AUTOMATED METHODS OF FIELD HARMONIC SIGNAL EXTRACTION AND PROCESSING FOR THE MAGNETS IN SUPERCONDUCTING SUPERCOLLIDER [*] [†]

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Abstract

A versatile field measurement system HAL2 was developed and used for SSC magnet measurements. The system based on V/F converter and 32 bit counters are set on a VME /modified VME bus. The system was capable of measuring the high ramp rate harmonics which was a vital issue especially for the construction of SSC High Energy Booster. System description and the implementation techniques for high ramp rate application is presented together with the measurement data in SSC dipole model magnet. The measurement up to $128A/s$ was successful. Anomaly in the eddy current quadrupole was clearly observed.

I. INTRODUCTION

Measurement of magnetic fields, generated by high field magnets such as in SSC, with high accuracy is very important to fully understand the design construction, installation and operations issues of machines in which these magnets will be used. Many techniques and instrumentation systems have been developed and are commonly used for magnetic field quality measurements. Measurement systems for SSC superconducting magnets were mostly developed and used by the laboratories involved in R&D efforts of magnet development. The description of the field in particle accelerator is made using a concept of harmonic components. Very accurate measurement of the field is done directly measuring the harmonic components. Such method of direct harmonic field measurement[1] in superconducting dipole magnets was found very efficient during the TEVATRON construction at Fermilab and became a standard method for superconducting accelerator magnets. The requirement and restriction of the measurement are different in every case. SSC dipole magnets are required to be measured in a small space of radius 1.6 cm. First priority of measurement was the precision up to 30 pole with DC field. However, the eddy current effect in the superconducting cable was found to be much larger and complicated than what was estimated in the design phase[4]. The field measurement at high ramp rates became important. Such change in measurement priority happens to superconducting magnet project because state of the art technologies are always under development. The versatility of the measurement system is thus an important feature for the measurement system. The system, named HAL2, described in this paper is the system used for SSC magnet R&D at Fermilab. This system allows to use various kinds of harmonic probes and measurement modes. Although the versatility of the system is capable of doing many other things, the emphasis is put on the high ramp rate measurement of the harmonic components in this report. We developed a technique of measuring harmonic components under high ramp rates of up to $128\ A/s$ using the HAL2 system as described here.

II. FIELD HARMONIC COMPONENTS

The magnetic field, in the long straight section of the magnet can be considered as two-dimensional and the harmonic coefficients can be defined by following equation:

$$B_y + iB_x = B_0 + \sum_{n=1}^{\infty}(B_n + iA_n)\left(\frac{x+iy}{r_0}\right)^n \qquad (1)$$

where B_0 is the dipole field strength, B_x and B_y are the x and y-components of the field, A_n and B_n are the skew and normal 2(n+1)-pole field coefficients respectively with r_0 as the reference radius chosen to be $1cm$ for SSC magnets. The x and y direction is chosen so that the skew dipole term (A_0) is zero for non-zero transport current, and the normal dipole term (B_0) is positive for positive transport current. The coefficients A_n and B_n are in units of Gauss evaluated at the reference radius r_0. It is customary to normalize A_n and B_n and suppress them by a factor of 10^{-4}. These normalized resulting multipole coefficients a_n and b_n are said to be in units. For a perfectly constructed dipole having both up-down and left-right symmetry, all the terms except b_n with even n are zero. Even b_n are minimized in magnet design but have some finite values. For n=odd, non-zero b_n and a_n are due to left-right and up-down asymmetries respectively. Non-zero a_n, n=even, are caused by rotational asymmetry. The mechanical size differences between the upper and lower coils can be responsible for up-down asymmetry. The manufacturing errors in a magnet can cause the asymmetries which can lead to “non-allowed” multipole coefficients. Similarly for a perfectly constructed quadrupole, the skew terms vanish and only the normal terms with $n = 4m+1 (m = 0, 1, 2, 3..)$ are the “allowed” components.

