the capacitors. Distributed capacitor banks and distributed chokes proved to be the most desirable system. A modular approach was used in which two magnets together with their resonant capacitor and choke form one resonant cell. A second winding on each choke was used to provide coupling between resonant cells.

In earlier machines, such as NINA, DESY, CEA, Princeton Penn, and Cornell machines, two separate power supplies were used to generate respectively the dc and ac current needed. The basic system for separate ac and dc excitation is shown in Figure 1.

The different systems that were considered for excitation of the booster synchrotron were as follows:

1. Solid state dc power supplies for the bias current and a solid state, pulsed supply for ac excitation.

2. Solid state dc power supplies for the bias current and an MG set for ac excitation. Both systems 1 and 2 have been used previously at other machines (Ref. 3, 4, 5, 6, 7).

   System 2 has the advantage that the ac excitation is sinusoidal rather than pulsed, and, therefore, has less harmonic content. Less harmonic content in the drive wave form means less problems with excitation of delay line modes of the magnet circuit.

3. Solid state dc power supplies for the bias current and a cycloconverter for ac excitation.

   The cycloconverter considered for the booster ac power supply was a 30-phase converter, using 5 transformers, extended delta primary, wye secondary with phase displacements to achieve a 30-phase system.

   Thyristors were used on the secondaries. The control system would provide the proper firing sequence to achieve a sine wave output.

A scaled-down prototype of this cycloconverter was built at NAL. The system has merit over systems 1 and 2 because it can be programmed for different frequencies or combination of frequencies.

4. Programmed solid state power supplies in series with the resonant system.

   This circuit, shown in Figure 2, completely eliminates the need for separate ac excitation and is therefore more economical and also far less complex than systems 1, 2, and 3. A prototype of this system was built, using a thyristor-type dc power supply to energize a resonant cell. The firing circuit for the phase-angle controlled thyristors was controlled by means of a series combination of a dc power supply and a sine wave generator.

   In the final version of the booster power supply, a total of four programmed thyristor power supplies were used, inserted in the resonant system at symmetrical points, so that power supply voltages and voltages to ground were kept at reasonably low values.

Operating Frequency of the Resonant System

The frequency range considered for operation of the synchrotron was between 7½ and 30 Hz. The main frequencies considered were 30, 15, and 7½ Hz.

Studies were made for each of these three operating frequencies to compare system losses, resonant system component parameters and cost, RF accelerating system cost, and total system cost. Based on these studies, it was determined that the most desirable operating frequency was 15 Hz. The resonant system was, therefore, designed for operation at 15 Hz.

Second Harmonic in Magnet Field

Studies were made to investigate if addition of a second harmonic component in the magnet excitation could result in an overall system cost savings. It was indicated that maximum cost savings to the rf accelerating system would occur if the magnet excitation had a second harmonic component with 1/8 of the amplitude of the fundamental and a lead of 1 radian with respect to the fundamental (Ref. 2).

Calculations showed that the power needed to drive this second harmonic was about five times larger than the power needed for the circuit at resonance.

A more economical approach is, therefore, to make the system resonant at both the fundamental and the second harmonic. This approach is described in Reference 1. The circuits considered for the booster resonant system were as indicated in Figure 3. Figure 4 shows the excitation current wave form. It is apparent from the waveform that power supply power increase is needed also to achieve the same peak magnetic field. Cost studies indicated that the extra components and extra complexity added about 20% to the power supply system cost, which offset the cost savings that could be achieved in the rf accelerating system. Therefore, no second harmonic was added to the magnet excitation current.

The Resonant Power Supply System

The basic power supply system is as shown in Figure 2. The synchrotron magnets, together with the distributed capacitor banks form a resonant circuit tuned for 15 Hz. The chokes provide a dc current bypass around the capacitors. The programmed thyristor power supplies provide the power needed for the magnet excitation. The complete system is comprised of 48 identical resonant cells, coupled by means of the choke secondary windings. The choice of the number of resonant cells was based on economy considerations and on limits set by the permissible operating voltages to ground of the system. Each resonant cell includes one F magnet, a D magnet, a choke, and a capacitor bank.

The resonant cell parameters are as follows:

Number of resonant cells	48
Number of magnets per resonant cell	1F, 1D
Number of chokes per resonant cell	1
Number of capacitor banks per resonant cell	1
Magnet inductance per cell	20.4 mH
Choke inductance per cell	40 mH

Capacitance per cell	8341 μF
Magnet dc resistance per cell	29.5 mΩ
Choke dc resistance per cell	25 mΩ
Magnet effective ac resistance per cell	60.3 mΩ
Choke effective ac resistance per cell	94 mΩ
Choke Q	40
Peak voltage per cell	926 V
Maximum voltage to ground	710 V
Magnet peak stored energy	10.68 kJ
Choke peak stored energy	12.5 kJ
Capacitor peak stored energy	3.6 kJ
Magnet ac power loss	6.8 kW
Choke ac power loss	2.75 kW
Capacitor ac power loss	1.0 kW
Magnet dc power loss	8.9 kW
Choke dc power loss	7.5 kW

Magnets

There are a total of 96 magnets in the synchrotron, 48 of the focusing type (F magnets) and 48 of the defocusing type (D magnets). The focusing and defocusing properties are needed to provide stability of the proton beam inside the magnet gap. Each magnet is 10 feet long. The magnet excitation coils are made of .460 inch square copper conductors with a .25 inch diameter hole in the center. Low conductivity cooling water is passed through the center hole to provide cooling of the coils. Each magnet is enclosed in a stainless steel jacket which is used as a vacuum chamber. Since the coils are also in vacuum it is important to have proper insulation and to keep the voltage to ground to a low value.

