ELECTRONICS FOR PRECISE MEASUREMENTS OF ACCELERATOR PULSED MAGNETS

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Abstract

Injection and extraction systems of modern accelerator complexes have high requirements for measurements accuracy of pulsed magnets field parameters. To satisfy these demands the fast and precision digital integrators were elaborated in BINP, Russia. These devices are intended for measurements in pulsed magnets (septum magnets, bumps, etc.) with the field duration, ranging from 5 µs, providing a relative accuracy better than $5\cdot10^{-5}$. The set of these devices are the main measuring electronics in injection and extraction section of 3 GeV Booster Ring at NSLS-II facility, which is under construction now in BNL (USA).

INTRODUCTION

Pulsed magnetic field stability is one of the most important parameter affecting on injection and extraction system performance. Therefore, field stability measurement is a common task to be solved by control systems of accelerator. For this purpose the control system should be equipped with fast and accurate measuring electronics. The induction method of magnetic measurements is widely used method for accelerator pulsed magnets. This method generally requires integration of an input signal. The value of magnetic field should be sampled at the time of beam passing across the magnet (magnetic field instantaneous value). The typical duration of the measured signals starts from microseconds, and typical accuracy 10^{-4} is required. There was invented and implemented many techniques of hardware integration, e.g. double integration method [1] or voltage to frequency conversion [2].

However, modern electronics capabilities make attractive the way, when input signal which is proportional to magnetic flux derivative is converted into digital form by an ADC, and the required integral is calculated digitally as the sum of ADC samples, Fig. 1. The FDI2056 [3] employs similar technique. This device is able to calculate partial integrals of input signals between timing pulses. The summing of these partial integrals gives the waveform of magnetic field transient. However, this method has a significant restriction on the dynamic characteristics of the induction signal. Let's show what that means. In many accelerators pulsed magnets the signal of induction probe has cosine form with short front edge (Fig.1, green plot). Rise time of such signals is determined by semiconductor switching devices and can be as short as few hundred nanoseconds. Using approximation algorithms (blue plot in Fig.1) it is possible to maintain low level of integral counting error during cosine part of the signal while the rise edge is an inevitable reason of error.

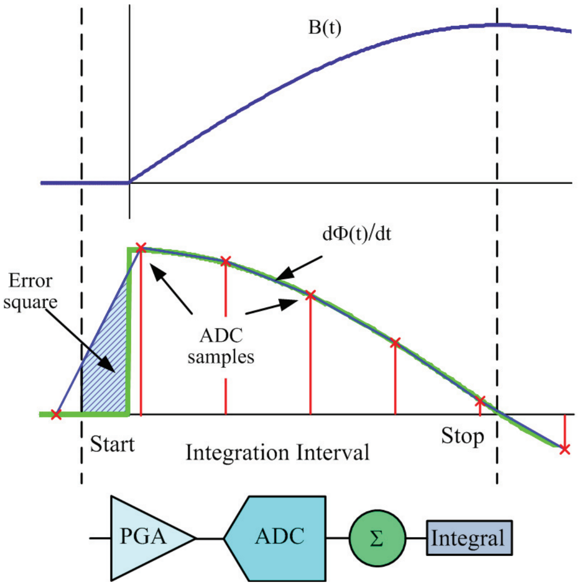

Figure 1: Typical induction signal of pulsed magnetic field and error source of "direct" digital integration technique.

In the worst case the error value δ can be approximated as follows:

$$\delta = \frac{(\delta\Phi)_{\max}}{\Phi_0} = \frac{\pi\Phi_0 / 2T}{\Phi_0}\cdot\frac{\tau_{ADC}}{2} = \frac{\pi\cdot\tau_{ADC}}{4T}$$

Where Φ_0 - magnetic flux amplitude, T – time to maximum of the magnetic field, τ_{ADC} – ADC sampling period, linear approximation is assumed. If the internal clock of digital integrator is asynchronous to input signal this error results in poor measuring repeatability i.e. noise of the integral. If suppose τ_{ADC} = 2 µs (FDI2056) and $\delta=10^{-4}$ is required, then minimum acceptable magnetic field duration is only 16 ms. It is suitable for measuring the slow ramping fields, but it is not satisfactory for injection/extraction systems. The reason of such error lies in wide spectrum of pulsed signals and in aliasing which occurs during analog to digital conversion. This error can be reduced by using a low-pass filter in analogue path of the device, but accurate integration timing is lost due to filter phase response.

Recently, the new type of the integrators with rigid triggering has been developed in Budker INP (Russia). These devices are based on the digital integration method which is free from the discussed limitations providing high accuracy for integration of pulses even shorter than ADC sample interval.

