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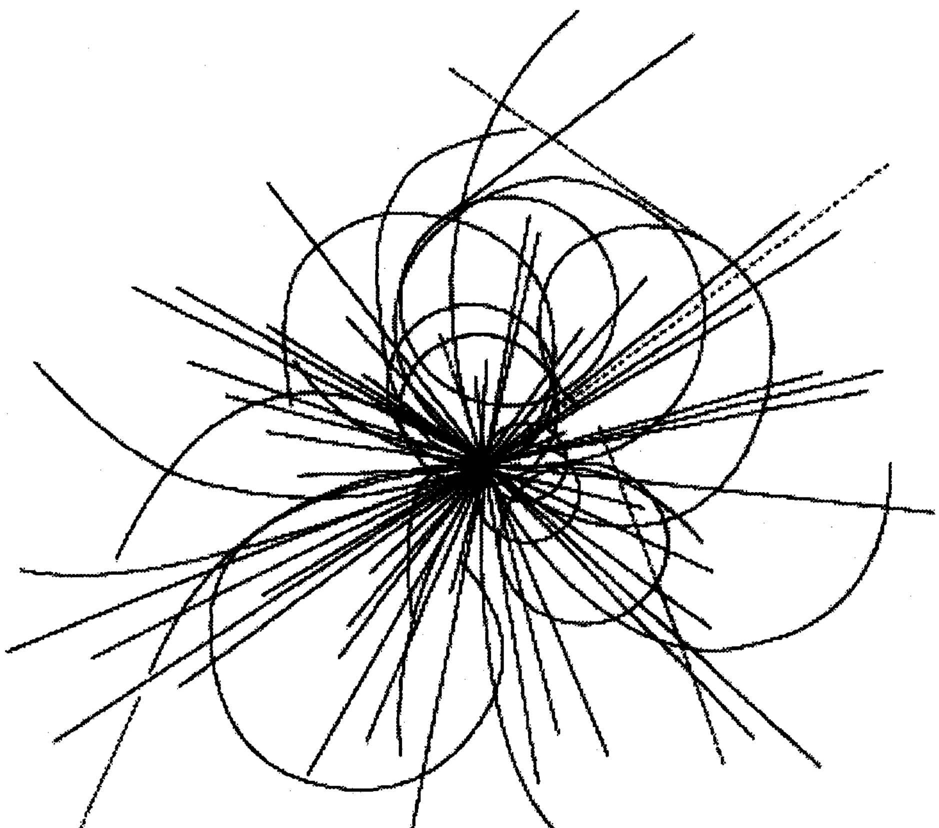

Superconducting Super Collider Laboratory

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Regulation Loops for the Ring Magnet Power Supplies in the SSC Accelerator Complex

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Abstract

The SSC complex consists of five cascaded accelerators: the linear accelerator (linac) and four synchrotrons: the low energy booster (LEB), the medium energy booster (MEB), the high energy booster (HEB), and the collider. Twelve- or 24-pulse phase-controlled SCR power supplies are used to energize the ring magnets. Each power supply has a voltage loop designed to regulate the voltage applied to the magnets. The voltage regulation loops for these synchrotrons and the current regulation for the LEB are analyzed in this work. The digital voltage regulator is fiber-optic isolated from the power converter. It has a closed-loop bandwidth of 150 Hz with band rejections for 60-Hz and 120-Hz perturbations. The LEB has a very precise current regulation system composed of a feedforward compensator, a fast feedback regulator, and a slow synchronous regulator. The current regulation design is corroborated by computer simulations.

I. INTRODUCTION

The SSC basic design goal of the Superconducting Super Collider (SSC) is to collide beams of oppositely-directed protons at 20-TeV energy. A cascade of accelerators provides protons at successively higher energy into the following accelerator. Protons are brought to 0.6 GeV in a linear accelerator. Following that are three booster synchrotrons: the LEB, which accelerates to 11 GeV in a 0.54-km circumference ring of magnets; the MEB, which accelerates to 200 GeV in a 3.96-km ring; and the HEB, which accelerates to 2 TeV in a 10.9-km ring. The collider itself consists of two vertically separated rings, each a 20-TeV proton accelerator 87 km in circumference. The LEB and MEB are synchrotrons using room temperature magnets, while the HEB and collider use superconducting magnets cooled to liquid-helium temperature.