The magnet parameters are as follow:

Excitation	$i = 548 - 475 \cos 2\pi\, 15\, t$
DC bias current	548 A
Magnet current at injection	74 A
Peak current density in magnet conductor	3148 A/sq in

	D Magnet	F Magnet
Peak ampere turns	28631	24541
Number of turns	28	24
Inductance at peak field	12.2 mH	12.2 mH

	D Magnet	F Magnet
DC resistance	15.9 mΩ	13.6 mΩ
Maximum ac voltage	455 V	455 V
DC voltage	8.7 V	7.5 V
Peak stored energy	5.34 kJ	5.34 kJ
DC power loss	4.8 kW	4.1 kW
AC power loss	3.6 kW	3.2 kW

The synchrotron design determines the main magnet parameters, such as peak and minimum magnetic field and magnetic length. Economy considerations determined the magnet design resulting in values for inductance and dc resistance. Starting from number of ampere-turns, inductance, and dc resistance we arrive at the other parameters. Since each resonant cell is identical, we can limit the calculations to one cell. The magnet inductance for one cell is the combined inductance of one F magnet and one D magnet.

The effective ac resistance of a cell magnet was calculated as follows (Ref. 8):

Due to Eddy currents $R_{ac} = 1.5 \times R_{dc} = 1.5 \times 29.5 = 44.25$ mΩ.

Copper losses $I_{ac}^2 R_{ac} = \frac{475^2}{2} \times .04425 = 5$ kW.

Core losses .2w/lb = .2 x 9000 = 1800 W = 1.8 kW.

Total ac power losses $P_{ac} = 6.8$ kW.

R_{ac} eff $= \frac{6800 \times 2}{(475)^2} = .0603\ \Omega = 60.3$ mΩ.

Magnet reactance $jwL = j\ 2\pi\ 15 \times .0204 = j\ 1.92\ \Omega$.

Magnet impedance $Zm = .0603 + j\ 1.92$

Peak ac magnet voltage =
$2\ (475 \times 2\pi\ 15 \times 10.2 \times 10^{-3}) = 910$ volts.

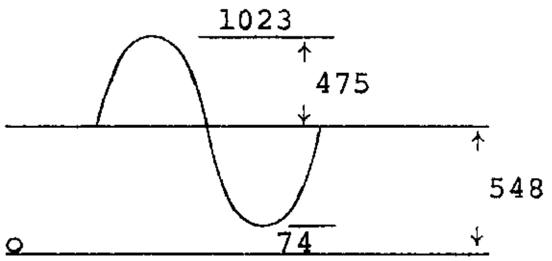
Magnet dc voltage =
$548\ (15.9 + 13.6) \times 10^{-3} = 8.7 + 7.5 = 16.2$ volts.

$Q = wL/R_{ac}$ eff $= 32$

$P_{dc} = I_{dc}^2 \times R_{dc} = 8.9$ kW

$$\begin{aligned}\text{Peak stored energy} &= 1/2\ LI^2 \\ &= 1/2 \times .0204 \times (1023)^2 \\ &= 10675\ \text{J} \\ &= 10.675\ \text{kJ}\end{aligned}$$

Magnet Current



Magnet rms current:

$$I^2 rms = \frac{1}{2\pi}\int_0^{2\pi}(I_{dc} + I_{ac}\cos\theta)^2\, d\theta$$

$$= \frac{1}{2\pi}\int_0^{2\pi}(I_{dc}^2 + I_{ac}^2\cos\theta + 2\, I_{dc}\, I_{ac}\cos\theta)\, d\theta$$

$$= \frac{1}{2\pi}\left(I_{dc}^2\,\theta + 2\, I_{dc}\, I_{ac}\sin\theta + I_{ac}^2\left(\frac{\theta}{2} + \frac{1}{4}\sin 2\theta\right)\right)\int_0^{2\pi}$$

$$= \frac{1}{2\pi}\left(I_{dc}^2 \times 2\pi + I_{ac}^2 \times \pi\right)$$

$$= I_{dc}^2 + \frac{I_{ac}^2}{2}$$

$$I\ rms = \sqrt{I_{dc}^2 + \frac{I_{ac}^2}{2}}$$

$$= \sqrt{548^2 + \frac{475^2}{2}} = 643 \text{ amperes.}$$

Chokes

The economics of energy storage in chokes with respect to capacitors governs the choice of choke inductance. The optimum ratio of magnet inductance to choke inductance in this regard, turned out to be .5 (also see Ref. 3).

Shell-type chokes with distributed gap were specified (Ref. 9). The shell-type was chosen to minimize stray magnetic fields.

Each choke was provided with a secondary winding for coupling between resonant cells, the winding ration being 1:1. Two, separate, single turn monitoring windings were provided on each choke. The primary winding was made with the same water-cooled hollow copper conductor as used for the magnets. Measurements made on a prototype choke indicated that a $Q = 40$ was economically realistic.

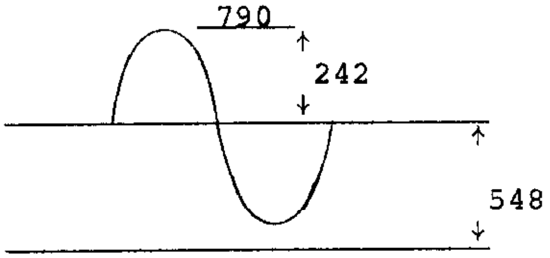
Since the inductance, the dc resistance and the Q are now established, we can determine the choke impedance and losses.

