HALL EFFECT MAGNETIC REGULATION SYSTEMS for the CESR INJECTOR*

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Abstract

Two distinct Hall regulation systems have been designed for reduction of hysteresis effects in the linac and transfer line magnets used for injection into the Cornell Electron Storage Ring (CESR) synchrotron. One magnetic field probe described integrates a precision Hall sensor element with low-drift preamplification electronics in a temperature regulated remote sensing module. Magnetic field stability better than 5 parts in 10^4 is achieved by a prototype system which includes this module and its associated signal processing electronics. A second Hall effect regulator design utilizes an inexpensive monolithic linear sensor/amplifier device to attain a minimum repeatable accuracy of 0.5%. Radiation and mechanical stress sensitivity of the Hall sensors employed is evaluated to estimate their operational viability in the injector environment.

Introduction

Installation of the CLEO II detector at Cornell has created a one year "window of opportunity" for completion of several upgrade programs for improved injection efficiency into the CESR storage ring. Revisions include substantial changes in the linac and injection line optics and the addition of a distributed, precision, injector beam monitoring capability[1]. This paper addresses considerations for cost-effective injection line quadrupole and dipole Hall field stabilization subsystems.

In CESR, the field setpoint accuracy of such devices is significantly limited by the cycle-dependent hysteresis offset found in common grain-oriented transformer steels[2]. Field stability and repeatability through the injection line analyzer dipoles is an important consideration with respect to injection efficiency. Here, the field integral must meet a relative setpoint and stability specification of better than 8 parts in 10^4 for consistent injector performance. In contrast, evaluation of expected hysteresis-induced error in the dipoles indicates a variation of 4.6 parts in 10^3 for common 1020 silicon steel. Low hysteresis steel alloys, such as type 1040, have been investigated and found to be too costly for large core assemblies. Our alternative remedy implements inexpensive Hall-effect sensor technology for direct stabilization on field.

Previous experience at Cornell with installation of commercially available Hall probe readouts shows field stabilization of about 0.1% to be feasible over a limited temperature range using uncompensated probes. Temperature stabilized sensors are required to meet a more stringent long-term accuracy specification. Unfortunately, commercial devices of the temperature compensated type are far too costly for general application in the CESR injector. To attain our stability specification, we have instead designed a proprietary temperature stabilized Hall-effect probe utilizing a commercially available discrete InAs Hall sensor. A prototype module has been constructed which easily meets the repeatability and long-term accuracy requirements of our injector application. Consequently, the injector rebuild program will implement several relatively inexpensive, precision, Hall magnetic regulation systems designed around this probe assembly.

In quadrupole elements, the hysteresis associated with type 1020 steel could contribute an error on the order of 1.5% at the maximum specified gradient of $3T/m^3$. While focusing errors of this magnitude do not represent an insurmountable problem in situations where element settings do not vary appreciably, the hysteresis error becomes onerous when element parameters are adjusted over a large range, then returned to previous levels. To address this problem, we have developed a field monitor using an inexpensive active monolithic silicon Hall-effect device of better than 0.5% relative accuracy. The device is procured in chip form and wire-bonded to a fiberglas substrate which also carries the necessary external surface-mount trim components. This construction technique results in a hybrid-like integrated probe assembly of small dimensions suitable for placement within the quadrupoles.

HPHR Dipole Magnet Hall Regulation System

Overview

A preliminary High Precision Hall Regulation (HPHR) system for the transfer/injection line dipole analyzer magnets is outlined in Figure 1. Local regulation systems associated with each of the three bending magnets consist of a Hall sensor assembly located within the magnet's good field region, a field signal processing sub-system and a series pass trim regulator shunting the magnet coils. The three injector dipoles are powered in series. Because current through each of the bending magnet coils is controlled by its local Hall sense loop, precise regulation of the primary supply is unnecessary. Regulation characteristics of the overall system are defined by a slow (<10 Hz) loop which includes the Hall sensor module and signal processor, and a faster (~2 KHz) AC feedback loop within the shunt regulator subsystem.

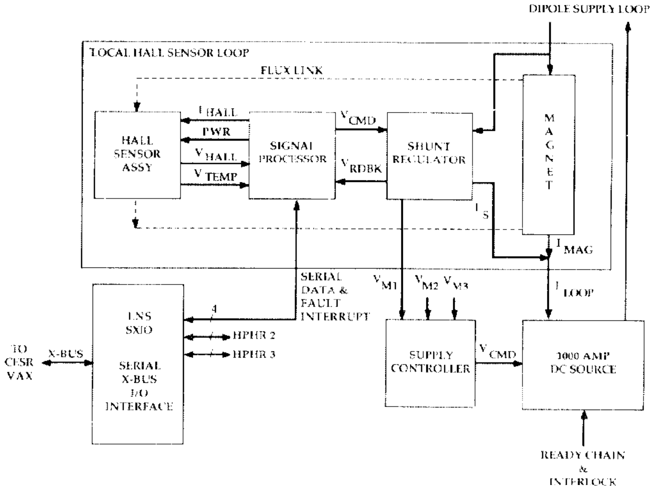

Fig.1 HPHR system block diagram.