DIGITAL INTEGRATION METHOD WITH RIGID TRIGGERING

The suggested digital integration method is shown in Fig. 2.

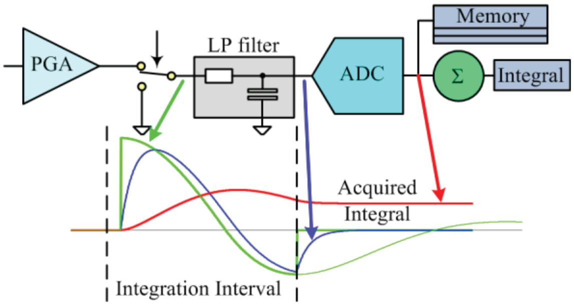

Figure 2: Digital integrator structure and signal passing.

An input signal is converted to an appropriate scale by low noise preliminary amplifier with programmable gain (PGA). The integration interval is determined by the fast analog switch. During the integration interval the scaled input signal passes through the switch to the low pass (LP) filter input. Remaining time the LP filter is connected to ground. The required integral equals to volt-second square of the signal shaped by the analog switch. After LP filtering the signal is converted to the digital form by the ADC, and samples are summed in digital part of the device. High theoretical accuracy of digital integration method is achieved by choosing appropriate relation between LP filter parameters and the ADC sampling rate. Moreover, LP filter spreads incoming signal in time, so it allows the middle speed but precise and low noise ADC to be used. A number of theoretical issues of digital integration method is discussed in [4]. Finally, let's list main features of the method described:

- Rigid triggering is determined by the fast switch and a few nanosecond synchronization errors could be achieved.
- Wide bandwidth is required only for input amplifier.
- The rest part of the device works with narrowband signal and can be made as low noise.

Additionally, you can see that presented structure allows measuring the "slow" magnetic field transients like in direct digital integration method (Fig.1), if the switch is closed all the time. Nevertheless, two points should be taken into consideration. First – this structure allows a simple summation of samples and doesn't require interpolation, because of the filter. Second – the position of field waveform in time axis is shifted, with respect to the real position.

INTEGRATORS VsDC2 AND VsDC3

The cited above integration method has been implemented in integrators VsDC2 and VsDC3. Integrator VsDC2 is a 3U and 4HP Eurocard module equipped with two identical channels and CAN bus communication interface. VsDC3 is its subsequent development. It has slightly improved performance and is designed as a 6U 4HP module with VME64 interface, Fig. 3.

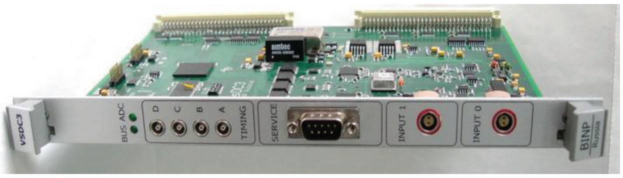

Figure 3: VsDC3 board.

In addition to elements mentioned above, the real devices also comprise versatile synchronization logic, powerful digital part and built-in precision calibrator thereby achieving zero-offset and high gain stability.

The magnetic fields stability is well-known and often solved task for pulsed measurements. Thus the noise of the integral versus integration time is one of the most important parameter of the measuring device. Discussed integrators show outstanding noise performance allowing one to achieve 10^{-5} measurement stability for pulses with duration longer than a few microseconds. For higher integration time noise decreases enough to become less important than the other error sources (see Table 1, SNR parameter).

Rigid timing to reach precise and stable integration interval is a significant condition for accurate measurement. Both devices have complex synchronization logic and can be triggered from a number of external events with uncertainty less than the 2 ns. Integrators store digital plot of signal and can be used as waveform recorder with 110 dB SNR at 100 kHz bandwidth. This oscilloscope mode of operation is very useful especially during system tuning.

These devices are suitable not only for pulsed measurements. They have excellent linearity making them ideal for plenty of constant field measurement tasks with different integration time, e.g. [5]. Table 1 lists VsDC2 and VsDC3 main features.

