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Synchrotron Power Supply Light Source Note

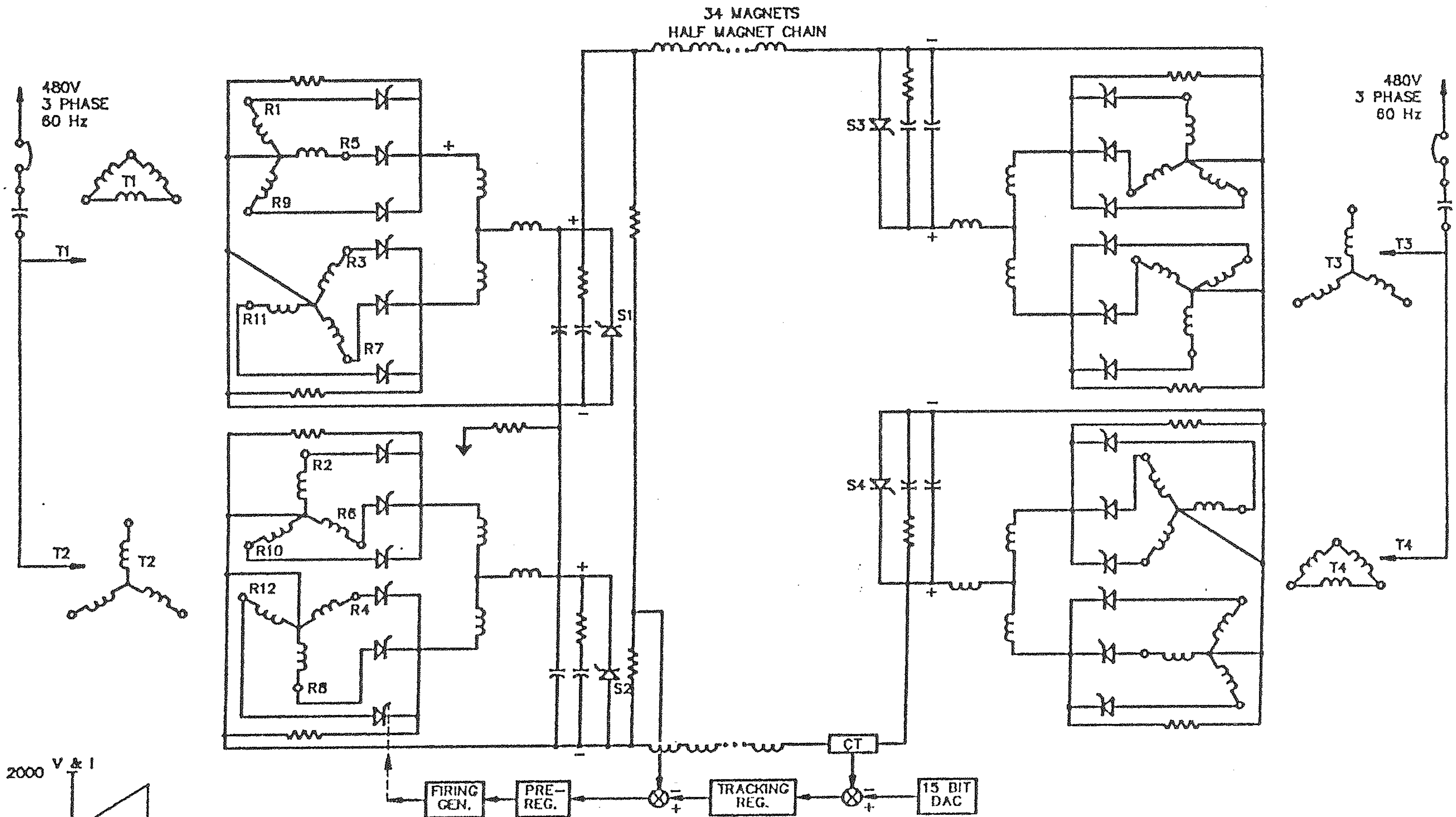
by: Masoud Fathizadeh

1. Introduction:

The ring magnet of the injector synchrotron consists of 68 dipole magnets. These magnets are connected in series and are energized from two feed points 180° apart by two identical 12-phase power supplies. Figure 1 shows a block diagram for the power supplies along with the voltage and current output of one power supply. The current in the magnet will be raised linearly to about 1 kA level, and after a small flat top (1 ms to 10 ms typical to provide sufficient time for the bridge to go to inversion mode) the current will be reduced to the injection level of 60 A. The repetition time for the current waveform is 500 ms. In the following the theory of operation for the power supply along with its design characteristics will be given.

2. Power Supply : Theory of Operation

Each power supply consists of four phase controlled half-wave converters. Each of the two half-wave converters are connected through interphasing transformers to obtain a full-wave bridge with 120° conduction. The input voltage for these two half-wave bridges are 60° apart. In order to obtain the high voltage needed for the load, two of the full-wave bridges are connected in series. This action not only provides the required voltage, it also improves the power factor of the power supply. The output of the bridges is filtered through a passive L-C-R filter to meet the current ripple limit requirement. In order to ramp the current in the load, the conduction angle of the power supply is varied. During the injection the converter operates as a rectifier and injects current into the magnet, while during the extraction the converter operates as an inverter and bucks down the voltage across the magnet. At the low current values of the power supply the current ripple is high, thus a large filter is needed, which adds to the cost of the power supply. However, at the high current level the current ripple is less severe. The large size of the filter can be reduced by adding an anti-parallel Silicon Controlled Rectifier (SCR) to the output of the power supply as shown in Figure 1. At low current level the SCRs (S1,S2,S3,S4) are turned on until the current reaches the flat top level, then the firing pulses of these SCRs are removed and the output voltage of the bridges will back bias the SCRs and force them to commutate. In order to keep the bridge conducting continuously, a small circulating current in the bridge is needed. For this purpose a diode with a resistor in series, is connected in parallel with each bridge.