III. MEASUREMENT SYSTEM

HAL2 system was used to measure the field quality of SSC R&D dipole magnets in Lab2 of Fermilab[6]. The probe used in the field quality measurement is a rotating coil inside the bore of the magnet. Geometry of the coil is made so that the coil picks up the field deviation from the magnet center. There are several types of measurement coils. Multipole coil is used to pick up

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particular order of multipole. Radial coil is arranged in a radial plane so that it picks up the difference of the azimuthal component of the field at different radii. The one mostly used at LAB2 was a tangential coil. Tangential coil picks up the difference of the radial components of the field at different azimuth. The coil was made from formvared wire that were located onto the grooved surface of G-10 cylinders which has maximum rigidity in torsion and flexion. The induced voltages, due to the field, across the coil terminals are integrated and sampled over equally spaced angular intervals. Signal level from the multipole fields are smaller for slower rotation speed and to increase the signal level the coil has to be rotated faster. The HAL2 rotation speed is limited by the mechanical stability of the probe shaft system otherwise it can accept wide range of rotation speed. the nominal coil rotational speed was set at 6Hz. Commonly used measurement systems without integrators[3] are operated in slower rotation speeds not only to avoid the mechanical vibration but also to average out the noises. Slow rotation speed in such system limits the ability to measure high ramp rate harmonics, because the magnet current changes by many amperes during a rotation.

The coil cylinder is attached to G-10 shafts that are joined together by journals made with delrin . The twisted coil leads pass through this shaft. Bearings placed on the journals snugly fit into the inner wall of the warm bore tube when the assembly is lowered into it for measurements. The other end of the shaft was connected to a gear shaft which could travel vertically through the entire length of the magnet bore. A stepping motor controlled by a PC moved the probe assembly vertically. A rotational encoder module was placed in series with the probe gear shaft. The coil leads coming through the G-10 shaft are attached to slip rings or mercury wetted contacts. The slip rings or contacts transfer the coil signal from the coil wires to the signal processing system. A periodic noise introduced due to vibration across the silver coated graphite slip rings may distort the harmonic signals. However, the use of mercury wetted contacts minimizes these noise. The stepper motor, used for vertical motion of the probe, had to be completely stopped before taking data. This is necessary to avoid the effect of stray field from the motor which can affect the harmonics signal.

HAL2 has modular input channels with a gain/attenuator, a V/F converter and a scaler. Normally the system was operated with 6 channels but it can increase the number of modules easily. Required number of channels depend on the configuration of the pick-up coil and the pole number of the magnet. The gain/attenuator card converts the differential coil signal into a single ended signal with an amplitude gained/attenuated to match the range of the V/F converter. The adjustment of gain/attenuation is controlled on-line. The V/F board has a bipolar AD652 with 1 MHz(+5 volts) full range V/F converter tied to a 2 MHz quartz clock for timing signal. The TTL logic pulses from V/F converter were sent to 32 bit scalers which can integrate the signal without saturation even if the signal has a offset due to thermal emf and base V/F frequency. The scaler counts are stored as the measurement data triggered by the encoder pulses. One of the input channels is used as the dummy to subtract the base signal. External noises are also cut down by the dummy signal subtraction. In standard configuration the rotational encoder with 256 pulses per revolution determined when the data was to be sampled. Each data point represents an encoder angle of 1.4 degree. Other encoder pulses such as 180/rotation were also used when the availability of the memory size is limited. Modules are installed on a digital/analog bus (L2bus) and interfaced to VME bus through an Force Computer IPIO module based on 68000 CPU. The data acquisition system used a UNIX based real time Concurrent 6400 with a VME bus and a GPIB interface through which a HP3457A DVM read the magnet current. The Concurrent acts as a user interface for the data acquisition hardware. An ethernet link on the Concurrent provided connection to MicroVax for data transfer and off-line analysis. The use of L2bus is considered as a transient to the future entire use of VME bus. The analog lines of L2bus were physically separated from the digital bus and it used its own linear power supply. Presently the VME bus is too noisy for low level analog signals. Although there are noise problems, VME is a widely accepted standard bus and has possibilities to have commercial modules available without using L2-bus in the future. We think VXI is over for low frequency application and yet, not quite feasible to low level signals. The schematic diagram of the system is shown in Fig. 1.