Choke inductance LcH = 40 mH
Choke dc resistance R_{dc} = 25 mΩ

Peak ac current = $\frac{Lm}{LcH} \times 475 = 242$ amperes

DC durrent = 548 amperes
Peak stored energy =
$1/2\ L\ I^2 = 1/2 \times .04 \times (790)^2 = 12500$ joules = 12.5 kJ

Choke Current



R_{ac} eff = $\frac{wL}{Q} = \frac{2\pi 15 \times .04}{40} \times 10^{-3} = 94$ mΩ

AC losses $P_{ac} = \frac{242^2}{2} \times .094 = 2753$ W = 2.753 kW

DC losses $P_{dc} = 548^2 \times .025 = 7500$ W = 7.5 kW

Total losses P = 10.253 kW
Reactance = jwL = j 2π15 x .04 = j 3.77 Ω
Impedance Zch = .094 + j 3.77
Choke rms Current:

$$I\ rms = \sqrt{\frac{242^2}{2} + 548^2} = 574 \text{ amperes}$$

Capacitors

Some of the requirements for the capacitors were as follows:

1. Low losses
2. Low stray capacitance to ground
3. Low variations of capacitance with temperature
4. High reliability
5. Easy replacement of faulted units.

Studies were made to determine the most economic solution to these requirements (Ref. 10), resulting in the following final capacitor parameters.

Total capacitance per bank	8300 μF ± 30 μF
Number of modules	3
Number of capacitor units per bank	17 + 1 trimmer
Operating voltage	815 V rms
Operating frequency	15 Hz
Voltage stress	450 Volts/mil
Material	Kraft Paper
Paper density	.9
Impregnant	Monsanto aroclor 1242
Number of layers	4
Thickness per layer	.00045 inch
Total paper thickness	.0018 inch
Foil	Aluminum
Construction	Tabbed
Number of tabs/foil	2
Number of sections/can	12
Can dimensions	26" x 13½" x 6"
Capacitance per can	490 ± 10 μF
Dissipation factor	.2%
Losses per bank at 815 Vrms	1040 watts
ΔC over 50° F to 120° F	2.37%
Can temperature rise at 1120 V peak	15° C
Spacing between cans	1½"
Life expectancy	20 years
Fuse rating	1200 V-75A
Fuse type	Westinghouse CLC

Each capacitor bank for a resonant cell was also made to contain one trim capacitor with four bushings at respectively 1/8, 1/8, 1/4, and 1/2 of the capacitance value of a standard can. This trim capacitor was used to tune each resonant cell independently for exactly 15 Hz.

The capacitance needed for a resonant cell can be determined by summing:

1. The capacitance needed for series resonance with a cell magnet.
2. The capacitance needed for parallel resonance with the choke.

The capacitance needed for series resonance with a cell magnet is found from the resonance condition:

$$C_1 = \frac{1}{W^2 Lm} = \frac{10^3}{(2\pi 15)^2 \times 20.4} = 5524 \times 10^{-6} \text{ Farads}$$

The capacitance needed for parallel resonance with the choke is:

$$C_2 = \frac{1}{W^2 Lch} = \frac{10}{(2\pi 15)^2 \times 40} = 2817 \times 10^{-6} \text{ Farads}$$

Total cell capacitance = 5524 + 2817 = 8341 μF.

$$\begin{aligned} \text{Capacitor peak stored energy} &= 1/2\ CV^2 \\ &= 1/2 \times 8341 \times 10^{-6} \times (926.2)^2 \\ &= 3578 \text{ J} \\ &= 3.578 \text{ kJ} \end{aligned}$$

Losses at .3% dissipation factor =
.003 x 2π 15 x 3.578 = 1.0 kW.

$$\text{Capacitor rms current } I_C = Vwc = \frac{910}{\sqrt{2}} \times 2\pi\ 15 \times 8341 \times 10^{-6}$$

$$= 506 \text{ Amperes.}$$

$$\text{Equivalent resistance} = Rc = \frac{1000}{(506)^2} = .0039\ \Omega = 3.9\ m\Omega$$

$$\text{Capacitor reactance} = \frac{1}{jwc} = -j\ \frac{10^6}{2\pi 15 \times 8341} = -j\ 1.27$$

$$\text{Capacitor impedance } Z_C = .0039 - j\ 1.27$$

Choke-Capacitor Impedance

$$Z = a + jb = \frac{(.094 + j\ 3.77)\ (.0039 - j\ 1.27)}{.094 + j\ 3.77 + .0039 - j\ 1.27}$$

$$Z = .033 - j\ 1.92$$

The reactance checks with the resonance condition for the magnet.

Power Supply

The required magnet excitation current is of the form:

$$Im = 548 - 475 \cos 2\pi\ 15t$$

Using series excitation, the power supply current is the same as the magnet current.

At resonance, the ac impedance of a resonant cell is:

$$R \text{ cell} = 60.3 + 33 = 93.3\ \text{m}\Omega$$

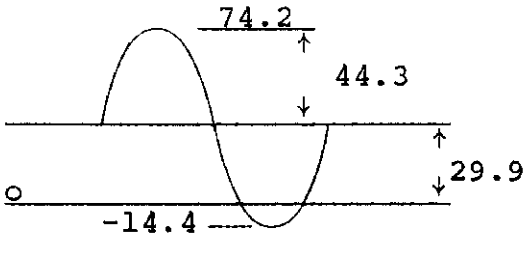
The peak ac voltage required per cell is:

$$V_{ac} \text{ cell} = 475 \times 93.3 \times 10^{-3} = 44.3 \text{ volts peak}$$

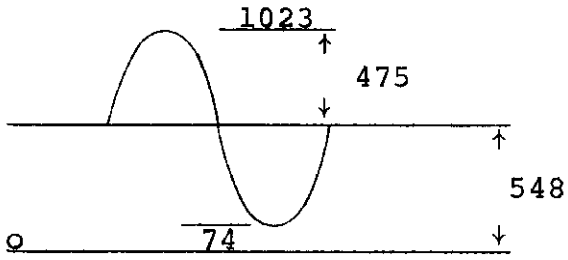
The required dc voltage per cell is:

$$V_{dc} \text{ cell} = 548\ (29.5 + 25)\ 10^{-3} = 29.9 \text{ volts}$$

The resulting voltage and current wave shapes required for excitation of one cell are as follows:

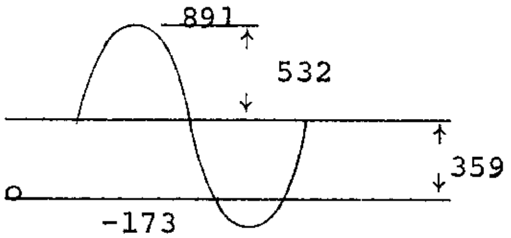


Power Supply Voltage Cell

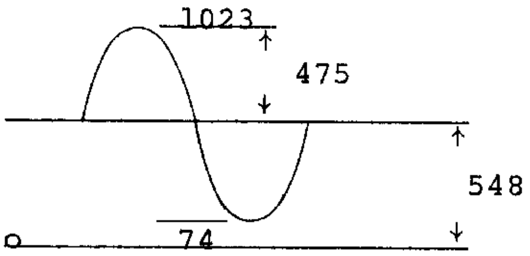


Power Supply Current

Using a total of four (4) power supplies to power the complete Booster synchrotron resonant circuit, each power supply has to power twelve (12) resonant cells in series. This results in the following current and voltage wave shapes per power supply.



Power Supply Voltage



Power Supply Current

The power supplies were designed (Ref. 11) for 12-phase operation in order to limit ripple. Figure 5 shows the basic power supply circuitry. A delta-double zigzag transformer with three-phase full wave thyristor bridges, operated off the 13.8 kV input line. The double zigzag was chosen in order to achieve 12-phase rectification and at the same time keep the impedance of both rectifier bridges the same. Diodes across each power supply output provide a path for magnet discharge currents.

Programming of the power supplies is achieved by means of phase angle control of the thyristors. Each power supply has a pulse amplifier and pulse transformers for the thyristors.

A chassis containing all firing circuitry and a main control amplifier is located at a remote location and is used to control all four power supplies simultaneously. This chassis can be mounted also in any one of the four power supplies for testing of the particular power supply individually.

The four power supplies are inserted in the total system at symmetrical locations, with each power supply separated from the next one by one quarter of the total number of resonant cells. This is shown in Figure 6. The interconnecting buswork for the resonant system is connected in a foldback arrangement to eliminate any net flux inside the ring and to keep stray flux to a minimum.

The power supplies are inserted in the resonant system in such a way as to limit the voltage to ground as can be seen in Figure 6. The system voltage to ground can be found as follows:

The peak voltage across a cell magnet is:

$$V_{dc} = V_{dc}\ \text{cell} + \vec{V}_{ac}\ \text{cell} + \vec{V}L\ \text{cell} =$$

$$29.2 + \sqrt{(44.3)^2 + (910)^2} = 29.2 + 911 = 940\ \text{volts}$$

The peak voltage to ground is:

$$Vg = \vec{V}L\ \text{cell} + \vec{V}_{psac} + V_{psdc} =$$

$$\sqrt{(910)^2 + (532)^2} + 359 = 1054 + 359 = 1413\ \text{volts}$$

Since the connection point between two magnets is at virtual ground potential, the actual instantaneous peak voltage to ground is:

$$V_{gnd} = 1413/2 = 707\ \text{volts.}$$

Protective System

The magnets and chokes are water-cooled, therefore, a protection is needed against loss of water. The cooling system for these components has many parallel paths, protection is needed for loss of cooling in any one of the parallel paths.

The protective system used was as indicated in Figure 7. The midpoint of the series connected windings was brought out and both halves of the windings connected in a bridge arrangement. A temperature imbalance in the coils will create a resistance imbalance in the bridge. A meter relay was used to detect imbalance in the bridge and to trip the power supplies.

The individual capacitor cans are protected by means of fuses.

The power supplies have protection against:

ground
overcurrent
thyristor failure
control power failure
insufficient cooling

In addition, there are door interlocks on the power supplies to prevent access to energized equipment. The transformers have protection against overtemperature, overpressure, and sudden pressure.

System Parameters

Combining the complete system, the system parameters are as follows:

Total magnet peak stored energy is:

$$Um = 48\ (1/2 \times Lm \times Im^{2}) = 48\ (1/2 \times 20.4 \times 10^{-3}) \times$$

$$102\ 10^{-3} = 512.4\ \text{kJ}.$$

Choke peak stored energy =

$$48 \times (1/2 \times Lch \times Ich^{2}) = 48\ (1/2 \times .04 \times 790^{2}) \times 10^{-3} = 600.$$

Capacitor peak stored energy =

$$1/2\ CV^{2} = 48 \times 3.6 = 173\ \text{kJ}.$$

Total magnet stored energy	512 kJ
Total choke stored energy	600 kJ
Total capacitor stored energy	173 kJ
AC power losses	510 kW
DC power losses	790 kW
Number of distributed power supplies	4
Power supply peak voltage	890 V
Power supply peak current	1023 amps

The voltage, current, and stored energy wave shapes are shown in Figure 8.

System Layout and Component Assembly

Each resonant cell, consisting of magnets, choke, capacitor banks, and protective equipment was assembled as one complete unit together with its support structure as can be seen in Figure 9.

All 48 resonant cells are located in an underground circular tunnel.

The power supplies are located in the equipment yards, Figure 10. The transformers are outdoor type, oil-cooled. The rectifier compartment is outdoor, walk-in type. An overall picture of the synchrotron with the central utility plant and cooling pond is shown in Figure 11.

Conclusion

Series excitation of a resonant system has proven to be the most economical, least complex, and most reliable power supply system for a rapid cycling synchrotron. The advancement of solid state technology and, especially the development of high power thyristors, has made this novel approach possible.

The machine has been operational since January, 1971, with a high degree of reliability. The author wishes to thank R. Thomas from Brobeck Associates for the many valuable contributions and ideas; R. Cassel, Fermilab, for the many helpful ideas; J. Dinkel, Fermilab, who wrote a computer program for evaluation of the system; R. Hodge who was helpful in building the prototype power supply; and R. Janes who built the prototype controls and interlocks and who tested all components and the final system.

