Conf-810314--180

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PHASE LOCK OF RAPID CYCLING SYNCHROTRON AND NEUTRON CHOPPERS*

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Summary

The 500-MeV synchrotron of Argonne's Intense Pulsed Neutron Source operates at 30 Hz. Its beam spill must be locked to neutron choppers with a precision of ± 0.5 μs. A chopper and an accelerator have large and different inertias. This makes synchronization by phase lock to the 60-Hz power line extremely difficult. We solved the phasing problem by running both the Ring Magnet Power Supply (RMPS) of the synchrotron and the chopper motors from a common oscillator that is stable to 1 ppm and by controlling five quantities of the RMPS. The quantities controlled by feedback loops are dc current, injection current, ejection current, resonant frequency, and the phase shift between the synchrotron peak field and the chopper window.

Introduction

At Argonne National Laboratory a Rapid Cycling Synchrotron (RCS) accelerates protons from 50 to 500 MeV at a 30 Hz repetition rate. An economical way to energize the ring magnets of the RCS is with a series resonant network where the RMPS compensates for circuit losses.[1] Figure 1 is a block diagram of the RMPS and its waveforms. The RCS has single-turn extraction. The extracted beam hits a target which serves as an Intense Pulsed Neutron Source (IPNS) providing up to 7 x 10^{14} neutrons per pulse at energies ranging from 25 x 10^{-3} eV to 100 eV. In the neutron's flight path, is a chopper comprised of a rotating cylinder with a slot that allows selected neutrons to bombard a sample under investigation. Figure 2 illustrates such an experiment. Multiple experiments may use choppers with different slot sizes and rotational speeds (apertures), to accommodate several bands of neutron velocities simultaneously.

To insure proper beam extraction, the RCS and the chopper passing the smallest band of neutron velocities must be phase locked. Synchronizing to the 60 Hz power line, which energizes the 30 Hz RMPS, appears a possibility. However, because of load changes, the magnitude and frequency of the line fluctuates. The large inertias of the RCS and choppers and their time constants are different. They, therefore, react differently to power line fluctuations making synchronization with the power line impractical if not impossible. One can avoid these problems by using a common stable oscillator for synchronization. The large inertias of the RCS and choppers now aid phase lock. Speed variations of the feedback controlled choppers are negligible. The RCS is less stable. Due to temperature changes the phase shift between the RMPS voltage (phase locked to the chopper) and the field of the magnets (which holds the accelerating particles in a fixed orbit) changes as the ring magnet circuit detunes. Detuning of the circuit can be corrected by changing either the choke inductance L_{CH} or the capacitance C shown in Fig. 1. A feedback loop controlling a dc bias winding of the choke could provide continuous phase correction. However, we chose a feedback loop to the capacitor bank, providing phase correction in small steps, because high voltage contactors and capacitors were available from surplus.

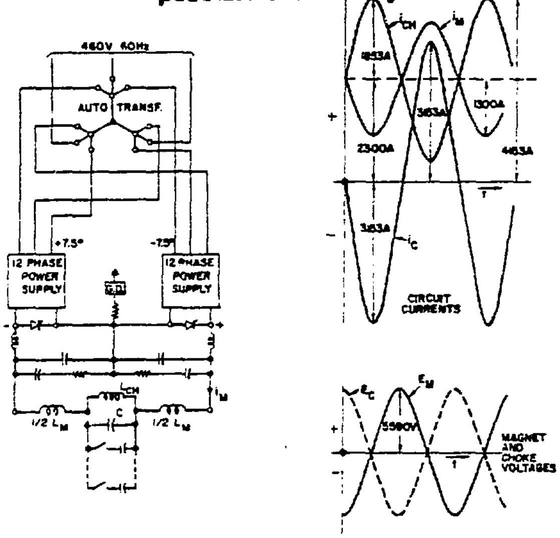

Fig. 1 Ring magnet power supply and waveforms of resonant circuit.

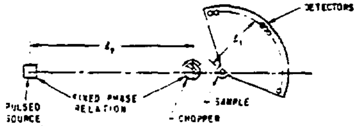

Fig. 2 Experiment using a chopper at the IPNS.

With the RCS and chopper phase locked, the beam spill can be synchronized to occur when the chopper has the correct azimuthal position.

RCS and Chopper Phase Lock Circuit

A block diagram of the RCS chopper phase lock circuit is shown in Fig. 3. It is not necessary for successful IPNS operation to have a perfect phase lock between the choppers and the RCS field. As indicated in Fig. 3, beam can be extracted during time Δt at the crest of the sinusoidal B field. Tolerable limits for phase shift between a 1 μs chopper and the peak field of the RCS and the septum extraction magnet were measured. Little difference in extraction efficiency was observed within ± 250 μs of the crest of the 30 Hz RCS field and within ± 60 μs of the crest of the 278 Hz field of the septum magnet.

The time interval Δt during which the crest value of a sine wave of duration T stays within ΔP of its peak value P is:

$$\Delta T = T\left[0.5 - \frac{\sin^{-1}\left(1 - \frac{\Delta P}{P}\right)}{180^{0}}\right] \qquad (1)$$

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*Work supported by the U.S. Department of Energy.