Table 1: Features of the Integrators

	VsDC2 (CAN version)	**VsDC3** (VME version)
# Channels	2	2
Input ranges	±0.2V; ±0.5V; ±1V; ±2V; ±5V; ±10V	±0.2V; ±2V program selectable
SNR		
at 10 μs	$5{\cdot}10^{-5}$	10^{-5}
at 1 ms	10^{-6}	$5{\cdot}10^{-7}$
at 1 s	$5{\cdot}10^{-7}$	$\sim10^{-7}$
Absolute error		
at 10 μs	10^{-3}	10^{-3}
at 100 μs	$<10^{-4}$	$<10^{-4}$
> 1 ms	$\sim10^{-5}$	$\sim10^{-5}$
Non-linearity	±20 ppm max	±20 ppm max
Gain error	±5 ppm max	±5 ppm max
Offset error	±0.5 ppm max	±0.5 ppm max
From factor	3U 4HP Eurocard	6U 4HP Eurocard

MEASUREMENTS OF PULSED MAGNETS AT NSLS-II FACILITY

The set of four VsDC3 devices is used in measurements of pulsed magnets in the injection and extraction sections of 3 GeV Booster Ring at NSLS-II facility. These sections contain two septum magnets and four bump magnets. Stability of pulsed fields should be monitored permanently during booster operation while the other field characteristics have been tested once during the fabrication process. Measuring stands for testing during fabrication are based on VsDC2 integrators [6]. Table 2 summarizes the main characteristics of booster pulsed magnets, built-in sensors and stability requirements.

Table 2: Parameters of Pulsed Magnets

	Inj. Septum	Ext. Septum	Bump
B_{MAX}, T	0.11	0.8	0.5
T to max. field	50 μs	75 μs	800 μs
Current, kA	2.7	10.2	1.5
Sensor wS, m^2	$3.34 \cdot 10^{-3}$	$3.66 \cdot 10^{-3}$	$4.85 \cdot 10^{-2}$
Stability	10^{-3}	$2 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
R_{NORM}, Ω	2*402	2*1k8	2*1k5

Measuring system contains 8 channels with identical structure, Fig. 4.

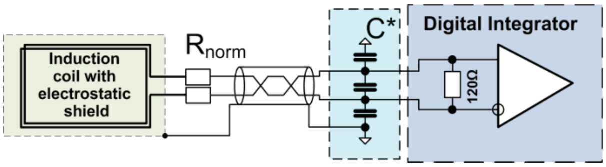

Figure 4: Measuring channel structure.

Every channel consists of:

- induction coil, built in magnet;
- high stability normalized resistors;
- twisted pair transmission line;
- VsDC3 digital integrator channel.

At the beginning of 2013 pulsed magnets power supplies and magnetic field measuring system were put into operation in BNL.

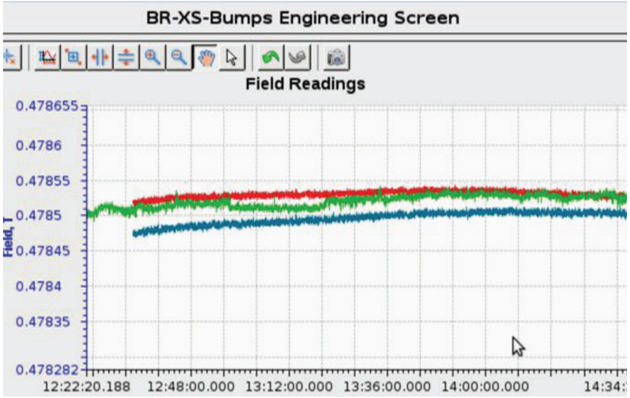

Figure 5: Bump magnet field stability (red and blue plots).

Two sorts of measured data were of interest. First of all, the long term stability and noise of magnetic field have been measured, Fig. 5. The scale has 10^{-4}/div relative level and it can be seen that long term stability fits into requirements. Fig. 6 presents waveforms of built-in sensors.

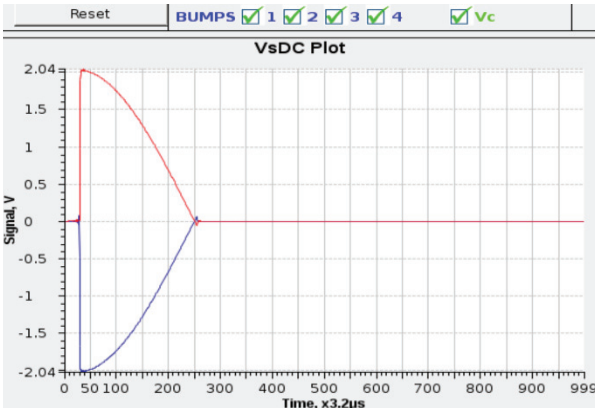

Figure 6: Waveforms of bump magnets probes, recorded in VsDC oscilloscope mode.

SUMMARY

The suggested digital integration method possess a unique combination of wide bandwidth, precision and rigid triggering. Based on this method two models of digital integrators are elaborated. These devices can successfully solve a plenty of task in the sphere of accelerator magnets measurements.

ACKNOWLEDGMENT

This work is supported by the Ministry of Education and Science of the Russian Federation.

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