The magnet current has to be regulated with a tolerance of a few parts in 10^6 (ppm) in all synchrotrons' magnets. This high current accuracy is obtained by using a fast voltage regulation loop and a slow current regulation system. The dynamic behavior is improved by using feedforward compensation, while adaptive techniques are needed to achieve long-term stability. Both voltage and current regulation systems are described in the following sections.

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II. VOLTAGE REGULATION

Twelve- or 24-pulse power supplies are inserted into the ring to energize the ring magnets. The number and ratings of the power supplies are as follows: LEB, three 24-pulse power supplies, 2000V, 4000A; MEB, ten 24-pulse power supplies, 2000V, 5200A; HEB, four 24-pulse power supplies, 1000V, 7000A; collider, forty 12-pulse power supplies, twenty 200V, 7000A, and twenty 40V, 7000A.

Each power supply has its own voltage loop and output passive filter. The voltage loop is designed to have a high frequency response and its main function is to regulate the voltage applied to the magnets. It must follow a predetermined voltage reference related to the current reference, rejecting line voltage changes, offset errors, and other voltage perturbations. Due to bandwidth limitations, the voltage loop rejects only voltage perturbations up to 120 Hz, while the output filter rejects the ripple at 360 Hz and other higher frequency perturbations [1].

The design of the digital voltage regulator is similar in all ring magnet power supplies. The block diagram of the voltage loop is shown in Figure 1.

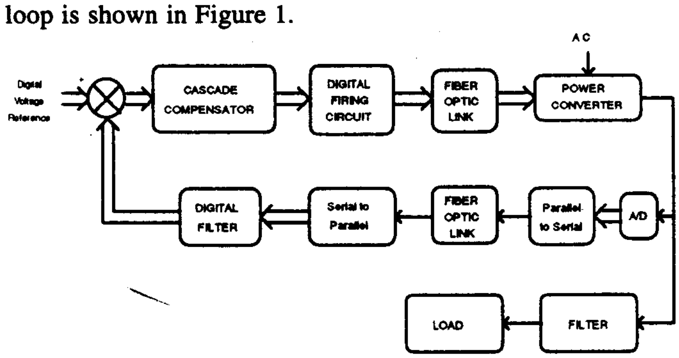

Figure 1. Block diagram of the digital voltage loop.

A distributed grounding system is used in the magnet string. The power supplies voltage to ground changes from one synchrotron to another and also depends on the synchrotron operating condition. The worst case is in the LEB, where an electrical isolation of 7.5 kV is required. In order to obtain this high voltage isolation, optical links are used in the voltage regulation to fire the power converter thyristors and to monitor the output voltage (Figure 1). A 12-bit A/D converter digitizes the power converter output voltage at a frequency rate higher than 50 kHz. The 12-bit digitized voltage is serially transmitted across the fiber-optic link. The optical receiver is followed by a digital filter, which calculates the voltage mean value at a frequency rate of 1440 Hz.

The error between voltage reference and voltage feedback goes through a digital cascade compensator that also operates with the 1440-Hz clock. The compensator has an integral action with very high dc gain and two passband filters at 60 Hz and 120 Hz, respectively. The compensator also includes a linearizer to compensate the non-linear transfer function of the power converter.

The digital firing circuit is basically an open loop system with a single 60-Hz PLL. It presents a high-frequency bandwidth, having a time resolution better than 0.1°.

The voltage loop feature includes a bandwidth of 150 Hz, with more than 20 dB rejection to 60-Hz and 120-Hz perturbations. The ripple at 720/1440 Hz and other higher frequency perturbations are rejected by the output passive filter.

A prototype of the digital voltage regulator has been developed and tested, with good results, in a 12-pulse phase-controlled SCR power supply.

III. CURRENT REGULATION

The period of the magnet current waveforms ranges from 0.1 s for LEB up to about 24 h for the collider. A current regulation tolerance of a few parts in 10^6 is required in all synchrotron magnets. In some cases (MEB–Collider), a precise tracking between bending magnets and quadrupoles or between sectors is also required. In order to satisfy these requirements, different regulation schemes, including feedforward, feedback, and adaptive techniques, are used. In fast-cycling synchrotrons (LEB, MEB) the emphasis is on obtaining a good dynamic behavior, while in the slower superconducting magnets (HEB, Collider) the main current regulation problems are related to long-term stability and to noise and ripple reduction. Among the different ring magnet current-regulation loops, only the current-regulation design for the LEB 10-Hz biased sinewave operation mode is described in this paper.

