MULTIMODE DIGITAL INTEGRATORS FOR PRECISE MAGNETIC MEASUREMENTS

A. Batrakov, A. Pavlenko, D. Shickov, BINP, Novosibirsk, Russia
P. Vagin, DESY, Hamburg, Germany

Abstract

Increasing demands of the accelerator techniques and modern electronics capabilities stimulate the creation of more accurate and fast instrumentation, based on the induction method. This report describes multimode integrators VsDC2 and VsDC3 (**V**olt-**s**econds to **D**igital **C**onverter), intended for precise measurements of the magnetic fields, both pulsed and constant. These integrators utilize new, digital integration method, which allows reaching accuracy close to the 10^{-5}.

INTRODUCTION

The induction method of magnetic measurements is the most important, widely used and oldest measurement method for particle accelerator magnets. This method generally requires integration of an input signal. In recent years, two types of the integrators have been developed in Budker INP (Russia). These devices are based on the digital integration method. Integrators provide high accuracy both for the constant magnetic field measurements using movable coils and for the pulsed measurements also. It is possible to achieve relative accuracy better than the 10^{-4} and even better than the 10^{-5} in special cases.

DIGITAL INTEGRATION METHOD

The digital integration method is shown in Figure 1.

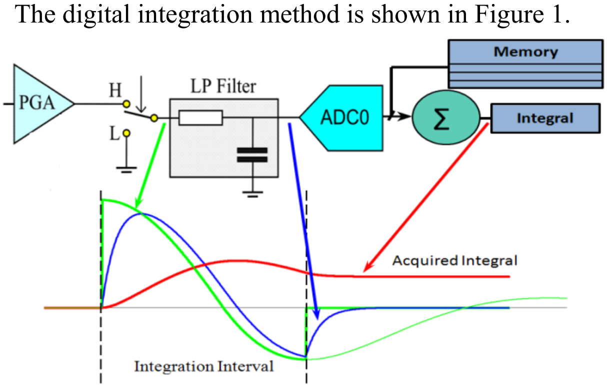

Figure 1: Digital integrator stricter and signal passing.

An input signal is converted to appropriate scale by preliminary amplifier with programmable gain (PGA). The integration interval is determined by the fast analog switch. During integration interval the scaled input signal passes through the switch to the low pass (LP) filter input. Remaining time 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.

Let's mention, that similar structure one may found out in the device FDI2056 [1], but the last one doesn't contain the fast switch and LP filter, which are principal elements in the described integrators.

It should be noted that LP filter does not change integral of the incoming signal. Let's show it. Suppose that input signal *f(t)* is non-zero only in the interval from 0 to τ. This signal spectrum equals to:

$$S_{in}(\omega) = \int_{-\infty}^{\infty} f(t)\cdot e^{-j\omega t}\,dt = \int_{0}^{\tau} f(t)\cdot e^{-j\omega t}\,dt\,.$$

Note that spectral component at zero frequency equals to required integral. It is known that the LP filter output is given by:

$$S_{out}(\omega) = K(\omega)\cdot S_{in}(\omega)\,.$$

Where $K(\omega)$ is the filter transfer function. So the output integral equals to the required one if the LP filter has unity transfer function value at zero frequency:

$$\int_{0}^{\infty} f_{out}(t)dt = S_{out}(0) = S_{in}(0) = \int_{0}^{\tau} f(t)dt\,.$$

Digital integration method implies that the signal integral is calculated by summing ADC samples multiplied by the ADC time quant. Consider now the accuracy of continuous integral interpolation by the sum of discrete samples. Suppose that the LP filter limits the incoming signal spectrum to half the ADC sampling frequency. Therefore, according the Kotelnikov theorem [2], the continuous input can be precisely interpolated by a digital string as:

$$f(t) = \sum_{n=-\infty}^{n=+\infty} f(nT_s)\,\mathrm{sinc}\left(\pi\frac{(t-nT_s)}{T_s}\right).$$

Hence, for input signal integral we can write:

$$\int_{-\infty}^{+\infty} f(t)dt = \int_{-\infty}^{+\infty} dt \sum_{n=-\infty}^{n=+\infty} f(nT_s)\,\mathrm{sinc}\left(\pi\frac{(t-nT_s)}{T_s}\right).$$

Changing summing and integration order and integrating we obtain:

$$\sum_{n=-\infty}^{n=+\infty} f(nT_s)\int_{-\infty}^{+\infty} \mathrm{sinc}\left(\pi\frac{(t-nT_s)}{T_s}\right)dt = \sum_{n=-\infty}^{n=+\infty} f(nT_s)\cdot T_s$$

i.e. <u>in the case of the ideal filter and infinite discrete sequence the required integral exactly equals to the digital sum</u>.