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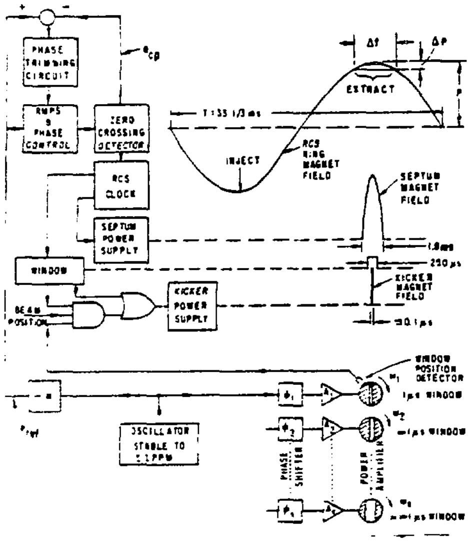


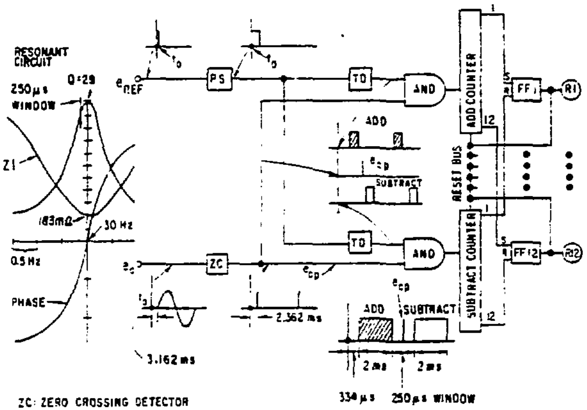
Fig. 3 Phase lock of RCS to choppers.

For the RCS with $\Delta t = 500$ µs and for the septum magnet with $\Delta t = 120$ µs, the field fluctuations are $\Delta P = 0.111\%$ and $\Delta P = 0.548\%$ respectively. Our design phase locks the RCS to within ± 125 µs ($\Delta t = 250$ µs) and the most critical chopper to within ± 0.5 µs to the stable oscillator. The circuit shown in Fig. 3 operates as follows.

- A 3.932 MHz oscillator, stable to ± 1 ppm, is the timing reference common to the RCS-RMPS and the choppers.
- The azimuthal position of the different choppers is adjusted with individual phase shifters ($Ø_1$.. ....$Ø_n$) relative to the chopper with the smallest aperture (≈1 µs).
- A feedback loop to each chopper drive keeps the azimuthal position of the choppers phase locked.
- The RMPS is synchronized to the oscillator by dividing the oscillator frequency to obtain 60 Hz synchronization pulses.
- The phase shift between the RCS field and the RMPS voltage is kept within limits compatible with chopper operation by adding or subtracting trimming capacitors.
- The RCS-clock triggers the extraction septum pulse, thereby aligning the peak of the septum field with the crest of the RCS field. The clock also triggers a 250 µs extraction window.
- A pulse from the smallest aperture chopper initiates beam extraction via the RCS extraction kicker magnet. It kicks the proton beam from its acceleration orbit into the septum extraction magnet. If the kicker pulse does not occur during the 250 µs extraction window, the trailing edge of the window pulse triggers extraction. In this case the neutron beam hits the body of the chopper and is lost.

RCS Phase Trimming Circuit

The phase trimming circuit makes corrections in steps by adding or subtracting capacitors to the ring magnet circuit. The capacitor bank of approximately 3000 µF has trimming capacitors of 0.79 µF, 1.58 µF, 3.17 µF, 4.75 µF, 9.5 µF, and 19 µF. The average rate of trimming is 0.017 µF/ms with the circuit of Fig. 4 which operates in the following sequence.



ZC: ZERO CROSSING DETECTOR
TD: DELAY CIRCUIT
FF: FLIP FLOP
R : RELAY
PS: PULSE STRETCHER

Fig. 4 RCS phase trimming circuit.

1. Of the two input pulses shown in Fig. 3, the reference pulse e_{ref}, occurring at time t_0, is stretched 2 ms and the zero crossing of the capacitor voltage is detected generating pulse e_{cp}.
2. The 2 ms pulse e_{ref} goes through two time delays. One gives an add and the other a subtract pulse. These pulses are spaced by 250 µs to form a window which is delayed from t_0 by 2.334 ms; this window sets the operating point on the resonant curve.
3. The circuit is in standby if e_{cp} is within the 250 µs window.
4. If e_{cp} coincides with the add pulse, the add counter will count up one count. When the counter reaches hardwired flip flops (FF's) it will set them sequentially. The setting or resetting of an FF will reset both the add and subtract counters.
5. If pulse e_{cp} coincides with the subtract pulse, the subtract counter will count up one count. When the counter reaches hardwired FF's it will reset them sequentially.
6. When an FF is set, it picks up a relay that closes a contactor which in turn will add a trimming capacitor to the resonant circuit.
7. When an FF is reset it drops out a relay which will open a contactor subtracting a trimming capacitor.
8. The smallest capacitor value is always added or subtracted first. Therefore, the size of trimming capacitance increases as the number of counts increase.