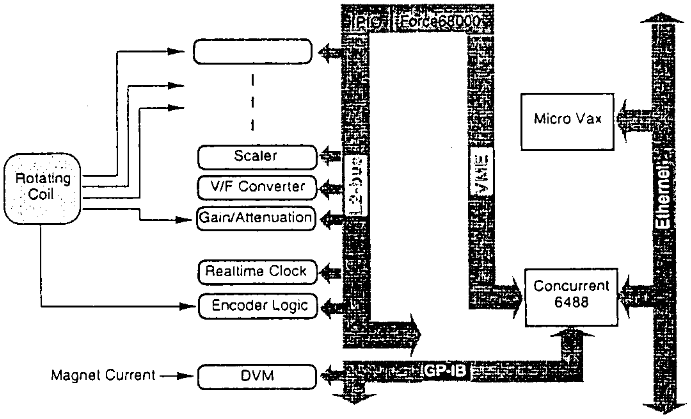

Figure. 1. System Schematic Diagram

IV. DATA PROCESSING

Since the field quality measurement is a relative measurement to the central field. The signal is always processed as the difference between the data at poriferal and the reference data at the center. It is intended to cancel the effects of mechanical noise and slip ring noise at the same time when the reference signal is subtracted. The reading of the scaler count of the V/F converter output as a function of angular encoder pulse gives the magnetic flux as a function of the rotation angle. The integration technique , in general, is immune to the effects of probe speed variations. The signals were normalized for geometric factors and amplifier gains.

Since the radial component of the n-pole field gives a sinusoidal signal of period $2\pi/n$, the Fourier components of the signal give the harmonic components of the field. To get harmonic coefficients a Fast Fourier Transform algorithm was used on the flux data collected. Since the function is periodic and the result is a Fourier series so the encoder having 2^N points per turn is simpler to use. Any noise, if uncorrelated, reduces with the square root of the number of points. When the encoder is not divided into suitable power of two increments, discrete Fourier transformation is used. Since physical location of the rotating coil can not be exactly at the magnetic center, there is always an off center of Δx and Δy. The measured harmonics have mixing among terms because of the off center. The true harmonics are: $b_n + i a_n = \sum_{k=n}^{\infty} \left(\begin{array}{c} k \\ n \end{array} \right) (b'_n + i a'_n)(\Delta x + i \Delta y)^{k-n} where,b'_n$ and a'_n are the components given by the Fourier analysis. Δx and Δy are determined to make unlikely poles such as 17 or 21 pole to be zero.

V. Fast Ramp Measurement

The HAL2 system with a $3.155\ cm$ diameter tangential coil was successfully used to measure harmonics at high ramp rates. The encoder pulse of 180/rotation are generated to trigger the measurement. In the standard configuration 180 data points are taken every rotation of the coil. The current measurement of the magnet is the average of 10 line cycles readout by HP3457A DVM. The measurement time is limited by the rate of data transfer. The data sampling rate was modified in the acquisition software to acquire faster ramp rate measurement. The data sampling frequency was cut down to 90 sample/rotation so that 57 points of data could be stored and analyzed at every rotation. In this measurement method, 57 data points at the rate of 6Hz were taken for 9.5 second with an interval of 5 seconds to repeat the burst. Simple software modifications allowed us to measure harmonics in the magnet, DSA333, at $8A/s$, $16A/s$, $32A/s$, $64A/s$ and $128A/s$. SSC magnets showed the existence of large skew quadrupole components[2]. This was explained by the size asymmetry of the upper and lower coils. However, some of the magnets showed unexpectedly large quadrupole components sensitive to the ramp rate. By making harmonics measurements at high ramp rates we were able to show the linear dependence of eddy current harmonics on dI/dt. Fig. 2 shows the hysteresis width of skew quadrupole field at various ramp rates. This confirms that the large skew quadrupole comes from eddy current. Skew quadrupole is created by the eddy current distribution difference between upper and lower coil. If such a large effect in skew quadrupole component is left for the accelerator construction, it is influential to the accelerator operation.