It is impossible to satisfy these conditions strictly in the real device. Therefore, high theoretical accuracy of digital

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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 precision and low noise ADC to be used.

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 a subsequent development. It has slightly improved performance and is designed as a 6U 4HP module with VME64 interface, Figure 2.

Figure 2: VsDC3 board.

The magnetic fields stability is well-known and often solved task for pulsed measurements. Thus the relative noise ratio of the output integral versus integration time is one of the most important parameter of the measuring device. Plot in Figure 3 shows this relation.

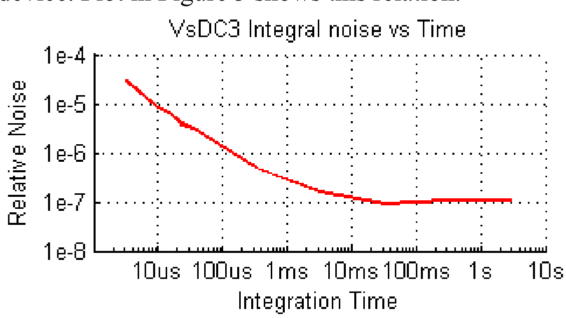

Figure 3: VsDC3 SNR of integrals versus time.

At integration time larger than few milliseconds noise decreases enough to become less important and the influence of other error sources rises. For constant field measurements, one of the most important parameter is nonlinearity of the device. Figure 4 demonstrates relative to scale non-linearity of the VsDC2.

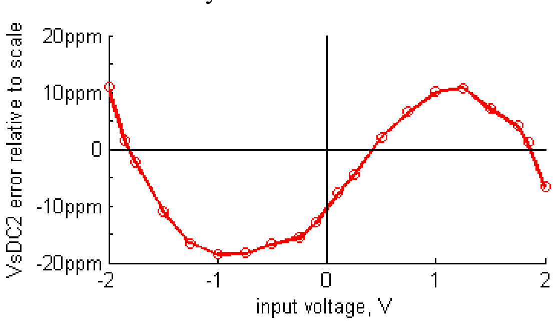

Figure 4: VsDC2 non-linearity versus input voltage.

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 stores digital plot of signal and can be used as waveform recorder with 110 dB SNR at 150 kHz bandwidth. Oscilloscope mode of operation is very useful especially during system tuning. Table 1 lists VsDC2 and VsDC3 main features.

Table 1: Parameters of the integrators

	VsDC2 (CAN version)	**VsDC3** (VME version)
# chanles	2	2
Input ranges	±0.2V; ±0.5V; ±1V; ±2V; ±5V; ±10V	±0.2V; ±2V program selectable
SNR at 10 µs at 1 ms at 1 s	 $5\cdot10^{-5}$ 10^{-6} $5\cdot10^{-7}$	 10^{-5} $5\cdot10^{-7}$ $\sim10^{-7}$
Absolute error at 10 µs at 100 µs > 1 ms	 10^{-3} $<10^{-4}$ $\sim10^{-5}$	 10^{-3} $<10^{-4}$ $\sim10^{-5}$
Non-linearity	±20 ppm max	±20 ppm max
From factor	3U 4HP Eurocard	6U 4HP Eurocard

PULSED FIELD MEASUREMENTS

As the example of the digital integrators implementation for pulsed measurements, consider the system for measurement of pulsed magnets of NSLS-II 3GeV-booster. The next magnet parameters were measured:

- Transverse distribution of the first field integral.
- Influence of vacuum chamber on it.
- Field stability.

The system was equipped with 4 VsDC2 integrators, timing and power control electronics. Two ways of transverse distribution measurement has been used: some magnets we processed with long coil, the rest were worked on with PCB coil matrixes. Figure 5 shows BUMP with measuring coil installed on positioning system.

Figure 5: BUMP with coil sensor.

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Figure 6 presents first integral distribution for BUMP magnet.

