© 1987 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers

or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

HARMONIC-ERROR-ANALYSIS MEASUREMENTS OF DIPOLE AND QUADRUPOLE MAGNETS AT LAWRENCE BERKELEY LABORATORY*

M. I. Green, P. J. Barale, D. H. Nelson, and D. A. Van Dyke Lawrence Berkeley Laboratory, University of California, Berkeley, California 9472^

Abstract

Error harmonics are detected using slowly rotating search-coil arrays feeding a digital integrator. The fundamental signal is detected during the first rota-The search-coil arrays are reconfigured tional cycle. to "buck" the fundamental and lower harmonics during the second rotational cycle, allowing the measurement of higher harmonics with excellent resolution. Data are first drift corrected, then harmonic analyzed using the fast Fourier transform technique. The measurements, data processing, and generation of both tabular and graphic output require about 80 seconds. Data are later postprocessed using spreadsheets allowing easy manipulation and comparison of measurements during a test series and between magnets. Hardware and software will be described. Accuracy. precision, and resolution will be discussed, and the measurement technique for Superconducting Super Collider (SSC) model magnets will be described.

Introduction and Overview

At the Lawrence Berkeley Laboratory (LBL) harmonic-error analysis of accelerator beam-line magnets is used to predict the behavior of particle beams and to screen substandard magnets (and sometimes facilitate corrective action.) Our measurements are routinely used as diagnostics in the development of Superconducting Super Collider (SSC) model dipoles¹ and will be used to diagnose SSC model guadrupoles.

The quadrupole and dipole systems that we have developed are just two configurations of the LBL general-purpose magnetic measurements Data Acquisition System (DAS). The DAS is also used for field mapping, 2 permeability measurements, 3 and wiggler magnet tuning.

Both the dipole and quadrupole systems generate, in "real time" (approximately 80 seconds), magnet test and performance parameters. The test parameters include: date and time of run, magnet identification, searchcoil identification and configuration, test-series and run descriptions, the operator's name, shunt resistances, data-set identification, initial, final, and average currents, period of revolution, and voltage-tofrequency converter range. All of the preceding, plus raw up-down counter outputs, are saved in a binary file on a hard disk. The signal strength for each harmonic is printed as a quide to the significance of the data. Magnet performance parameters that are generated in real time include field strength, transfer function, and the magnitude and phase of each harmonic relative to the fundamental. In addition, the dipole system prints out normal and skewed harmonics relative to the dipole. Magnet performance parameters are not saved, since they can be derived from the saved test parameters. Upon completion of measurements, the data on hard disk are transferred to floppy disks for archiving.

Dipole Program Major Options

The operator is allowed the choice of two searchcoil arrays, each consisting of three search-coil pairs. In response to options selected by the operator, coils may be connected to measure the central 10-cm length of the dipole, either end, or the full length of the magnet. The operator may also specify whether the search coil is cryogenic, in which case the dipole program incorporates a shrinkage factor into the calculation of the sensitivity array for the search coil.

The dipole system can be set up to run in an automatic mode in which the run options are accessed from a file and the measurement cycle repeats after a specified delay between data sets.

Quadrupole Program Major Options

From a menu displayed by the quadrupole program, the operator indicates one of eleven search-coil arrays. The quadrupole program has six power-supply options: 1) no power supply for permanent-magnet quads, 2) operator manually sets and enters current, 3) operator sets current and enters current shunt potential, 4) operator sets current but computer monitors shunt potential, 5) automatic sequencing of power-supply current with monitoring of both shunt and quadrupole magnet potentials, and 6) the same as 5) except that the magnet power supply is turned off while the search coil is rotating backwards. For options 5 and 6, the operator can program magnet conditioning cycles and specify up to 30 currents for sequential measurements of strength and harmonics.