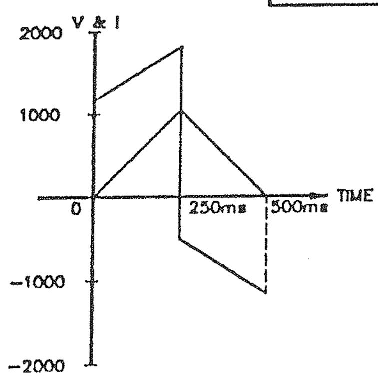


FIGURE 1
BLOCK DIAGRAM FOR SYNCHROTRON
DIPOLE POWER SUPPLIES.

To regulate the current in the magnet a high precision, low drift, zero flux current transductor will be used. This transductor senses the magnet current and then provides the controlling signal for the firing pulses of the SCRs in the bridges. A 15 bit Digital to Analog Converter (DAC) is programmed by the control computer for the required current shape. The DAC provides the reference for the current regulator. Fast correction for the line transients is provided by a relatively low gain voltage loop controlled by the high gain current loop. Only one regulator circuit is used for the two main power supplies. This regulator controls the firing pulses for two sets of identical 12-phase SCR bridges. These pulses are transmitted via optical links.

2.1 Base Line Requirement and Modifications

The base line estimate uses the peak output current rating of 517A and peak output voltage rating of 3886V. At this high voltage rating, several components with lower voltage ratings are connected in series to obtain the required voltage rating of the power supply. This procedure of connecting devices in series increases the number of components in the power supply which consequently reduces its reliability. Power supplies with 1kA and 2kV rating will be used. At this rating, the power supply is more reliable than at its base-line estimate. The increase in the reliability is due to the decrease in the part count and reduction in the component voltage stress. The mean time between failure (MTBF) for the base-line estimate power supply is 26000 hours while MTBF for the 1 kA, 2 kV power supply is 44000 hours, which is an increase of 70%. The new rating of the power supply will effect the following areas:

i) X.1.2.2.1.12 Magnet Wiring and Installation
ii) X.1.2.2.1.1 Dipole Magnets

2.2 Circuit Rating

The circuit rating is given in the following [1]:

Number of Power Supply	2
Injection Current [A]	61
Extraction Current [A]	1044
RMS Current [A]	602
Number of Magnets	68
Resistance of Magnet [Ω]	0.01856
Inductance of Magnet [H]	0.00815
Injection Voltage [V]	42 , 1140

Extraction [V]	724 , 1822
Reset Voltage [V]	-373 , -1055
RMS Voltage [V]	1163
P_{max} [kW]	1902
P_{rated} [kW]	699.9
Total P_{max} [kW]	3803.1
Total P_{rated} [kW]	1399.8
Input Voltage [V]	480 ± 48
Input Frequency [Hz]	60 ± 0.2
Input Voltage Unbalance	3%
Available Short Circuit Current [kA]	30
Maximum Ambient Temperature [°C]	50
Minimum Ambient Temperature [°C]	10
Cooling Water Temperature [°F]	90 ± 10
Water Conductivity [μ mho/cm]	10
Maximum Inlet Pressure [psi]	200
Differential Pressure [psi]	70
Power Supply will be tested at [psi]	250
Total Cooling Water Required [gal/min]	40

	Regulation $\Delta I/I_{max}$
Reproducibility	$(\pm)1\times10^{-4}$
Current Ripple	$(\pm)2\times10^{-4}$
Tracking Error	$(\pm)5\times10^{-4}$
Reference [bits]	15

3. Calculations and Results

The power supply design calculation comprises five sections.

i) Power Section and Cooling Requirement

ii) Control Scheme

iii) Calculation of Power Supply Rating

iv) Interlocks

v) Computer Simulation Results

3.1 Power Section and Cooling Requirement

In this section the transformers, SCRs, interphasing transformer, filter and start up circuit will be discussed, the cooling requirement for each section will be given and their corresponding calculations will be presented.

3.1.1 Transformer Design Requirement

Each power supply consists of two units of three-phase power transformers. The primary windings of one transformer are delta connected while its two secondary windings are connected in wye form. However, both the primary and secondary windings of the other transformer are connected in wye form. This arrangement is clearly shown in Figure 1. The phasor diagram for voltages at the secondary windings of the transformers is given in Figure 2.

In order to maintain the required current and voltage for the magnet load the following parameters for the transformers are specified.

Input Voltage:	480 VAC, 60Hz
Secondary Line to Line Voltage:	1320 V
Apparent Power :	465 kVA @ efficiency of 85%
Input Current :	560 A
Impedance:	5% on per unit basis.
Transformer Temperature Rise	30 °C
Cooling Water Required	5 gal/min

3.1.2 SCR Rating

The average current rating of each SCR is 1200 A with peak On-State Voltage of 2.5 V. The peak reverse blocking voltage is 4000 V. Each device is expected to have 8 °C Temperature Rise.