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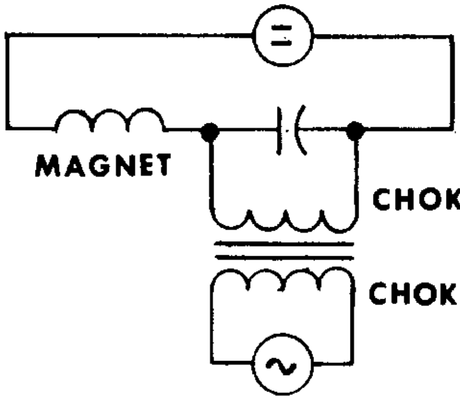


FIG. 1
BASIC SYSTEM FOR SEPARATE AC AND DC EXCITATION OF RESONANT SYSTEM.

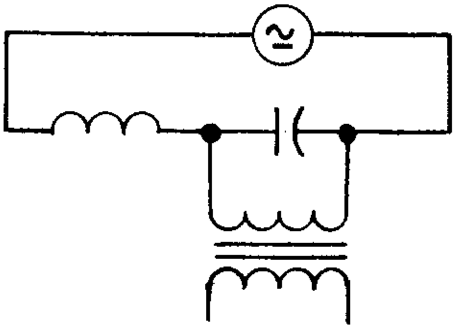


FIG. 2
SERIES EXCITATION OF RESONANT SYSTEM.

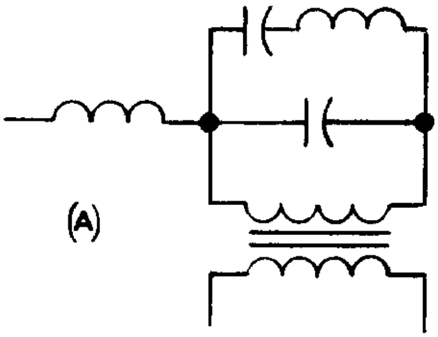
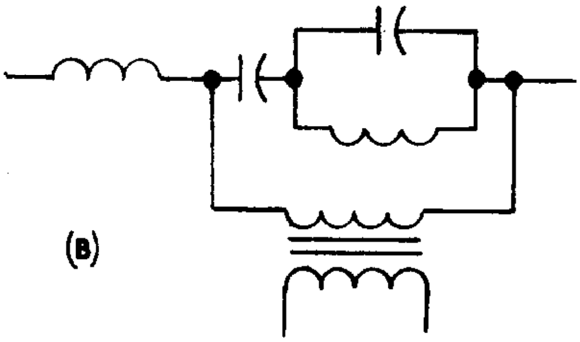


FIG. 3
CIRCUITS CONSIDERED FOR 2ND HARMONIC RESONANT SYSTEM.