The LEB magnet system consists of 48 dipoles and 90 quadrupoles connected in series circuit. The power system has to operate in either of two modes: 10-Hz biased sine wave and linear ramp. For 10-Hz biased sinewave operation, dipole and quadrupole magnets resonate with 12 distributed capacitors [2]-[4]. The capacitors are bypassed by a 40-mH choke to provide a path for the d-c component of the magnet current. For the linear operation mode, the 12 resonant banks are short-circuited. Three 24-pulse SCR phase-controlled power supplies are inserted into the ring to produce both current waveforms.

The maximum and minimum current flowing through the magnets has to be regulated, in both modes, within 50 ppm of the actual current. A typical required magnet current waveform for the 10-Hz biased sinewave mode is shown in Figure 2. To satisfy this requirement, a current regulation system with a high open-loop gain at dc and 10 Hz is necessary.

A high open-loop gain at 10 Hz with adequate closed-loop stability cannot be simultaneously fulfilled by using a conventional regulator. The regulation problem has been solved by combining feed-forward compensation and conventional feedback regulation with frequency conversion techniques.

The schematic diagram of the current loop is shown in Figure 3. The central computer provides the maximum and minimum current values, while the 10-Hz biased sinewave current reference, synchronized with the utilities, is locally generated.

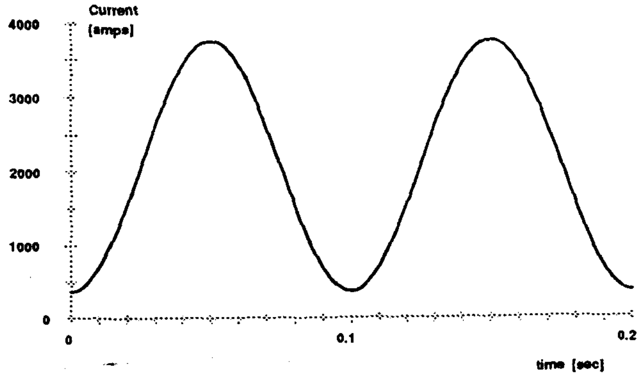

Figure 2. Magnet current waveform 10-Hz biased sinewave mode.

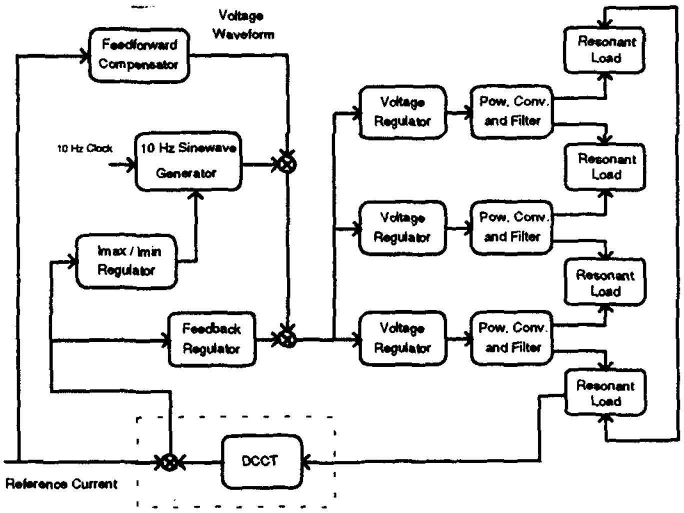

Figure 3. Block diagram of the current loop 10-Hz biased sinewave mode.

The magnet current is measured with a very precise Zero-Flux DC Current Transducer (DCCT). An analog differential amplifier with a gain of 30 amplifies the difference between the current reference and the magnet current. An 18-bit D/A converts the digital reference current, while a 16-bit A/D digitizes the differential amplifier output. D/A, A/D converters and the differential amplifier are built inside the DCCT in a temperature-regulated chamber with a precision of 0.01°. The same current-measuring system is used for both LEB operation modes, while at least two high-precision DCCTs were required in a former current-regulation design [5].

The digital current regulator is fully digital, operating at a frequency rate of 1440 Hz. It is composed of a feedforward compensator, a feedback regulator, and a synchronous I_{max}/I_{min} regulator. The voltage reference is generated by adding the outputs of the three regulation blocks. The three-ring magnet power supplies are driven by the same voltage reference.