3.1.3 Interphasing Transformer

In order to connect two half-wave converters in parallel an interphasing transformer is used. This interphasing transformer allows the half-wave converters to conduct for the maximum of 120° and share the load current. This transformer is basically a core and a coil with a center

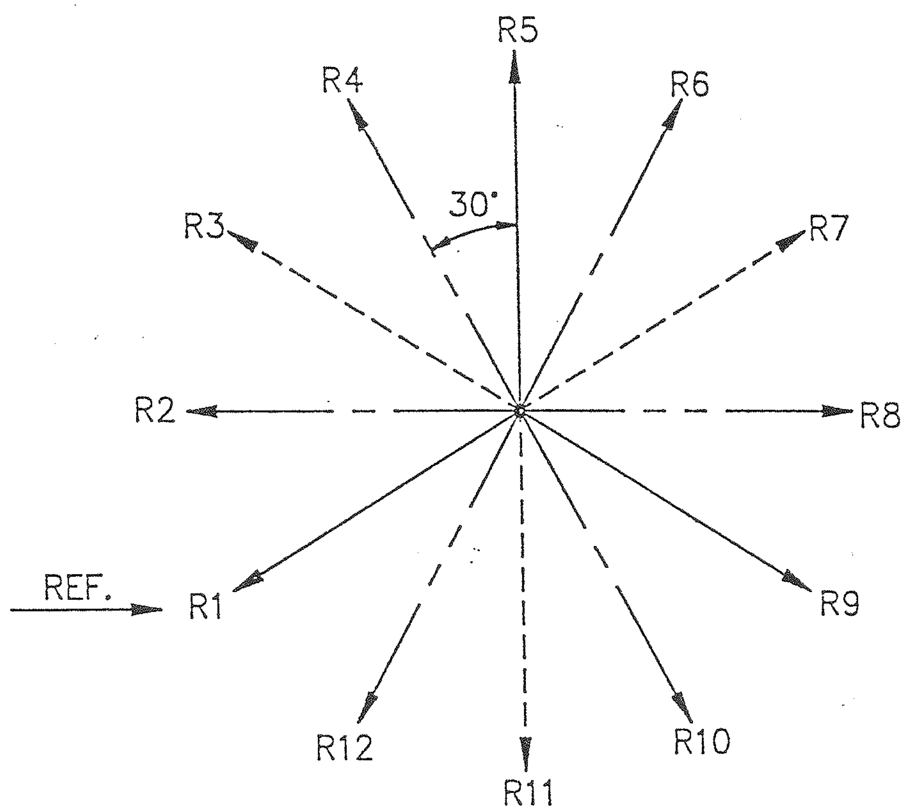


FIGURE 2

PHASOR DIAGRAM FOR CONVERTERS INPUT VOLTAGE tap. When the two half-wave converters are contributing equal amount of the voltage, the interphasing transformer is transparent, but when the output voltages of the half-wave converters are unequal, the windings of the interphasing transformer show enough impedance to correct for the voltage imbalance. The inductance for the interphasing transformer on each leg is assumed to be 10mH with 10mΩ resistance. This value of inductance is sufficient to correct 20% voltage mismatch across the interphasing transformer. The current produced due to the 20% voltage mismatch should not saturate the core of the interphasing transformer.

3.1.4 Filter Design

The basic ripple frequency of the power supply is 720 Hz. A filter with cut-off frequency of 720 Hz is designed to eliminate the fundamentals and higher harmonics of the current in the power supply. The circuit diagram of the filter is given in Figure 3. The filter consists of an inductance, two capacitor banks, and a damping resistor. The damping resistor is in series with one of the capacitor banks to reduce the heat loss in the filter. The transfer function of the filter is given in the following.

$$\frac{e_o}{e_i} = \frac{sT_2 + 1}{s^3 T_2 L_1 C_1 + s^2(T_1 T_2 + L_1 C_1 + L_1 C_2) + s(T_1 + T_2 + T_3) + 1} \qquad (1)$$

where $T_1 = R_1 C_1$, $T_2 = R_2 C_2$ and $T_3 = R_1 C_2$

The following parameters are used to design the filter:

Current Rating, $I_{max} = 1044$ A

No. of Magnets = 34

Resistance of Magnets, R = 34x0.01856 Ω

Inductance of Magnets, L = 34x0.00815 H

Current Ripple Factor, R.F = $2\text{x}10^{-4}$

Cut off frequency, f = 720 Hz

Output Voltage, V = 911 V

The impedance of the magnet load is given by:

$$Z = \sqrt{R^2 + (2\pi f L)^2} \qquad (2)$$

Thus for the above values the impedance is calculated to be, Z = 1253.57 Ω

$\Delta V = Z\,\Delta I$, where $\Delta I = \text{R.F. x } I_{max}$ then;

$\Delta I = 2x10^{-4}$ x 1044 = 0.2088 A and ΔV = 1253.57 x 0.2088 = 261.745 V

The gain of the filter is calculated as follows:

$$Av_{dB} = 20\log\frac{\Delta V}{V} \tag{3}$$

For V = 911 V and ΔV = 261.745 V then Av_{dB} = -10.84 dB. In the above formula the following relationships holds: m=C1/C2, $R_2 = 2\sqrt{L_1/C_2}$ and $\omega_o = \sqrt{1/L_1C_2}$.
Using the curve given in Figure. 10 of reference [2], for m = 0.1 and Av_{dB}= -10.84 dB, from the curve ω/ω_0 = 5.4 , thus: ω_0 = 837.76 rad/s .
For L_1 = 10 mH, then C_1 = 14.25 µF, C_2 = 142.5 µF and R_2 = 16.8 Ω .
The Bode plots for the magnitude and phase response of the filter are shown in Figures 4 and 5 respectively.