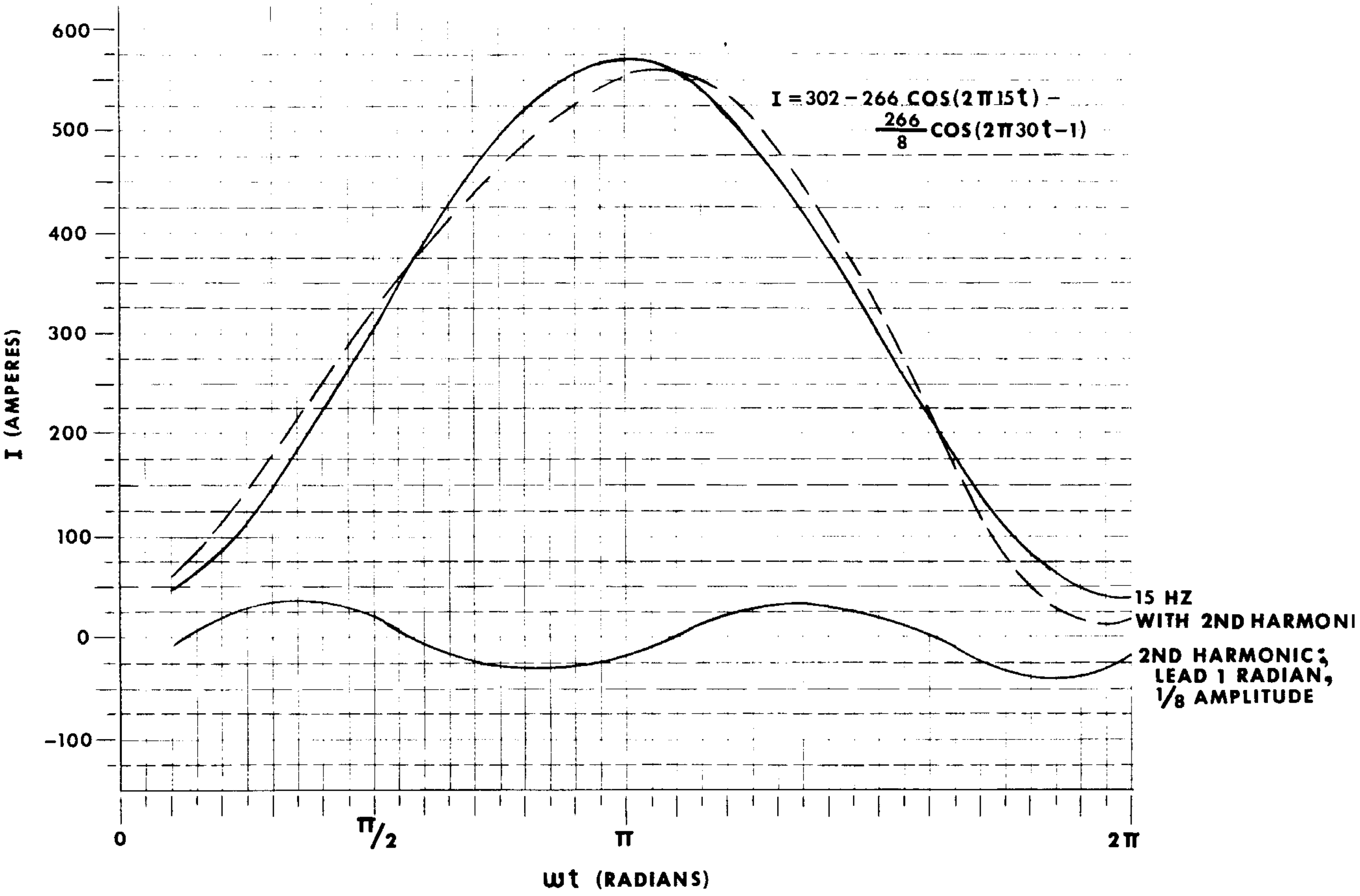

I = 302 − 266 COS(2π15t) −
266/8 COS(2π30t−1)
600
500
400
300
200
100
0
−100
I (AMPERES)
0
π/2
π
2π
ωt (RADIANS)
15 HZ
WITH 2ND HARMONI
2ND HARMONIC;
LEAD 1 RADIAN,
1/8 AMPLITUDE

