Design and Simulation of High Accuracy Power Supplies for Injector Synchrotron Dipole Magnets*

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Abstract

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. The current in the magnet will be raised linearly to about 1 kA level, and after a small transition period (1 ms to 10 ms typical) the current will be reduced to below the injection level of 60 A. The repetition time for the current waveform is 500 ms. A relatively fast voltage loop along with a high gain current loop are utilized to control the current in the magnet with the required accuracy. Only one regulator circuit is used to control the firing pulses of the two sets of identical 12-phase power supplies. Pspice software was used to design and simulate the power supply performance under ramping and investigate the effect of current changes on the utility voltage and input power factor. A current ripple of $\pm 2\times10^{-4}$ and tracking error of $\pm 5\times10^{-4}$ was needed.

I. INTRODUCTION

Each power supply consists of four phase controlled half-wave wye group converters. Each of the two half-wave converters are connected through an interphase transformer to obtain a 120° conduction. The input voltage for these two half-wave converters are 60° apart. In order to obtain the high voltage needed for the load, two of the full-wave converters are connected in series. The power supply is equipped with a passive L-C-R filter to reduce the ripple content of the output current. The large size of the filter is reduced by adding anti-parallel thyristors to the output of the power supply. At low current level these thyristors are turned on until the current reaches the flat -top then the firing pulses of these thyristors are removed and the power supply is pulsed for full conduction. The output of the power supply will back bias the thyristors and force them to commutate. The power supply output will be ramped. During acceleration the power supply will operate as a rectifier and inject current into the magnet while, during reset the power supply operates in inversion and bucks the voltage across the magnet. To regulate the current in the magnet a high precision, low drift, zero flux current transducer is used. This transductor senses the magnet current and then provides the controlling signal through the regulator for the firing pulses of the thyristors in the converters. 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 fast response voltage loop controlled by the high gain, slow response current loop. Only one regulator circuit is used for two power supplies. This regulator controls the firing pulses for two sets of identical 12-phase thyristor power supplies. These pulses are transmitted via optical links. Figure 1 shows the block diagram for power supplies connected to magnet load.

II. BASIC REQUIREMENT

The voltage, current and regulation requirements for synchrotron dipole magnets are given below [1]:

Injection Current [A]	61
Extraction Current [A]	1044
Injection Voltage [V]	42, 1140
Extraction Voltage [V]	724, 1822
Reset Voltage [V]	-373, -1055

Regulation $(\Delta I/I_{max})$

Reproducibility	$\pm 1\times10^{-4}$
Current Ripple	$\pm 2\times10^{-4}$
Tracking Error	$\pm 5\times10^{-4}$

III. DESIGN AND RESULTS

A. *Filter Design*

A filter with the cut-off frequency of 720 Hz was designed to eliminate the fundamental and higher harmonics of the current in the power supply. The transfer function of the filter is given in the following [2]:

$$\frac{e_o}{e_i} = \frac{sT_2 + 1}{s^3T_2L_1C_1 + s^2(T_1T_2 + L_1C_1 + L_1C_2) + s(T_1 + T_2 + T_3) + 1} \qquad (1)$$

where $T_1 = R_1C_1$, $T_2 = R_2C_2$, $T_3 = R_1C_2$, $L_1 = 10$ mH, $C_1 = 14.25$ µF, $C_2 = 142.5$ µF and $R_2 = 16.8\ \Omega$.