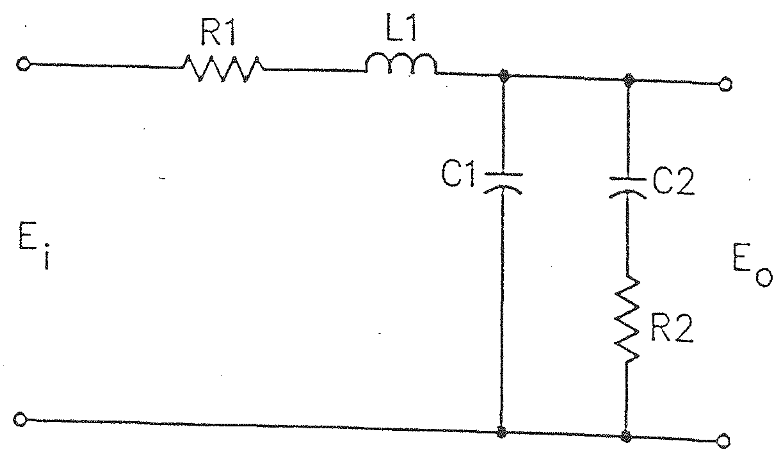


FIGURE-3 LOW PASS FILTER FOR POWER SUPPLY

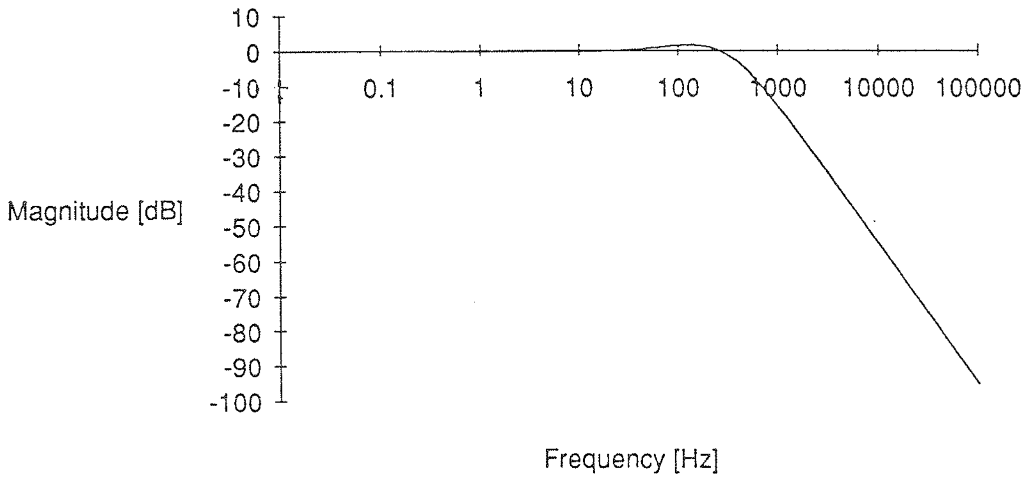


FIGURE-4 MAGNITUDE RESPONSE FOR POWER SUPPLY FILTER

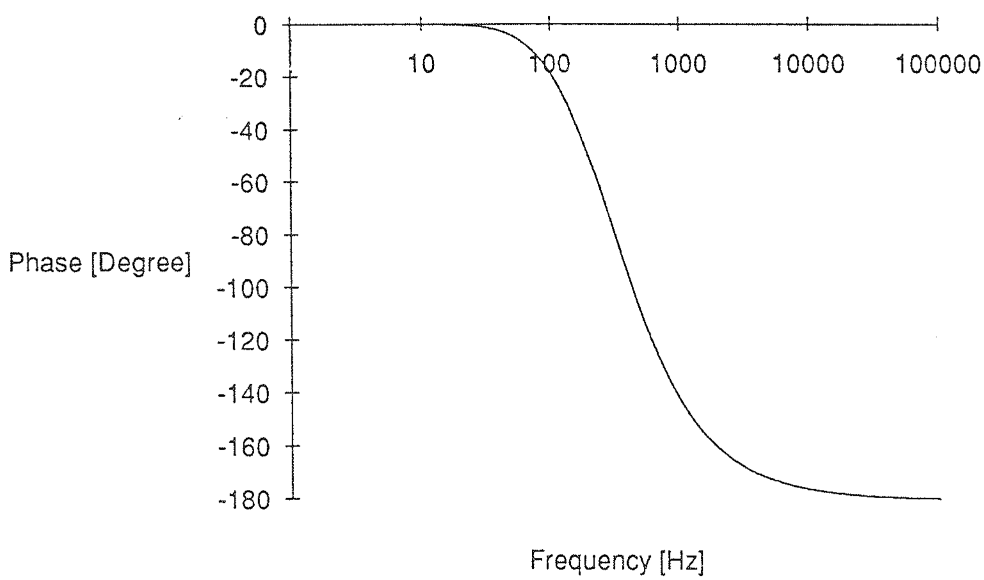


FIGURE-5 PHASE RESPONSE FOR POWER SUPPLY FILTER

In order to investigate the effectiveness of the filter on the power supply performance two different cases of simulation were considered. In the first case, the above values for the filter were used while in the second case the filter was completely removed from the circuit. It was observed that minimal filtering is needed to suppress the higher harmonic contents of the current in the magnet. Therefore no filter will be used in the power supply.

3.1.5 Start Up Circuit

In order to guarantee continuous conduction of the bridge, a start up circuit is used. This circuit consists of a diode in series with a resistor. A relatively low rating diode can be used since this circuit is required to operate only at the low current values. The diode must be rated at least 5 A and 2000 V. The resistor can be 1 kΩ with 2 kW power dissipation capability. The diodes and resistors are both water cooled.

3.2 Control Scheme

Two control loops are utilized to regulate the current in the magnet chain. These loops consist of a slow response current loop and a fast response voltage loop. A high precision, low drift, zero-flux current transductor is used to sense the current in the magnet chain. A 15 bit DAC which is programmed by the control computer for the required current wave-shape provides the reference for the current regulator. The difference between current reference and the current transductor output is fed to a high precision, proportional plus integral (PI) controller. This controller provides the controlling signal for the SCR firing circuit, and subsequently the firing circuit provides triggering pulses to the SCRs in the bridges. In the following, the controller, and the firing circuit will be discussed.

3.2.1 Controller

In order to track the reference current, a proportional control is usually needed. However, this control scheme always requires a small input signal to operate, which results in an offset between current in the magnet and the reference. This problem can be somewhat resolved by increasing the proportional gain of the controller, but high proportional gain may result in an oscillation which is not desirable. A better approach to the problem of providing a controller with a zero offset is to introduce an integrator to the controller, which will eliminate the offset current [3].