Measurement Cycle Description

The changing flux linkage between a slowly rotating search coil array and a stationary magnetic field generates electrical potentials. A low-noise search-coil switching module (SCSM),⁵ inputs selected search-coil-potential combinations to a bipolar voltage-to-frequency converter (V/f), 6 which feeds an up-down counter. This combination of a V/f and up-down counter forms a digital integrator. Pulses from an incremental optical encoder mounted on the shaft of the rotating search coil latch the contents of the up-down counter into a buffer and also produce a CAMAC "LAM" interrupt that informs the computer that it should read the buffer. We sample the up-down counter buffer 129 times for each 360degree forward revolution, and then the search coil rotates backwards in preparation for another cycle. The first and last samples are at the same azimuthal coil position and are used to "drift correct" the raw data, providing 128 data points for fast Fourier analysis. During the first forward rotational cycle the strength of the fundamental is determined. On the second forward rotational cycle, the output of pairs of search coils are connected in series opposition. The coils are designed so that when connected in series opposition they have good sensitivity for the higher harmonics yet the fundamental signal is dramatically reduced (bucked out). This allows highresolution measurement of the harmonics. Following both forward cycles, as the search coil is rotating backwards, the raw data are saved on a hard disk, drift corrected, plotted, Fourier analyzed, and converted to physical quantities that are printed and

^{*}This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

plotted. For each harmonic number we print the signal magnitude and phase of the harmonic relative to the fundamental. The dipole system also prints the relative skewed and normal harmonics. We plot the unbucked and bucked raw data versus azimuthal position and produce a semilog bar graph of the magnitude of the harmonics relative to the fundamental magnitude.

Hardware

Figure 1, is a block diagram of our hardware. A DEC LSI-11/73 microprocessor is interfaced to the rest our equipment by means of the DEC Q-BUS. On the Q-BUS are 4 Mbytes of ram, CAMAC and GPIB interfaces, a clock calendar, a 10-Mbyte RLO2 hard Disk, a 40-Mbyte Winchester Hard disk that emulates 4 RLO2's, a DLV11ED connected to a modem attached to a phone line that allows us to communicate with other computers and/or operate the DAS remotely, and two DLVIIJ 4-line RS-232 interfaces. Connected to the DLVIIJ's are a laser printer/plotter, a LA-120 printer/terminal, an Epson dot-matrix printer, a Hewlett-Packard plotter, and several graphics terminals. NIM and GPIB modules are used for high-precision analog data acquisition. CAMAC modules are used mainly for digital I/O such as control and monitoring of motors, reading up-down counter modules, etc.

Software

We use the S & H Inc. TSX-Plus time-sharing operating system. This operating system is used on DEC PDP-11 and LSI-11 computers and operates "on top" of the DEC RT-11 operating system. This multiuser system allows simultaneous data acquisition, program development, and postprocessing of data. All application programs are written in Fortran 77. Commercial software packages include DEC Laboratory Subroutines, DEC Scientific Subroutines, Tektronix Plot 10, National Instruments GPIB library, Standard Engineering CAMAC library, S & H Inc. RTSORT, Columbia University Kermit, and Saturn Systems Inc. Spreadsheet/Graphics/Wordprocessing Office Automation Package. Short structured programs are written that are primarily only calls to subroutines or groups of short subroutines. Structured programming has significantly reduced the effort necessary to design, debug, maintain, and modify complex real-time data-acquisition systems.

Data Postprocessing

A resume file that briefly describes the important test parameters for each data set is first created. Next, files consisting of a subset of the most important test and performance parameters are assembled and transported from the DAS by modem and telephone to an IBM AT personal computer, loaded into a LOTUS spreadsheet, and used to generate SSC magnet "prompt reports." LOTUS macros are used to produce reports on magnet behavior during cooldowns to \sim 4.3 K, warmups, decays (measurements at a single current), current sweeps (measurements while ramping the magnet current up and down). and Z-scans (measurements taken with the center 10-cm search-coil pair at various axial positions along the dipole). The output produced includes a table of magnet data (dipole field, transfer function, major harmonic values) and a series of graphs.

Another postprocessing function uses a local (on the DAS) spreadsheet and graphics package (Saturn Calc and Saturn Graph). All test and performance parameters are available in two standard spreadsheets, one of magnet performance parameters and one of test parameters. The test-parameter spread sheet allows the scanning of data sets for problems such as high drift, unusual module configurations, etc. This system is used to examine particularly interesting real-time runs and to generate graphs and tables used in routine quadrupole-magnet and specialized dipole-magnet reports.

Performance

The SCSM-V/f combination provides 22 ranges covering seven decades from 100 μ V/MHz to 1000 V/MHz in a 1, 2, 5 sequence. The calibration accuracy is 0.1% on the 100- μ V range and improves to 0.01% on the 10-V range.