FIGURE 4

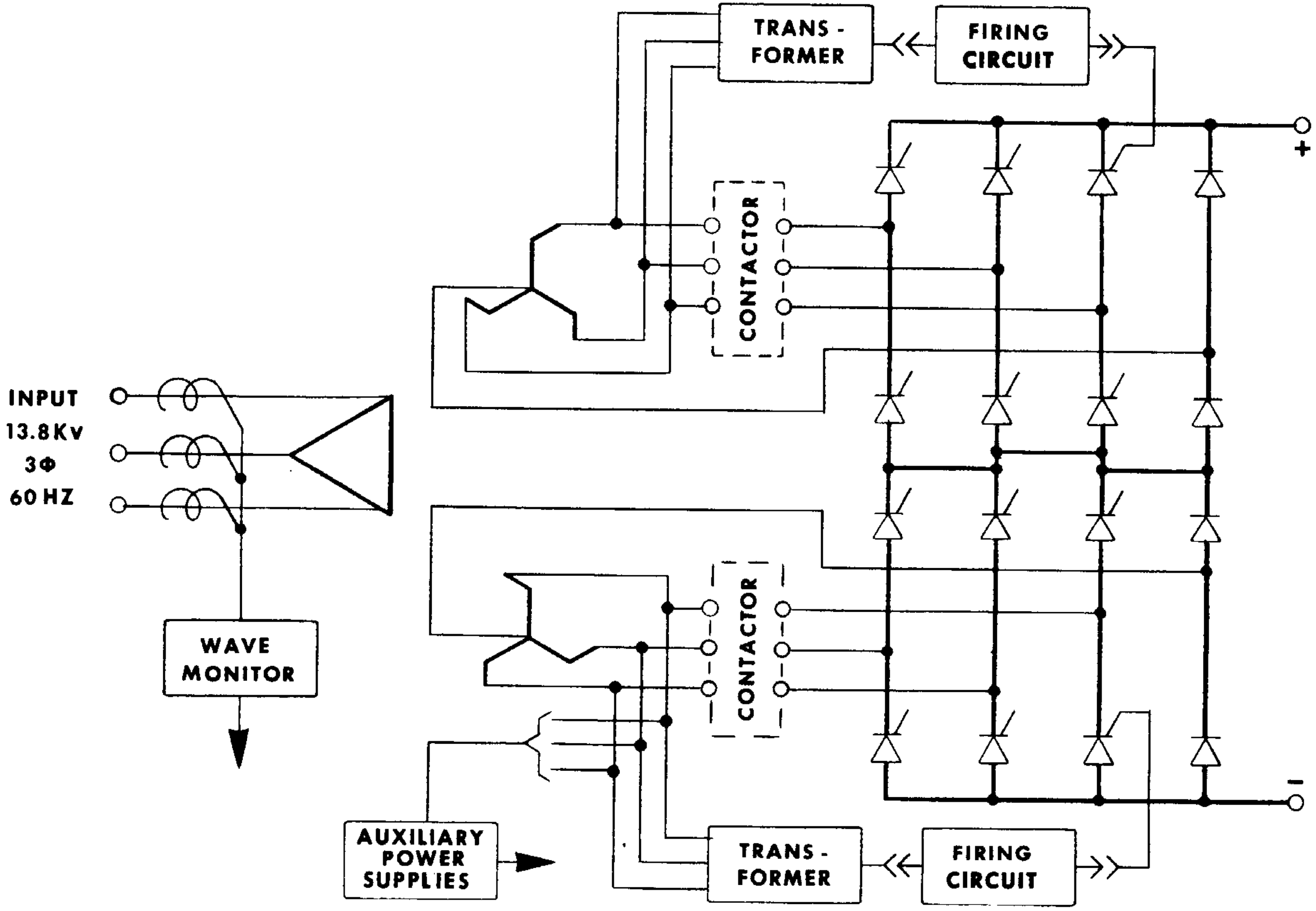


FIGURE 5
POWER SUPPLY CIRCUITRY

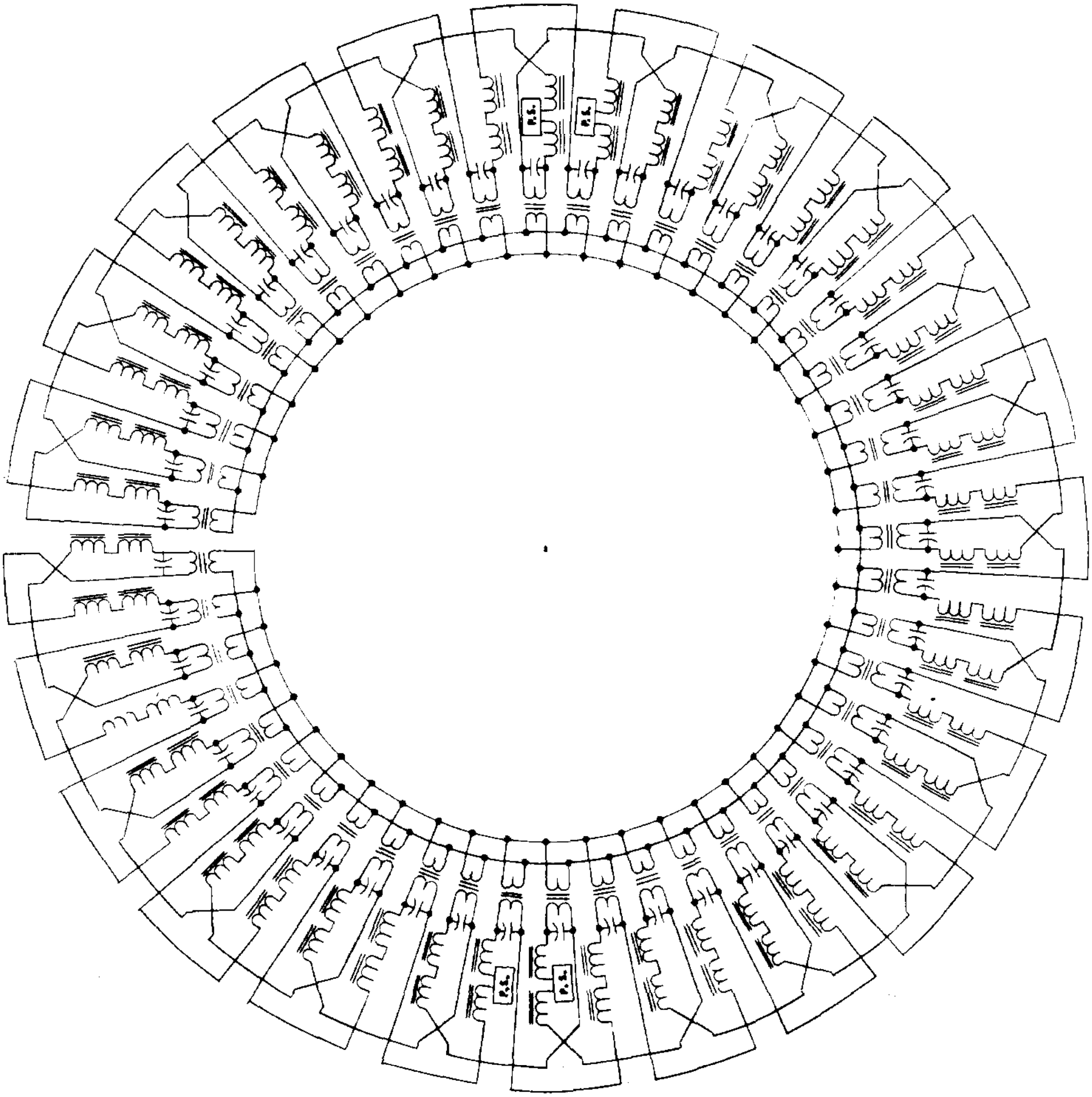


FIGURE 6

RESONANT POWER SUPPLY SYSTEM
FOR FERMI NATIONAL ACCELERATOR LABORATORY
BOOSTER SYNCHROTRON

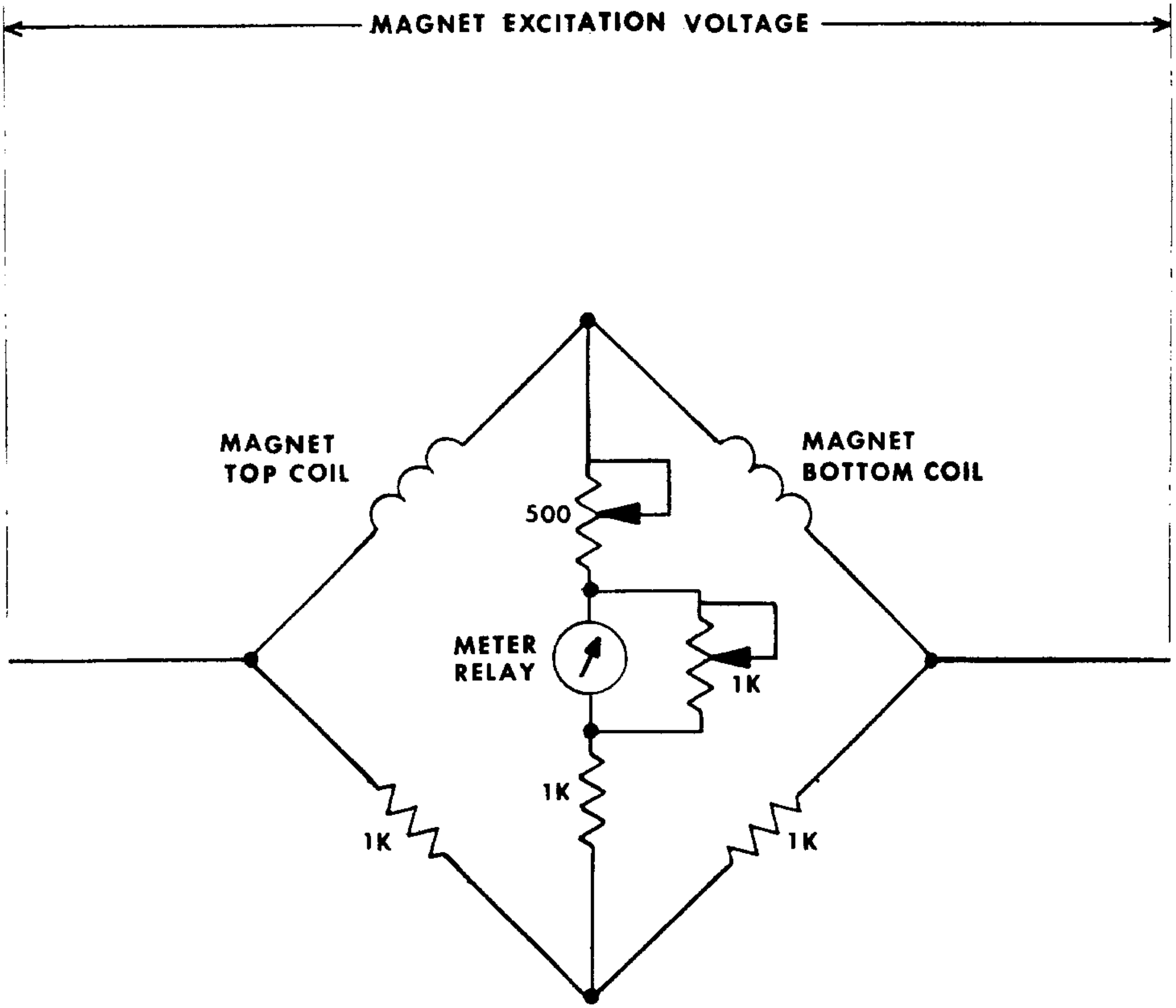


FIG. 7
PROTECTION SYSTEM FOR WATERCOOLED MAGNETS AND CHOKES.