Hall Sensor Module

Attainment of specifications set for the HPHR system is fundamentally limited by performance achieved at the Hall probe module. Performance of the module is, in turn, related to selection of a suitable Hall element. Specific parameters to be considered in selection of a Hall element must include sensitivity, temperature coefficient, linearity and expense. All vary with the type of semiconductor material employed in the sensor. Field sensitivity vs temperature coefficient is the important trade-off consideration for materials commonly used in Hall devices. Non-linearity due to magnetoresistive effects in the bulk semiconductor is also an obstacle to achieving high absolute accuracy[3,4]. Typical linearity error bounds for common semiconductor materials range from 0.25 to 1.0% of reading. In the HPHR system, however, any residual non-linearity error of one percent or less is negligible since only good repeatability is required of the regulation system.

It is assumed here that the reader is familiar with the Hall effect principle[3]. For reference, the salient properties of semiconductor materials most commonly employed in Hall sensor construction are summarized in Table 1.

Although InSb exhibits the highest known electron mobility and Hall coefficient of available semiconductor materials, its temperature coefficient is approximately 0.25 % per °C, which is undesirably high for the HPHR regulation system. Indium arsenide, with somewhat lower sensitivity, exhibits a temperature coefficient of only .05% per °C. A sensor fabricated from this material meets the HPHR system accuracy criterion, if operated in a thermally stabilized mount. Overall non-linearity of an InAs sensor is typically less than 0.5% through a

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range of ±1.0 T when driving the optimum load resistance as specified by the manufacturer.

Semi-conductor Material	Energy Gap eV	Hall Mobility, e$^-$ cm^2/V-sec
Ge	0.785	4.5×10^3
Si	1.210	1.3×10^3
InSb	0.250	80×10^3
InAs	0.450	30×10^3

Table 1. Comparison of Hall-effect Sensor Materials[5]

A review of available manufacturers' literature reveals several vendors[6,7,8] for low-to-moderate cost InAs Hall sensors. For the HPHR system we have selected Ohio Semitronics' HR-125A, a device of 100 mV/T sensitivity at I_H = 100 mA. Dimensions of the encapsulated device are 6.35 x 5.08 x 0.71 mm.

Electrical design of the Hall sensor module incorporating the HR-125A device is shown in the block diagram of Figure 2. Outside dimensions of the assembled module in Figure 3 are 72 x 77 x 18 mm, including a partial enclosure. This outline fits snugly in the inner gap of an injection line dipole. The Hall sensor itself is located as close as possible to one corner of the module, and is eventually positioned within one centimeter of the magnet vacuum chamber. Here, the field is essentially equivalent to that along the beamline within the magnet. Preamplification is provided within the probe to assure a reasonable S/N ratio, and to implement a convenient calibration scheme for compensating the relatively wide variation in Hall plate sensitivity. A notable feature of the preamplifier is inclusion of a commutating, auto-zeroing (CAZ) monolithic instrumentation amplifier[9] Use of the CAZ device facilitates low noise, extremely low offset front end amplification of the induced Hall potential. Over the preamplifier's bandwidth of approximately 10 Hz the combined maximum offset and long term drift of the CAZ stage is typically less than 10 µV, corresponding to approximately one Gauss. Setup calibration of the preamplifier to a nominal scale factor of 10.00 volt/T is effected by an on-board adjustment trimpot. A provision for vernier calibration of the probe scale factor by slight adjustment of the Hall plate excitation current is available at the remote signal processor panel. Temperature stability of the sensor mount to ±0.2°C is maintained by an on-board servo utilizing an active monolithic sensor and power MOSFET heat source. Readback of sensor mount temperature is provided at the signal processor.

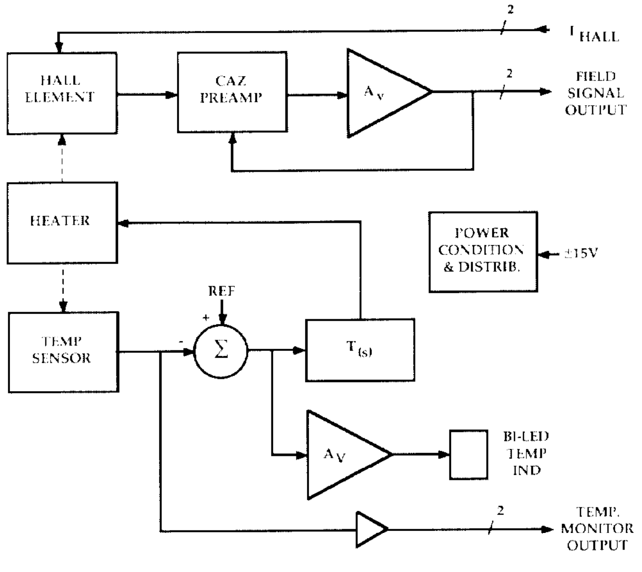

Fig.2 HPHR probe module.