For the fast response voltage loop only a proportional controller was used. The block diagram for the suggested control circuit along with the firing circuit is given in Figure 6.

3.2.2 Firing Circuit

The firing signal generator consists of a ramp generator, comparator, blanking logic, amplifier and pulse transformers. A precision ramp generator generates a chain of linear and equal ramp waveforms. Then a comparator is used to compare the ramp signal with the reference signal given by the current and voltage controllers. The comparator produces a chain of pulses. These pulses are fed to a timing circuit which squences the necessary triggering signals for the 12 SCRs in the bridge. Only one of the 12 pulses is synchronized to the input power line voltage signal. The remaining 11 pulses are produced through a delay timer. This scheme guarantees the exact timing for the triggering of the 12 SCRs in the bridges. The triggering pulses are fed to the gates of the SCRs via pulse transformers.

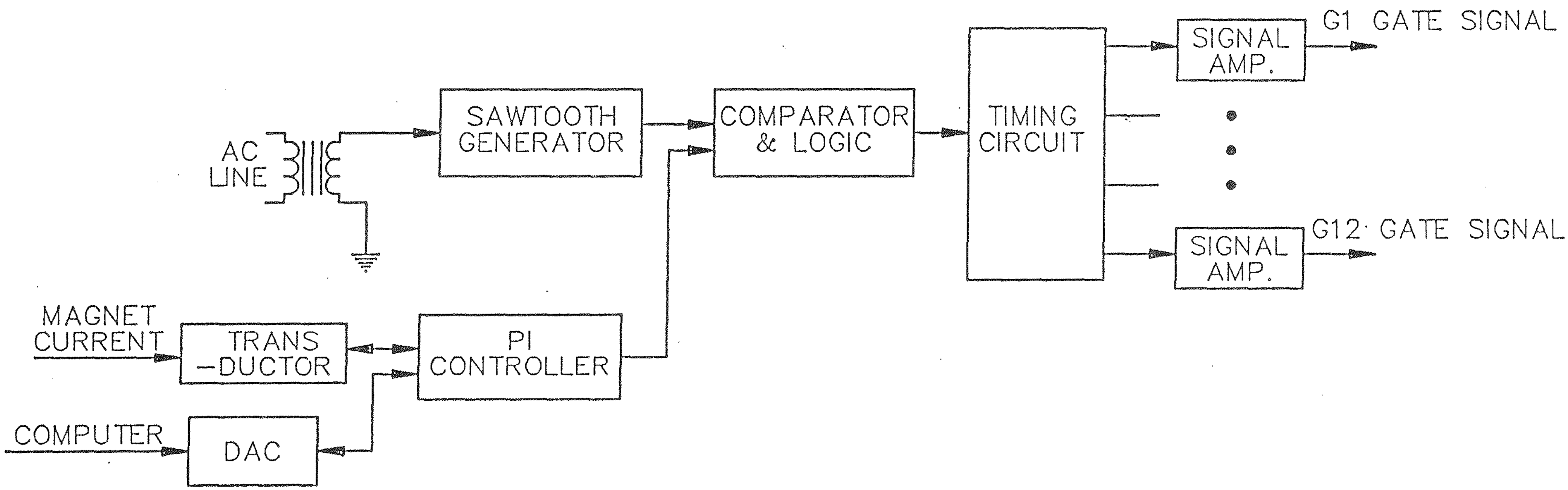


FIGURE-6 TRIGGERING CIRCUIT BLOCK DIAGRAM

3.3 Calculation of Power Supply Rating

The power rating of the power supply is calculated by the following method.

Voltage Rating: For half of the magnet chain (34 magnets) the voltage drop will be calculated as follows:

$$V=RI + L\frac{\Delta I}{\Delta t} \tag{4}$$

where $R = 34x0.0856\ \Omega$, $L = 34x0.00815$ H, $\Delta I = 1044$ A and $\Delta t = 249$ ms, thus: $V = 1822$ V

The rms value for the current and voltage is calculated as follows:

$I_{rms} = \frac{I_{peak}}{\sqrt{3}}$ where $I_{peak} = 1044$ A and then $I_{rms} = 602$ A.

Using trapezoidal curve of the voltage across the magnet for one cycle the rms value of voltage is :

$V_{rms} = 1163$ V

Injection Voltage:

$V_{in} = 34 \text{ x } 61 \text{ x } 0.01856 \text{ x } 1.1 = 42$ V due to Ldi/dt then the injection voltage will be:

$V_{in} = 42 + 34x.00815x(1044\text{-}61)/.248 = 1140.34$ V

Extraction Voltage:

$V_{ext} = 34 \text{ x } 0.01856 \text{ x } 1044 \text{ x } 1.1 = 724$ V then $V_{ext} = 724 + 34x.00815x(1044\text{-}61)/.248 = 1822$ V

Maximum Power:

$P_{max} = 1044 \text{ x } 1822 = 1902$ kW

Rated Power:

$P_{rated} = 602 \text{ x } 1163 = 699.9$ kW

Reset Voltage:

$V_{reset\text{-}max} = 1822 - 1098.34 - 1098.34 = -373$ V

$V_{reset\text{-}min} = 42 -374-724 = -1055$ V

The average output voltage of each three-phase half-converter is given by [4]:

$$V_{dc} = 3V_m \frac{\sqrt{3}}{2\pi} \cos\alpha \tag{5}$$

The rms value of the output voltage is given by:

$$V_{rms} = \sqrt{3}\, V_m \left(\frac{1}{6} + \frac{\sqrt{3}}{2\pi} \cos 2\alpha\right)^{1/2} \quad (6)$$

The output voltage harmonic is calculated as follows:

$$V_h = 3\, V_m \frac{\sqrt{3}}{2\pi} \sum_{p=1}^{\infty} (-1)^p \left\{ \frac{\cos(3p\omega_0 t + (3p+1)\alpha)}{(3p+1)} - \frac{\cos(3p\omega_0 t + (3p-1)\alpha)}{(3p-1)} \right\} \quad (7)$$

where V_m is the peak voltage value of the AC source , α is the firing angle of the converter, p is the harmonic order and ω_0 is the fundamental frequency of the converter.