As indicated on the resonant curve in Fig. 4, the network operates slightly detuned. We found, experimentally, that operation was more stable if we located the 250 μs window on the capacitive side of the resonant curve; it is not necessary to operate at resonance as long as the power supply can drive the desired magnet current.

The RCS Power Supply Regulator

The magnet current shown in Fig. 1 must be repeated within ± 0.02%. This is accomplished with the regulator shown in Fig. 5. It consists of a fast acting voltage loop controlled by the sum of two current loops.

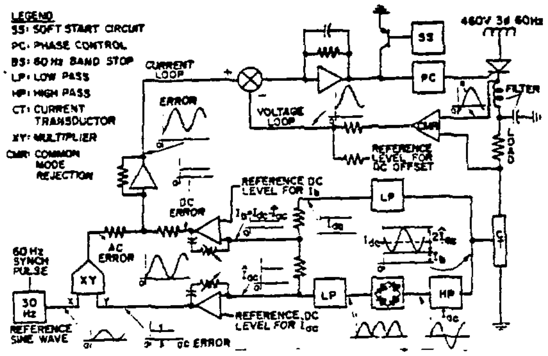


Fig. 5 RMPS regulator.

Beam is injected into the synchrotron when the current is at its minimum and ejected 16.66 ms later when the current is at its maximum. Therefore, the regulator was designed to maintain the minimum current of I_b = 1000 A and the ac peak-to-peak current of $2\hat{I}_{ac}$ = 2600 A. These current settings are independently adjustable and compared with dc reference levels regulated to 0.005%.

DC Reference Voltages -- There are three precision dc reference voltage sources. Two provide -10 V dc for two 14-bit digital-to-analog converters which serve as reference dc levels for two current error amplifiers. A third provides ± 10 dc for a 30 Hz sine wave generator. Stability of these reference voltages is 0.001%/°C.

AC Reference Voltage -- A precision 30 Hz reference voltage, $e = 10\ V\ (1 - \cos \omega t)$, which is stable within 0.001%, is generated[2] and synchronized with the chopper oscillator.

Voltage Loop -- The voltage loop provides fast correction for line transients. Operation with grounded controls requires a high common mode rejection (CMR) circuit. An operational amplifier provides both null adjustments and CMR. The voltage feedback loop requires 0-10 V for a -200 V to +400 V output adjustments of the RMPS.

The RMPS high current, low-pass (LP) filter[3] is designed to resonate at 137 Hz, with a ratio of $m = C_1/C_2 = 0.5$. The phase shift of the filter at 30 Hz is only -2°. The distortion of the filter output voltage has no noticeable effect on the magnet current because the Q of the 30 Hz resonant network is ≈29.

Current Loop for $\hat{I}_{ac}$ -- The magnet and the RMPS current are the same. It is measured with a precision coaxial shunt[4] with a repeatability of ± 0.002%.

As shown in Fig. 5, an active high-pass (HP) filter removes the dc component from the shunt signal. The remaining sine wave is fed into an ac-to-dc converter comprising a precision, active, full-wave rectifier and an active LP. The dc level equivalent to $\hat{I}_{ac}$ is compared with a precision reference voltage. The error signal controls the output of a multiplier into which a 30 Hz reference signal is fed. The output of the multiplier is a 30 Hz signal proportional to the ac error.

Current Loop for I_b -- By filtering the shunt signal with an active LP, a dc signal proportional to the average magnet current I_{dc} is obtained. By subtracting from it the dc signal proportional to $\hat{I}_{ac}$, we obtain a signal proportional to the minimum value I_b of the magnet current. This signal is compared with a precision reference voltage resulting in a dc error signal.

The current error signals for $\hat{I}_{ac}$ and I_b are summed and used as reference for the voltage feedback loop. The current loops lagging corner frequencies are matched by adjusting the time constant of the feedback circuits around their error amplifiers.

All regulator components are in a temperature-controlled oven providing system regulation and stability better than ± 0.005% in an ambient temperature range from 15°C to 55°C. A Bode diagram of the regulator is shown in Fig. 6.

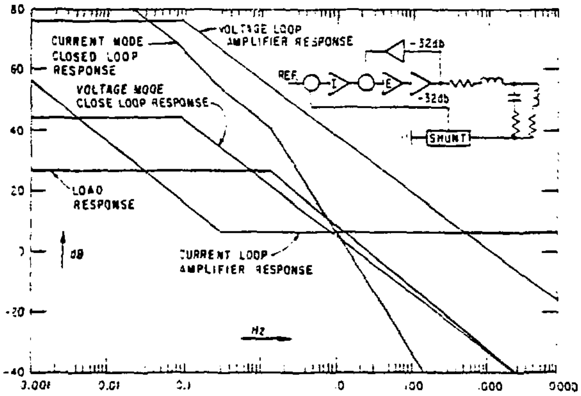


Fig. 6 Bode diagram of regulator.

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