The hysteresis width linearly increases with ramp rate indicating that there is a large eddy current in SSC magnets. The origin of the eddy current is due to the contacts between strands. However, the behavior of the eddy current is not as simple as uniform distribution. Fig. 3 shows the ramp dependence of the sextupole components. Sextupole component is supposed to have highest eddy current by symmetry but the observed effect was very small. Eddy current reconstruction from the measured harmonics and the ac loss data shows quite unequal distribution of the eddy current[5]. Contact resistance between strands have to be distributed in a wide variety. Control of the contact resistance will be an important problem to be solved for the construction of large superconducting accelerator. The magnet with larger cable width such as LHC magnets will have more serious problems on this matter.

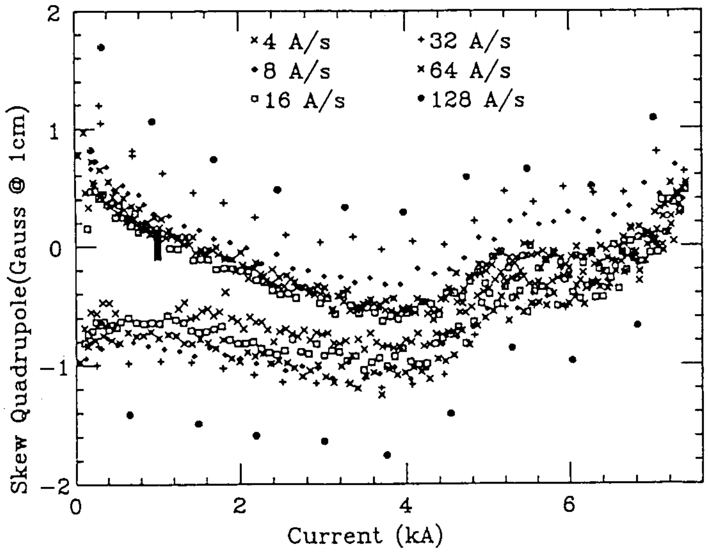

Figure. 2. Quadrupole Hysteresis

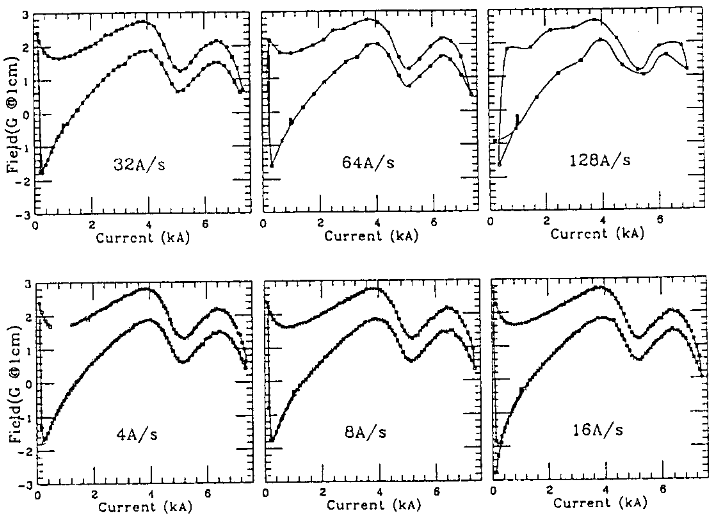

Figure. 3. Sextupole at various ramp rate

VI. CONCLUSION

A versatile magnetic field measurement system HAL2 was developed and successfully applied for the high ramp rate measurement of the harmonic components. Data shown above is the only set of 128 A/s data for SSC magnets to be ever recorded, and it was possible due to HAL2. The magnets ramped at $50A/s$ or higher, such as HEB of SSC, need to be measured at their operation ramp rate. Magnets with wider cable will also have the necessity for the measurement at high ramp rate. HAL2 system, with versatility and flexibility, showed a prototype for the magnetic field measurement system which is suitable for the R&D phase of the superconducting magnet projects.

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