The input power factor is defined as:

$$PF = \frac{V_{rms} I_1}{V_{rms} I_{rms}} \cos(\phi) \quad (8)$$

where I_1 is the fundamental rms component of the input current, and ϕ is the displacement angle between the fundamental components of the input current and voltage. It must be noted that since the power supply output voltage and current are not fixed, therefore the power factor of the power supply will not be a constant number. In our study the power factor is calculated for the different values of the magnet current.

In a three-phase half-wave converter, the average dc output voltage will be reduced due to the voltage drop in the converter transformer. Thus the output dc voltage of the converter is calculated as:

$$V_d = 3V_m \frac{\sqrt{3}}{2\pi} \cos\alpha - \frac{3\omega L_s}{2\pi} I_d \quad (9)$$

where L_s is the per phase transformer inductance and I_d is the dc output current of the power supply.

Cooling Water Requirement

One gallon of water per minute can cool 1 kW power dissipation with a 6.8 °F temperature rise.

For solid state devices we need only a 14 °F (7.8 °C) temperature rise. Since a 600 A current passes through each SCR at 2.5 V voltage drop, then the total power loss for 28 SCRs will be 42 kW. This power loss requires 42x6.8/14 = 20.4 gal/min cooling water to provide only 14 °F of temperature rise.

For buses and transformers a temperature rise of 30 °C (54 °F) is desired. We assumed that only 10% of total power (186 kW) represents the losses through the buses and transformers, with 80% of those losses cooled via water and the other 20% of power losses cooled through convection cooling. Therefore, for a 54 °F temperature rise, the amount of cooling water needed is calculated to be: 186x0.8x6.8/54=18.73 gal/min.

Thus the total amount of cooling water needed for 2 dipole power supplies is 20.4+18.73 = 39.2 gal/min. For the rating of power supplies 40 gal/min cooling water is specified.

3.4 Interlocks:

In order to operate the power supply safely the following interlocks are needed.

- Faults: Any fault such as line to line, line to ground , and short circuit of the output power will be detected and consequently the power supply will be turned off.

If any of the following take place the power supply will trip off.

- Low water flow
- Over temperature water
- Transformer and choke over temperature
- SCRs over temperature
- AC line current imbalance and AC over current (an indication of excessive AC input current)
- DC over current to ground (an indication of excessive flow of DC current to ground)
- DC over current indicator
- Door open.

The following parameters will be monitored continuously:

- AC line voltage
- AC line current
- DC output voltage
- DC output current

- Power supply cabinet temperature.

The following signals will be the inputs to the power supply:

- Reset Interlocks
- Power ON
- Power OFF
- Count up/ count down signals.

The above interlocks will be sufficient to operate the power supply safely.

3.5 Computer Simulation and Analysis of Results

The PSPICE software was used to simulate the behavior of the synchrotron dipole power supplies. In our studies the following assumptions were made:
a) The impedance of the AC source connected to the power supply was assumed to be 5% . This information was needed to study the voltage drop at the transformer terminals.
b) 20% imbalance of AC source voltage was considered to evaluate the effect of interphasing transformers.

Three cases of studies are considered, as follows:
1) The rated input voltage of the power supply was applied to the power supply and the current in the magnet was ramped form 60 A to 1044 A. The ripple content, linearity of current and controller tracking capability was then evaluated.
2) The effect of harmonics current injected from the power supply to the utility line is investigated.
3) Input kVA and power factor for the power supply were computed.

Case -1 The results which were obtained from the simulation of the power supply indicated that the controller can track the current reference within the specified limit. The following graph represents the tracking capability of the controller. In this current range the difference between the reference and the actual magnet current is always less than 0.5 A. The obtained value of the current error confirms the specified tracking capability of the power supply (for $\Delta I/I_{max}= 5x10^{-4}$,and I_{max} =1044 A , ΔI should be 0.522 A or less)

The current ripple in the magnet is less than 200 mA, which is acceptable. The results which are given in Figure-7 are obtained from a digital computer simulation, therefore the output current can be reproduced continuously. However the reproducibility of the current must be measured from the actual system.

The power supply has two basic modes of operations; during the injection it operates in the rectifier mode, while during the extraction the power supply operates as an inverter. A plot of converter firing angle α against time is shown in Figure-8 which explains the converter operation at different current levels.

During 0 to 250 ms the power supply is in the rectifier mode and injects current into the magnet load, while from 250 ms to 500 ms the power supply operates as an inverter and extract current from the magnet load.

The input AC power for the dipole power supplies is also computed and plotted in Figure - 9.