A. Feedforward Compensator

The feedforward compensator provides the necessary voltage for having a current flowing through the magnets equal to the reference current. This voltage waveform is also a biased sine wave calculated considering the load in perfect resonance. A feedforward system is an open-loop compensation unable to correct current perturbations. It usually has to be complemented with a feedback system.

B. Feedback Regulator

In designing the feedback loop, the load characteristic has to be fully understood. The voltage loop has a bandwidth of 150 Hz, and the output passive filter is basically a second-order, critically damped, low-pass filter with a resonant frequency of about 130 Hz. The admittance of the resonant load is represented in the frequency domain in Figure 4.

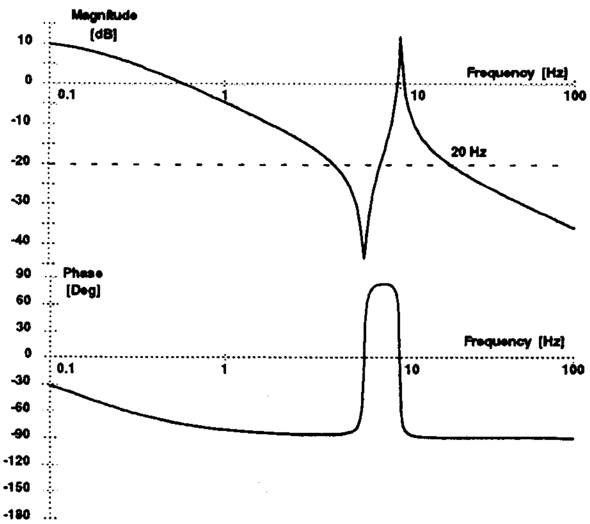

Figure 4. Magnitude and phase frequency response of the load admittance.

The feedback regulator has been designed with a proportional cascade compensator with a total gain of 20 dB. This additional gain is indicated by the dotted line in Figure 4. The feedback loop is stable, having a closed-loop bandwidth of 20 Hz. Considering that the phase introduced at 20 Hz by the voltage loop and passive filter is less than 30°, a 60° phase margin is obtained. The feedback loop has a gain of 30 dB at dc and 10 Hz. This gain is not enough to satisfy the regulation requirements. The gain at low frequencies can be increased using integral action, but the gain at 10 Hz cannot be substantially increased using standard techniques without reducing the phase stability margin.

C. Synchronous Regulator

The basic idea of the synchronous regulator is to take advantage of the periodicity of the reference current. The current error is measured during one signal period, and the correction is synchronously and gradually applied during the following periods. In this way, an equivalent high gain at 10 Hz can be obtained while limiting the closed-loop bandwidth of the synchronous regulator to less than 1 Hz.

The high gain in the low-frequency band is easily obtained by integrating the mean value of the error signal (dc). The integrator gain has been calculated to have a correction bandwidth of 0.6 Hz.

Frequency conversion techniques are used for obtaining high gain at 10 Hz. The residual 10-Hz sine wave on the error signal is detected in amplitude (ac component only) and integrated. The output of this integrating amplifier modulates the amplitude of a synchronized sine wave.

The first step to design the a-c amplitude regulation loop is to obtain a mathematical model of the system, including detection and modulation processes. The block diagram of Figure 5 will be used for this purpose.

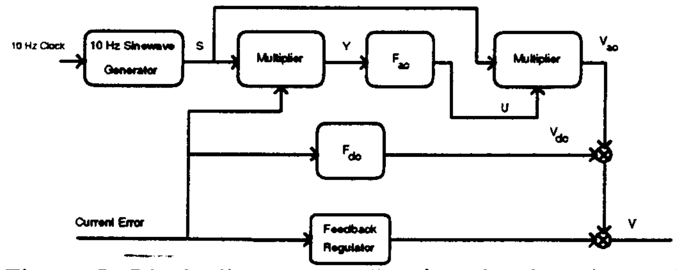

Figure 5. Block diagram representing the detection and modulation process.

In Figure 5, the signal demodulation has been implemented with a synchronous or a linear phase detector [6]. In fact, as the carrier frequency is available, this efficient method for amplitude or phase detection can be readily implemented. The ac and dc components of the error signal are filtered with the integrating amplifiers F_{ac} and F_{dc}, respectively.

$$F_{ac} = \frac{K_{ac}}{S} \qquad F_{dc} = \frac{K_{dc}}{S} \tag{1}$$

The amplitude modulation and detection are nonlinear processes that can be handled by the Laplace transform using s-plane convolution [7]. The same structure employing a multiplier excited by the 10-Hz sine wave is used in Figure 5 for implementing both modulation and detection processes.