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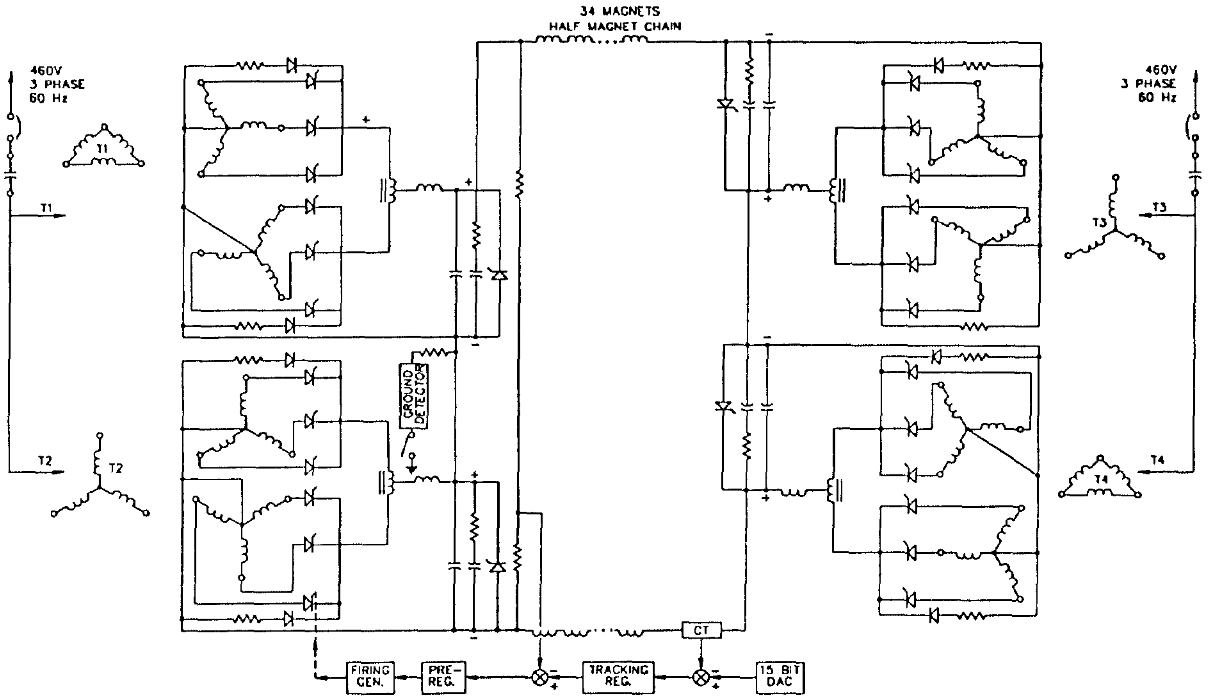

Figure 1. Block diagram for synchrotron dipole power supplies connected to magnets

B. *Regulator Design*

In order to track the current reference with the desired accuracy, a controller with very high gain is needed. A proportional plus integral (PI) controller can provide such a high gain. Both current and voltage loops utilize PI controllers. The voltage loop time response is set to correct for 720 Hz ripple produced before the main filter. However, the time constant of the current loop is set equal to the magnet time constant to obtain a proper control.

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 interphase transformers.

Our study consists of three parts as follows:

1) The rated input voltage was applied to the power supply and the current in the magnet was ramped 60 A to 1044 A. 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 was investigated.

3) Input kVA and power factor for the power supply at different load level were computed.

Part-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.

Figure 2 represents the tracking capability of the controller. For current level between 5% to 100% of rating current the difference between reference and actual magnet current is always less than 0.005%. The obtained value of the current error confirms the specified tracking capability of the controller.

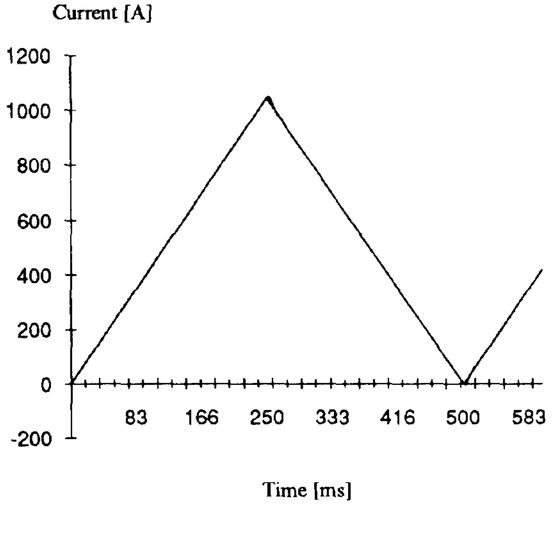

Figure 2. Typical synchrotron magnet current waveform

Part-2: The harmonic contents of the input current can be calculated by the following equation [3]:

$$i_a = \frac{6}{N\pi} I_d \left[\cos\omega t - \frac{1}{11}\cos 11\omega t + \frac{1}{13}\cos 13\omega t ... \right] \quad (2)$$

where I_d is the dc current in the magnet, N is the transformer turn ratio and i_a is the ac input line current. The above equation indicates that the line current has harmonics of the order $h = 12k\pm1$, where k is an integer with values $k = 1,2,\ldots$