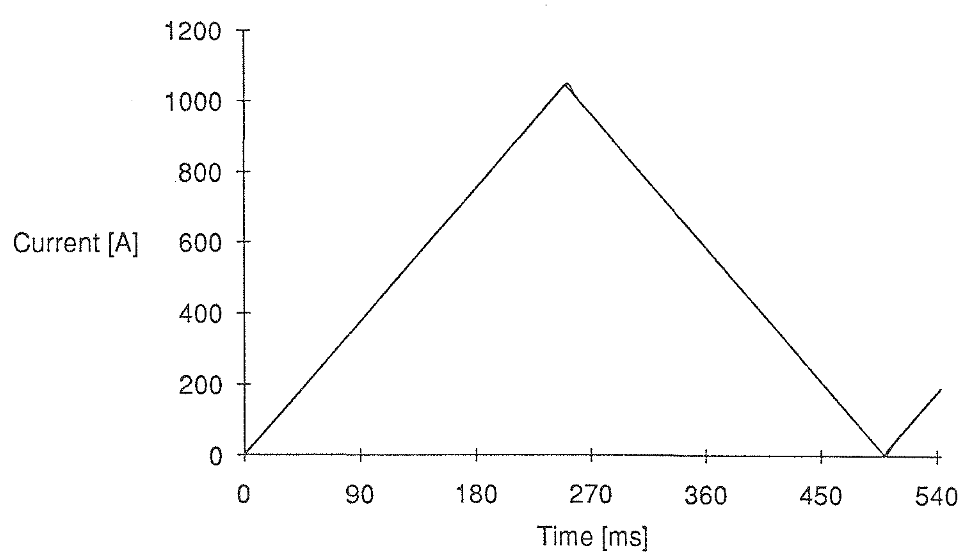


FIGURE - 7 TYPICAL SYNCHROTRON MAGNET CURRENT WAVEFORM

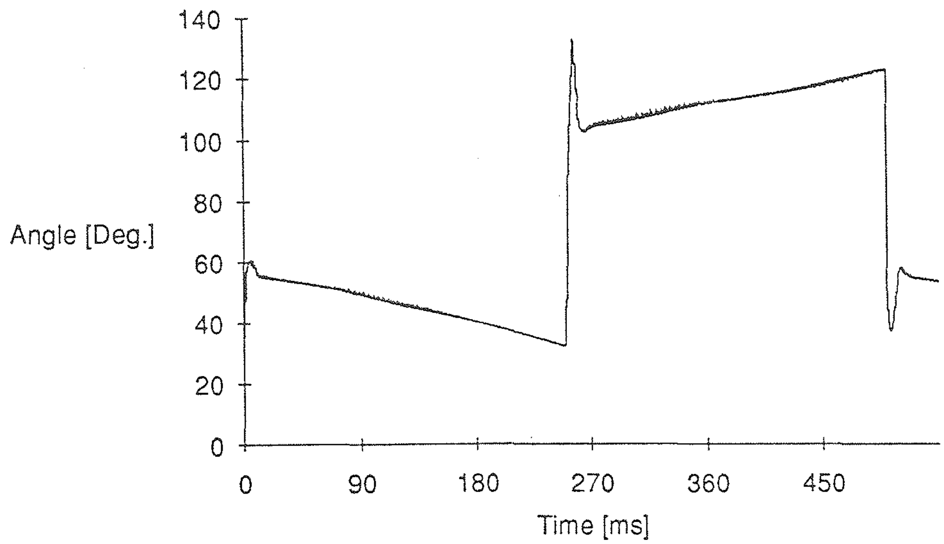


FIGURE-8 POWER SUPPLY FIRING ANGLE VARIATION FOR DIFFERENT CURRENT LEVELS

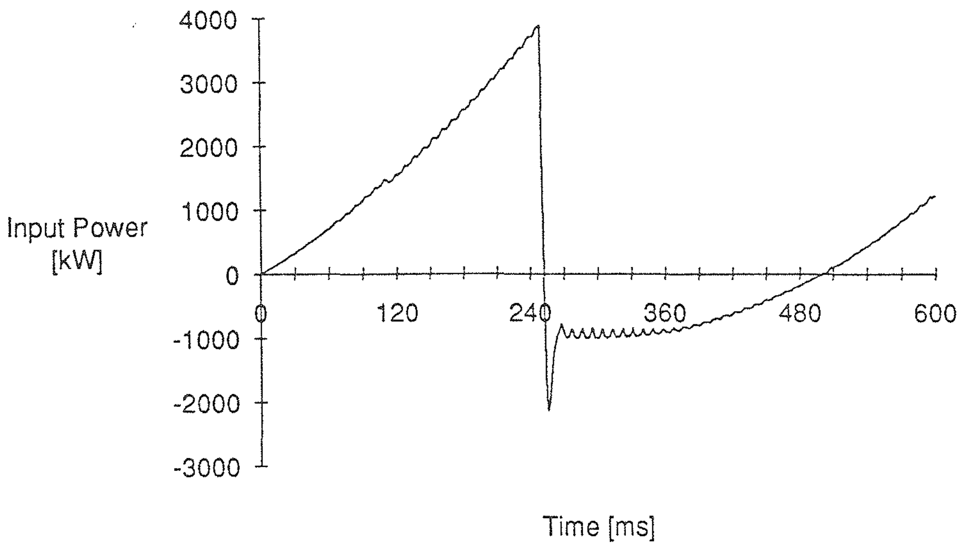


FIGURE-9 POWER SUPPLY INPUT POWER VARIATION DURING RECTIFIER AND INVERTER MODES

From the input power profile, it can be seen that, during the injection the input power to the power supplies follows the current pattern in the load magnet, but during the extraction the power supplies feed current back to the line.

Case-2 The harmonic contents of the input current can be calculated by the following equation [5]:

$$i_a = \frac{6}{N\pi} I_d \left[\cos\omega t - \frac{1}{11}\cos 11\omega t + \frac{1}{13}\cos 13\omega t ... \right] \quad (10)$$

where I_d is the dc current in the magnet, N is the transformer turn ratio and i_a is the current in the input line. The above equation indicates that the line current has harmonics of the order $h = 12k\pm1$, where k is an integer with values $k = 1,2,....$ The harmonic currents injected into the utility system by the power supply can be eliminated by addition of a filter to the input of the power supply. However, the filter design must take account of the ac system impedance at harmonic frequencies in order to provide adequate filtering and to avoid certain resonance conditions. The system impedance depends on the system configuration, loads, generation pattern, and transmission line in service. Therefore, any change in the system configuration will require the modification of the filter. However, the harmonic contents of the current have a minimal effect on a stiff system. Transmission lines with low impedance and large substation transformer can provide a stiff system.