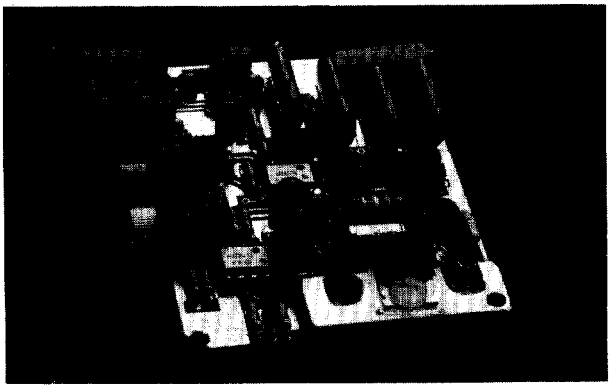

Fig.3 HPHR probe module assembly.

Processor

As the central control subsystem of the regulator, the signal processor conditions an input signal corresponding to the field level seen in the magnet, compares it to a precision reference and outputs an appropriate error-derived command signal to the active shunt regulator. An 18 bit DAC insures setpoint reference repeatability to one part in 2^{-17} over the expected operating temperature range. Field reference magnitude is downloaded to the DAC register from the CESR host CPU and is truncated to a 16 bit word length for convenience. Twelve bit resolution is actually sufficient for the HPHR system, if repeatability of 2^{-16} or better is preserved. All CESR control system I/O is transmitted to and from the unit via a bidirectional serial data link at 3.25 Mb/s. A proprietary SRIO transceiver module with appropriate plug-in interface cards is located in the chassis of the HPHR signal processor.

Shunt Regulator

Control of the dipole magnet field is effected by a shunt regulator scheme which avoids the usual auxiliary trim winding. Series pass elements in the regulator are driven by a servo loop which compares the input command voltage to current diverted through the pass elements and shunt. Local AC feedback is included to attenuate ripple at the magnet by approximately 18 dB. Detection and limiting of overcurrent, overvoltage or operation beyond safe-operating-area limits has been included in the design. The output devices are contained within a single power hybrid[10] of 140 ampere continuous current rating mounted on a water-cooled heatsink assembly. Additional hybrids may be parallel-connected for greater current capacity. Excluding the front panel, overall shunt regulator chassis dimensions are 13 x 35 x 43 cm.

Performance

Figure 4 presents preliminary data collected using the prototype Hall probe module in a standard field permanent magnet fixture. Recovery from a step offset simulating a 5° C thermal transient is shown. Baseline fluctuations seen are ascribed equally to electronic noise and minute thermal variations. Data taken during this run demonstrate the HPHR probe's stability performance to be approximately 300 ppm. The plot indicates a temperature coefficient of 510 ppm/°C, which closely approximates the expected value.

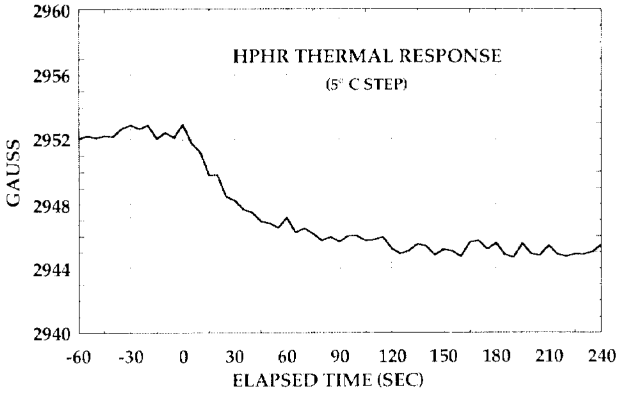

Fig.4 HPHR stability/thermal response data.

MPHR Quadrupole Magnet Regulation System

Overview

Quadrupole magnetic field regulation is useful if economically justifiable. With this constraint in mind, several inexpensive active silicon Hall sensors were reviewed. A suitable chip was selected, and is the basis of the Hall stabilization system design of Figure 5 presently under evaluation. As in the HPHR system, a Hall probe is installed in the subject magnet and the field-dependent output signal is processed by a servo loop. In the MPHR system, the servo control card outputs a quadrupole power driver command signal.