Figure 1. Block diagram of SSC model dipole system.



Figure 2. Harmonic analysis of noise from a stationary coil pair in "bucked" configuration.

The dimensions of the individual search coils are mechanically measured to + 0.001 inches, and their areas are magnetically calibrated at room temperature to better than 0.05%. Based upon the magnetic area measurements the coils are paired, resulting in a "dipole bucking ratio" of 500 or better.

At low currents the accuracy of the LBL system is limited by noise, which ranges from approximately 100 nanovolt-seconds for the n = 2 (quadrupole) term, to approximately 2 nanovolt-seconds for n = 19. Figure 2 is a plot of the noise signal vs harmonic number obtained by a stationary 10-cm center coil pair configured in the bucking mode. Average values are represented by the line.

The reproducibility of the dipole system at 20 A and room temperature is presented in Table 1. The deviations are greater for the central field values because of the small size of the coil (10 cm long) and the resulting small signals. At SSC operating currents, the reproducibility for the sextupole term is better than 0.01 units (1 unit = 10^{-4} of the fundamental magnitude).

Improvements

As time, personnel, and funds allow, the following expansions and/or improvements are planned: 1) complete the fabrication of a cryogenic quadrupole search-coil array and interface it to the existing dipole system, 2) replace the existing 16-bit, fast Fourier transform with a double-precision version, 3)

Table I. Standard Deviations of Main and Harmonic Fields for the LBL Measuring System (18 consecutive runs at 20 A).

Search	Transfer	Error Harmonics					
Coil	Function	C ₂	Ca	C ₄	C ₅	с ₆	C7
Configuration	(10 ⁻⁴ Tm/	A)	5	(10-	² Unit	s)	,
End 1	0.5	2.6	2.5	0.9	0.8	0.3	0.2
Central	2.8	33.2	16.2	9.9	5.2	4.9	1.5
End 2	1.0	1.5	1.4	0.5	0.4	0.2	0.3
Integral	1.9	1.8	1.9	1.8	0.4	0.3	0.2

Note: C_2 refers to the amplitude at the quadrupole field at l-cm radius.

automate the axial positioning of the magnet relative the search-coil array for making measurements of harmonic content as a function of axial position, and 4) expand the use of Saturn spreadsheet/graphics and consolidate the existing postprocessing code (to reduce the time for producing "prompt" reports).

Acknowledgments

We would like to thank Bill Gilbert, Bill Hassenzahl, and Clyde Taylor of the LBL Superconducting Group for their continuous advice and support. Klaus Halbach has been our theoretical consultant from the start. Others who have contributed to the development of our system include Les Callapp, Jim Greer, Sandy Goss, Ed Hartwig, Bill Hearn, Bob Main, Randy Michelson, Don Rondeau, Jack Tanabe, Lee Wagner, and Ron Yourd.

References

- 1. W.V. Hassenzahl, W.S. Gilbert, M.I. Green, and P.J. Barale, "Magnetic Field Measurements of Model SSC Dipole," Applied Superconductivity Conference, Baltimore, Maryland, Sept. 1986; to be published in IEEE Trans. Magnetics.
- 2. M.I. Green and D.H. Nelson, "The Lawrence Berkeley Laboratory General Purpose Magnetic Measurement Data Acquisition System," J. de Physique, Col. Cl, Suppl. No. 1, pp. 943-948, (1983).
- D.H. Nelson and M.I. Green, "88-Inch Cyclotron Mag-netic Deflector-Tests of Three-Steel Samples," LBL 3. Engineering Note MT 316 (LBID-537), April 1982.
- D.H. Nelson, M.I. Green, K. Halbach, and E.H. 4. Hoyer, "Magnetic Measurements for Tuning and Operating a Hybrid Wiggler," J. de Physique, Col. Cl, Suppl. No. 1, pp. 957-960 (1983).
- 5.
- SCSM LBL Engineering Drawing 16V1211 P-1 (1981). W.E. Hearn, M.I. Green, D.H. Nelson, and D.J. Rondeau, "A Precision Programmable Bipolar V/f Instrumentation Module," IEEE Trans. Nucl. Sci., Vol. NS-29, No. 1, pp. 578-581, February 1982.