Denoting the Laplace transform of $e_{ac}(t)$ and u(t) by $E_{ac}(s)$ and U(s), the transform of both products can be expressed by the following s-plane convolutions:

$$U(s) = \frac{1}{2\pi j} \int (\lambda) \cdot E_{ac}(s-\lambda) \cdot d\lambda \tag{2}$$

$$V_{ac}(s) = \frac{1}{2\pi j} \int S(\lambda) \cdot U(s-\lambda) \cdot d\lambda. \tag{3}$$

Both convolution integrals are readily evaluated by taking residues at poles of S(λ). Neglecting high-frequency components, the transfer function of the ac synchronous regulator can be approximated by

$$\frac{V_{ac}(s)}{E(s)} \cong \frac{K_{ac}}{2} \cdot \frac{s}{s^2 + w_o^2}. \tag{4}$$

Thus, the transfer function of the equivalent feedback regulator can be expressed by

$$\frac{V(s)}{E(s)} = K_p + \frac{K_{dc}}{s} + \frac{K_{ac}}{2} \cdot \frac{s}{s^2 + w_o^2}, \tag{5}$$

where K_p represents the proportional gain of the feedback regulator.

The frequency response of the equivalent feedback regulator is represented in Figure 6, using the following constant values: $K_p = 10$, $K_{dc} = 40$, and $K_{ac} = 160$. The effect of the proportional feedback regulator as well as the ac and dc components of the synchronous regulator can be easily identify in Figure 6. Using Eq. (5), the transfer function of the total open-loop feedback regulation can be calculated. Its frequency response is represented in Figure 7.

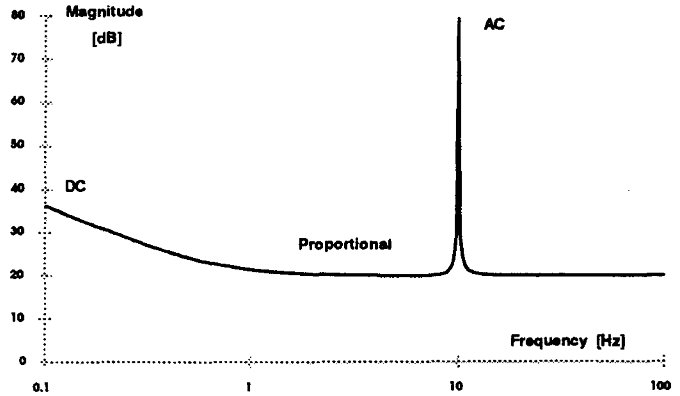

Figure 6. Magnitude frequency response of the equivalent feedback regulator.

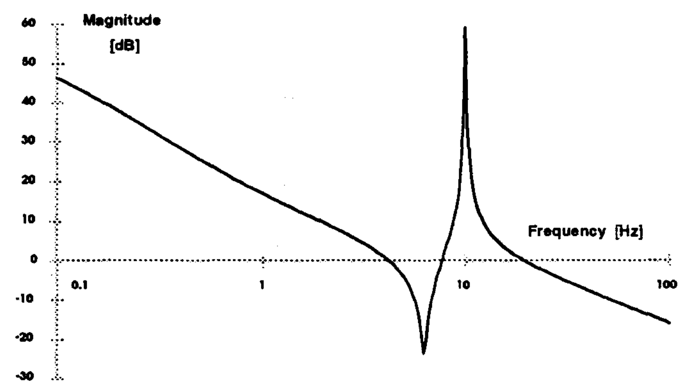

Figure 7. Magnitude frequency response of the total open-loop feedback regulation.

Comparing Figures 4 and 7, the improvement of the synchronous regulator is apparent. The 20-Hz closed-loop bandwidth, controlled by the proportional constant K_p, has not been modified. The system is stable, the phase margin has been reduced in only 6° (Eq. (5)), and the equivalent open-loop gain at dc and 10 Hz has been dramatically increased. The constant values K_{dc} and K_{ac} have been chosen to have a correction bandwidth of 0.6 Hz for both dc and 10-Hz components.