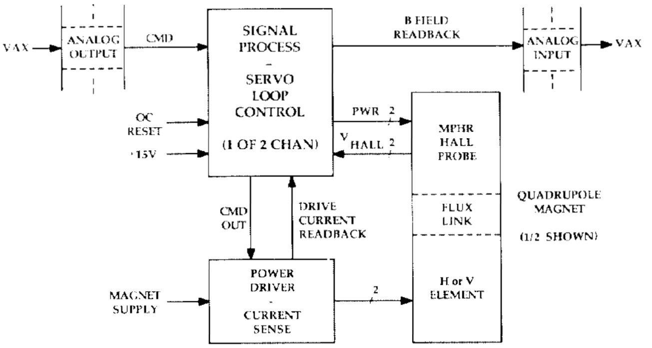

Fig.5 MPHR system block diagram.

MPHR Probe and Controller

Several inexpensive silicon monolithic Hall sensor I.C.types were evaluated for injector quadrupole installation. On the basis of linearity and stability measurements, we selected the UGN-3501-LI/XP-3008[11]. Its temperature coefficient is approximately -0.08% per °C (with the trim components chosen) and is therefore adequate for field regulation at the percent level for temperature excursions of ±5 °C. This device is unique among silicon active sensors in that it is capable of relatively linear (≈0.5%) operation to 0.35 T. The integrated circuit consists of paralleled orthogonal sensors followed by a differential amplifier stage and output buffers. Its balanced outputs provide adequate drive for twisted pair interconnects up to 75 m in length. For the MPHR application, a UGN/XP chip is directly bonded to a small pc board (chip-on-board technique), with remaining surface-mount discretes added at a later production step. Dimensions of the complete probe assembly, without the cable connector or trimpot profiles, are 6.1 x 10.2 x 2.6 mm (Figure 6). Its assembled materials cost is around $15.

Fig.6 MPHR probe assembly. The silicon linear Hall sensor chip is mounted on pcb underside.

In Situ Considerations

Radiation

When installed, both types of Hall sensors will be potentially subject to large high-energy (> 0.8 MeV) neutron fluxes. Therefore, a measurement series was undertaken to determine critical dosages affecting sensor performance. Suceptibility testing of discrete InAs sensors was conducted at Cornell's Ward Laboratory, using the laboratory's TRIGA reactor test chamber as a source of known >1 MeV neutron flux. Results of the exposure studies are tabulated in Table 2.

InAs threshold effects are seen in the 10^{13} n/cm^2 exposure regime. This is roughly an order of magnitude higher than the fast neutron sensitivity threshold for minority carrier devices. A liberal estimate for neutron flux in areas of the linac and injector away from the positron converter is on the order of 10^{10} n/cm^2/day. In those locations, active devices in the Hall sensor module will exhibit a worst-case useful lifetime of 3 years. We have determined a six month calibration schedule for HPHR modules will suffice to correct any minor offsets induced by neutron flux during the system's useful lifetime in CESR.

It is expected that the minority-carrier active devices on the silicon MPHR chip will similarly define its lifetime with respect to neutron induced damage. Therefore, the useful lifetime of MPHR probes in most sections of the CESR injector will be similar to that of the HPHR probes, except in linac quadrupole elements near the positron converter. Borated shielding will be investigated as a solution to the higher flux anticipated in those locations.

HR-125A	**Normalized V_H @ dosage level in n/cm^2**		
#	**6.97 x 10^{13}**	**6.28 x 10^{14}**	**3.23 x 10^{15}**
1	0.952	0.653	0.179
2	0.960	0.694	0.205
3	0.981	0.716	0.215

Table 2. Fast Neutron Damage in InAs Hall Sensor.

Mechanical Sensitivity

The HPHR InAs device is assembled on a rigid ceramic substrate and does not exhibit a measurable offset when subjected to mechanical stress. However, silicon sensors such as the device used in the MPHR probe design can exhibit a high degree of piezoelectric activity. Tests performed on the completed MPHR "chip-on-board" assembly demonstrate the offset induced with moderate flexure is on the order of only 0.1%, probably due to the rigid epoxy "glob" covering the COB die and bonds. Mechanically induced offsets resulting from installation of these probes will represent a negligible error source for the MPHR systems.

Conclusion

Two inexpensive Hall-effect magnetic regulation systems for installation in CESR injector analyzer and focussing elements have been described. Performance of a high resolution HPHR system at 5 parts in 10^{-4} is seen to be adequate for field stabilization in the injection line analyzer magnets. An inexpensive "hybrid" MPHR Hall probe based system demonstrates relative stabilization to 0.5%, a factor of three improvement with respect to constant current drivers presently in service. Radiation sensitivity of the InAs Hall sensor elements has been evaluated and the parametric threshold is seen to be at least an order of magnitude above that of minority-carrier solid-state devices. We conclude the service lifetime of either Hall probe type will be at least 3 years in the CESR injector, given an average neutron exposure rate not exceeding 10^{10} n/cm^2/sec.

Acknowledgement

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