Case 3 The kVA rating of the power supply is twice the kVA of each converter transformer which was given in section 3.1.1. Thus the rating of each power supply is 930 kVA.
The value of the power factor calculated for different values of magnet current of the converters and is given in Figure-10.

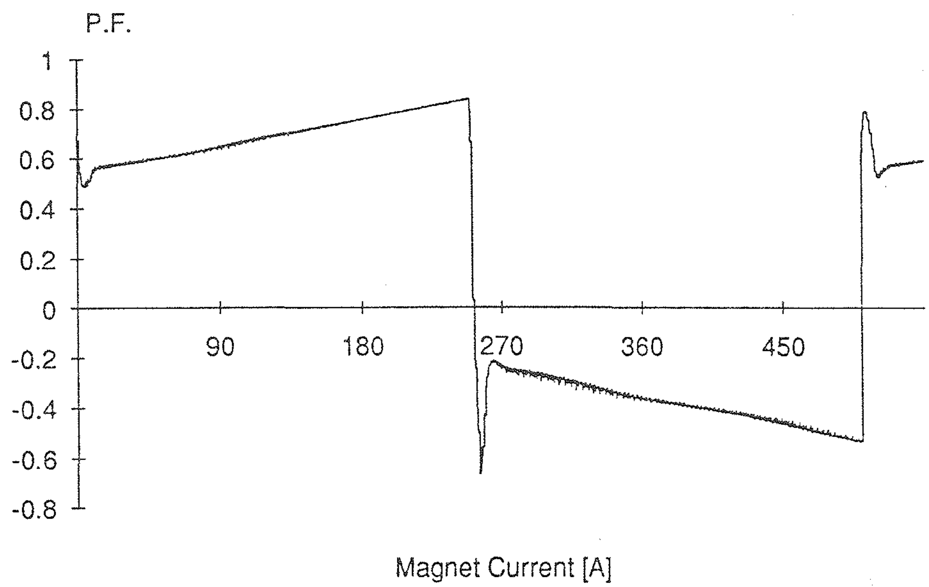


FIGURE-10 POWER FACTOR VARIATION OF POWER SUPPLY DURING DIFFERENT LOAD LEVEL

The input power factor of the power supply varies for different values of the magnet current. When the power supply is in the rectifier mode, the power is delivered from the utility to the magnet which explains the positive values for the power factor. However, during the extraction, the power supply operates as an inverter which ,therefore, delivers power to the utility. This action cause the negative power factor.
The effect of changes in the line voltage on the magnet current was also investigated. The line voltage was gradually dropped from 100% to 95% within 150 ms and then it was boosted to its rated value. The voltage plot in Figure-11 clearly shows the line voltage change at 150 ms, the magnet current, however, remained unaffected.

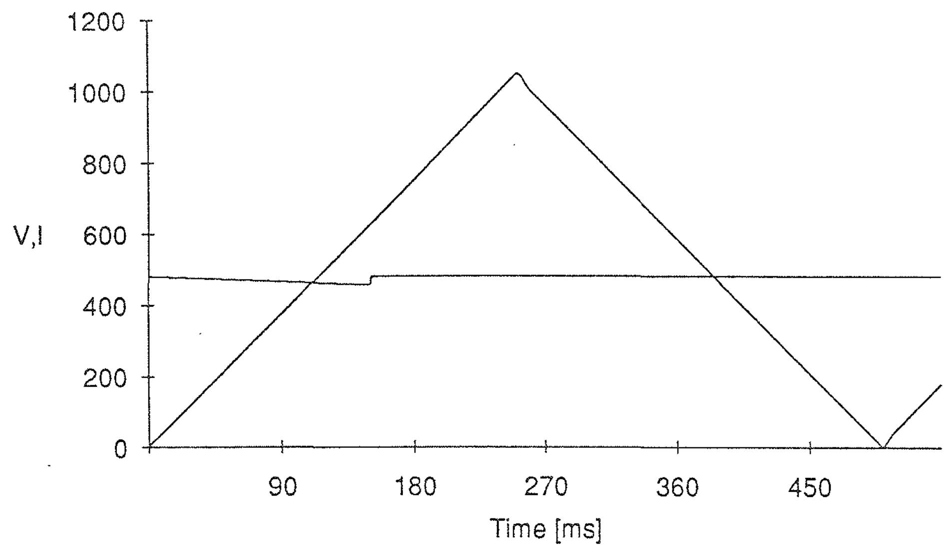


FIGURE -11 EFFECT OF LINE VOLTAGE CHANGE ON POWER SUPPLY OUTPUT CURRENT

4. Conclusion

A twelve-pulse phase controlled power supply was simulated to investigate the behavior of the power section, filter, and control loops. Based on our study the following conclusions can be drawn:

1) Due to the nature of the load, and large amount of the inductance in the load the power filter is not needed, and the current in the magnet has ripple values sufficiently small to meet the ripple limit requirement.

2) A proportional plus integral controller for the current loop and a proportional controller for the voltage loop properly controls the current in the magnet.

3) The effect of harmonic current due to the non-linearity of the power supply was investigated. The power supply injects current harmonics to the utility whose order is given by $h = 12k \pm 1$ where k is an integer. In order to eliminate the injected harmonic currents, a tuned filter at certain harmonic frequency must be designed. However, the design of the filter relies on the system impedance. The system impedance changes with any modification in the system configuration. Therefore, a tuned filter can operate properly as long as the system configuration remains unchanged. But any changes in the system configuration can disturb the correct operation of the tuned filter. It was concluded that a properly sized substation transformer can minimize the effect of harmonic current on the utility.

4) The input power factor for the power supply at different magnet current level was computed. The input power factor for the power supply varies from 0.6 to 0.9 in the rectification mode and from – 0.3 to – 0.75 in the inversion mode.

5) The input AC power to the power supplies will ramp and follow the current pattern in the load magnet. This is understandable, since the input current and power factor follow the same pattern, while input voltage remains constant.

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