IV. SIMULATION RESULTS

The linear phase detector of Figure 5 has been replaced in Figure 3 and in the computer simulations by a timing circuit and two sample-and-hold circuits. The timing circuit generates sample pulses synchronized with the maximum and minimum of the magnet current. Two sample-and-hold circuits measure the current error at the maximum and minimum points. Thus, this measuring system works in a way similar to a synchronous detector, but it has a different d-c gain. In fact, if the error signal is a non-biased sinusoid with amplitude $\hat{I}$ and the same frequency and phase of the carrier signal s(t), the difference between maximum and minimum sample-and-hold outputs will yield a d-c component of amplitude $2\hat{I}$. Under similar conditions, the output of a linear phase detector would be $\hat{I}/2$. The addition of the maximum and minimum sample-and-hold outputs is proportional to the error signal bias and is used to drive the dc regulator. The dynamic behavior of the feedforward compensation and the feedback regulation is shown in the simulation results of Figures 8 and 9.

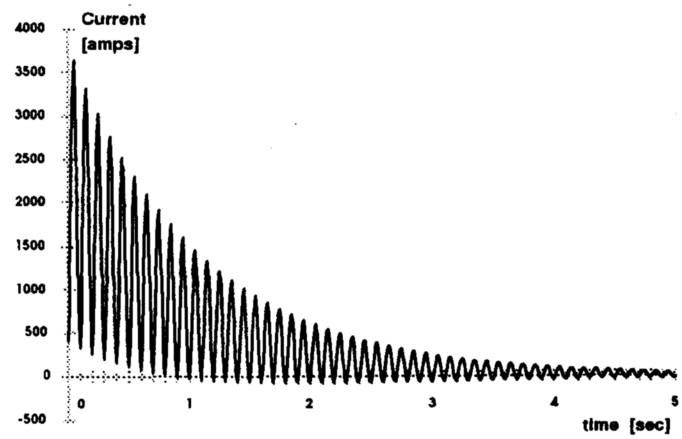

Figure 8. Difference between reference and magnet current by using feedforward compensator.

The time-domain response of the feedforward compensator is shown in Figure 8. At the time origin, the feedforward compensator is connected, while the feedback and the synchronous regulator remain disconnected. The reference current waveform is as shown in Figure 2. The figure shows that if a good model of the plant is available, due to the action of the feedforward compensator, the current error goes to zero in a few seconds.

Due to changes in the load, specially in the resonant capacitors, a good model of the load is not always available. In the following simulation the feedforward compensator output has a 10% error in the dc value as well as in the sinewave amplitude. The feedback regulator has a fast response (20-Hz bandwidth) and reduces the residual dc and ac current errors by a factor of 30.

In the first part of Figure 9, a 10%-error feedforward compensator and the feedback regulator are in steady-state. At a time of 1 s, the ac/dc synchronous regulator is connected. The figure shows that the residual current error goes to zero with a constant time, for both ac/dc components, of about 0.25 s, corresponding to a bandwidth of 0.6 Hz.

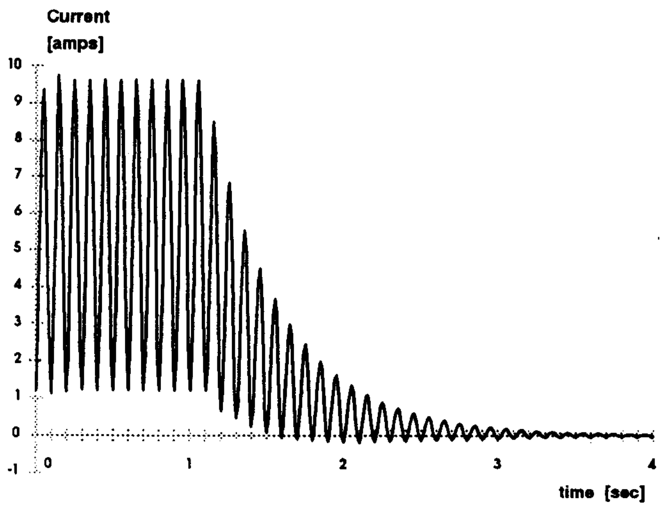

Figure 9. Difference between reference and magnet current by using feedback synchronous regulator.

V. CONCLUSIONS

The analysis and design of the digital voltage regulation for the entire ring-magnet power supply as well as the current regulation system for biased sinewave current mode of LEB have been presented.

Conventional feedforward and feedback techniques are not enough to maintain the magnet current within the required tolerance. A synchronous feedback regulator based on the periodicity of the current waveform has been used to improve the current regulation performance. The current regulation design has been corroborated by computer simulations. The prototype of the described digital current regulator is still under development.

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