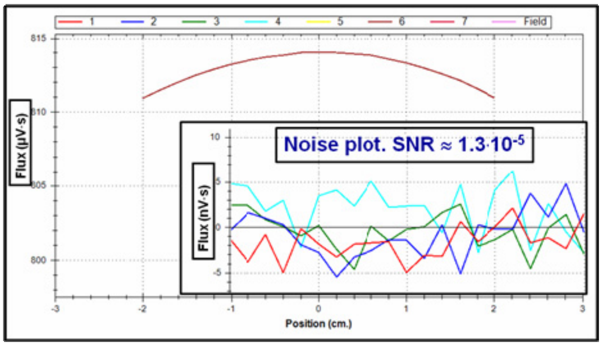

Figure 6: BUMP first field distribution and VsDC2 noise plot.

The whole measuring process was automated. The VsDC2 self noise lead to achieve measurements accuracy close to 10^{-5}.

The induction coil signal and capacitor bank discharge recorded by the VsDC2 are shown on Figure 7.

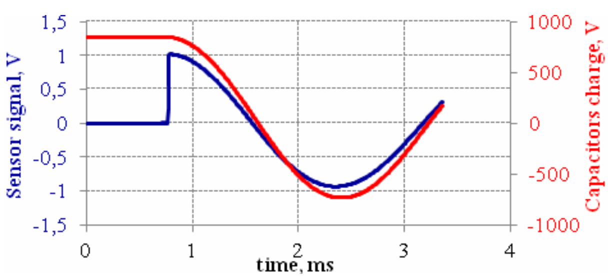

Figure 7: Waveforms of sensor signal.

Oscilloscope mode of operation allows one to tune start/stop integration time, and to study effects of phase delay between the pulsed magnetic field inside and outside the vacuum chamber.

CONSTANT FIELD MEASUREMENTS

To demonstrate constant field measurements application of VsDC's, consider the rotating coils system which was used to adjust and certify quadruples for the NSLS-II main ring. More detailed description of this system is presented in [3]. Two VsDC3 channels are combined together so as the end of the integration in one VsDC3 channel of each module coincide with the start in another. Such combination gives a non-stop measurement of the magnetic flux while coils rotate. The angular position of the coil is sampled every integration start/stop moment. Resulting dependence of the magnetic flux from the angle is used to calculate lens parameters.

Harmonics are calculated from compensated signals, resulting in cancellation of mechanical vibration and power supply noise sources. Figure 8 shows comparison between compensated and original channels.

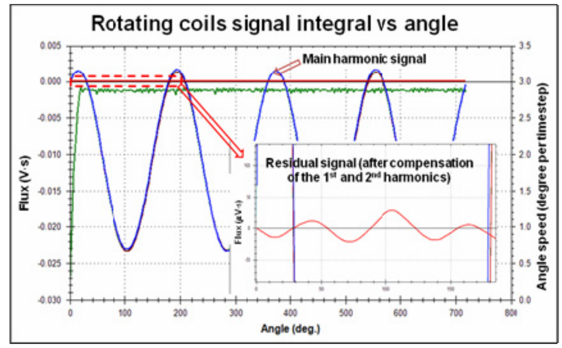

Figure 8: Layout of papers.

The 1st and the 2nd harmonics are compensated more than 100 times. It is possible to see harmonic with the naked eye. This features and outstanding VsDC3 noise performance result in extremely low harmonics noise (repeatability of results). Relative noise is better than 10^{-6} for the typical lens current, figure 9.

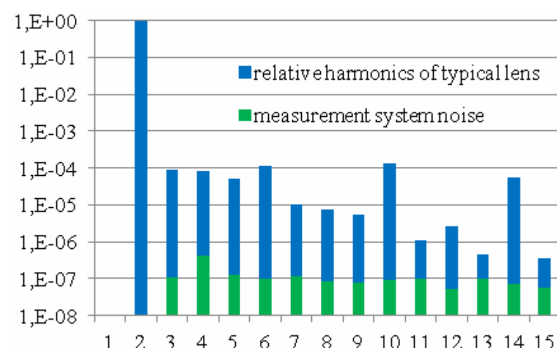

Figure 9: Relative harmonics of lens #9807-0029.

SUMMERY

Digital integrators possess unachievable before combination of high speed and precision. These devices can successfully solve a plenty of task in the sphere of magnetic measurements both constant and pulsed fields. Measurements accuracy better than 10^{-5} could be achieved.

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