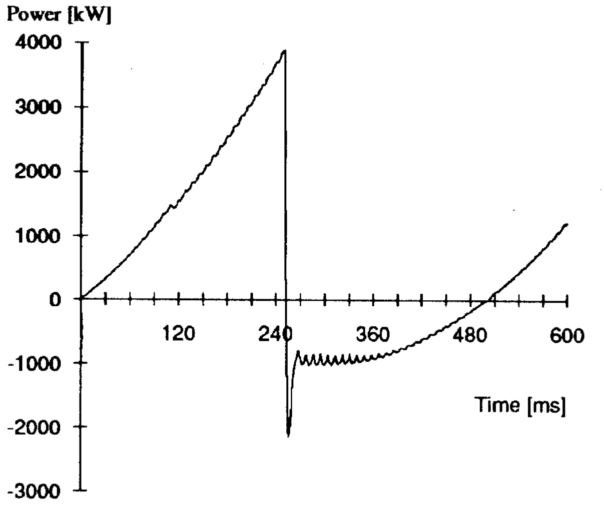

Figure 3. Input power variation during rectification and inversion

The harmonic currents injected into the utility line 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.

Part-3 The calculated rating of each power supply is 930 kVA. The power supply power factor for different output current values are calculated and plotted in Fig. 4. The effect of ac line voltage change on the output dc current was also examined. The line voltage was gradually reduced from 100% to 95% rating within 150 ms and then was boosted to its rated value. Figure 5 shows the line voltage change along with output dc current. It can be noticed that the fast response of the voltage loop can correct for the input ac line changes.

IV. CONCLUSION

A twelve-pulse phase controlled power supply was designed and simulated. i) It was concluded that due to the large amount of inductance in the load, a small amount of filtering was required to suppress the ripple contents of the output current. ii) Proportional plus integral controller for both current and voltage loop was required. iii) The power supply injects harmonics of the order of $h = 12k\pm1$ into the utility line. A stiff system with reasonably large substation transformer was recommended to correct this effect.

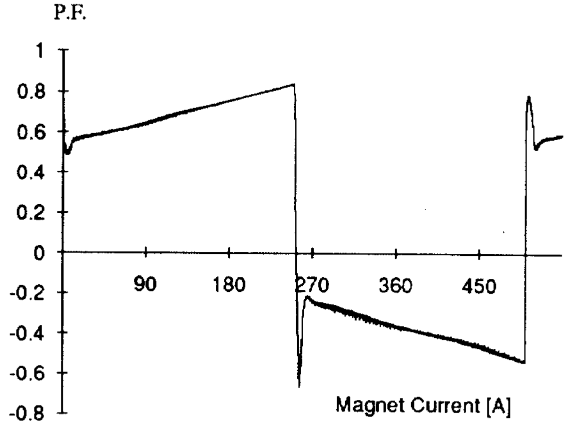

Figure 4. Power factor variation of power supply during rectification and inversion.

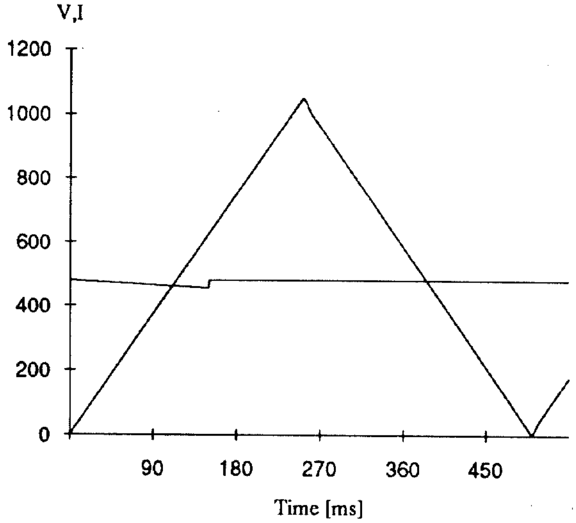

Figure 5. Effect of line voltage change on output dc current.

V. REFERENCES

[1] Advanced Photon Source Design Handbook Vol. II Dec. 1989

[2] W.F. Preag, "A high-current low pass filter for magnet power supplies," IEEE Trans. Industrial Electronics and Control Instrumentation, Vol. IECI-17, No. 1, pp. 16-22, Feb. 1970.

[3] N. Mohan, T.M. Underland, and W.P. Robbinson, *Power Electronics Convertors, Application and Design*, New York: John Wiley & Sons, Inc. 1987.