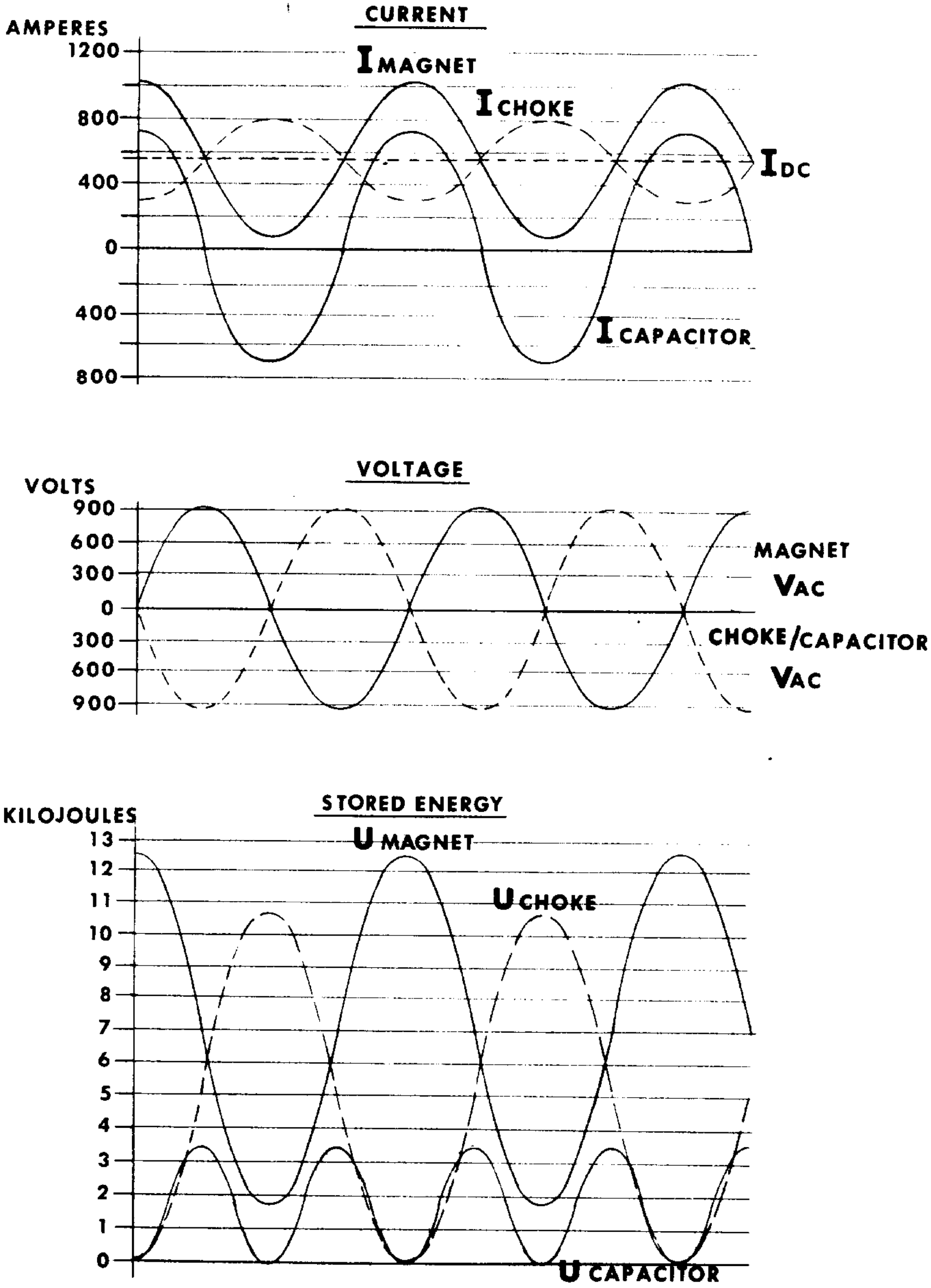


FIGURE 8
CURRENT - VOLTAGE - STORED ENERGY
TIME FUNCTIONS

FIGURE CAPTIONS - TO BE STRIPPED IN BELOW FIGURE

Fig. 9. Booster resonant cell.

Fig. 10. Booster with equipment yard (foreground).

Fig. 11. Overall view of the synchrotron, showing the central utility plant and cooling pond.