50 MHz Voltage-to-Frequency Converter

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Abstract. The Voltage-to-Frequency Converter (V2F) is an instrument commonly used in synchrotron beam line experiments for converting a slowly varying voltage signal representing x-ray flux to a high frequency pulse train, with each pulse representing a packet of x-ray energy. The pulses are commonly integrated with a digital counter to calculate total x-ray energy incident on a sample during an exposure. As x-ray experiment data is taken faster and faster and exposure times shrink, V2F frequencies must necessarily increase to preserve precision in measuring total x-ray energy. The APS Detector Group have designed and built two custom 50MHz V2F instruments for APS beam line experiments. The instruments are designed according to the Nuclear Instrument Module (NIM) standard and respectively reside at APS Sector 12-BM, and in the APS Detector Pool [1].

1. Introduction

Voltage-to-Frequency Converters (V2F) are ubiquitous instruments at synchrotron experiments. The instruments, as their name implies, convert a varying voltage into a series of pulses at a frequency commensurate with the voltage. A common use of the V2F in a synchrotron experiment is to convert a voltage output from an x-ray detector, such as an ion chamber, into a pulse train to trigger a scalar counter. Many detectors, such as ion chambers, are sensitive to x-ray flux and do not respond to individual photons. The flux measured from an ion chamber is proportional to x-ray power delivered to the sample, that is, energy per unit time. It is desirable to integrate that power to determine total deposited x-ray energy on the sample. One may ask the question on why to use a V2F when all is needed are a modern analog-to-digital converter (ADC) and digital integrator. As will be seen, the V2F is exactly this circuit: an ADC and digital integrator. The reason for using a separate V2F unit and scalar is that a single data acquisition system can be used for counting detectors, such as photomultiplier tubes, or flux sensitive detectors such as ion chambers. The V2F makes a flux sensitive detector produce an output similar to a counting detector.

Many beam lines, such as Sector 12-BM at the Advanced Photon Source, possess a commercial V2F from vendors such as Nova R&D [2]. These commercial units have a frequency range from 0Hz to 2MHz, with a voltage input from 0V to +/- 10V. For most measurements, these commercial instruments suffice for practicing good science. However, as detectors get faster and faster, and exposure times get smaller and smaller, faster V2F converters are necessary to preserve instrument resolution. To illustrate, for a 10ms exposure and 2MHz frequency, the V2F will deliver 20000 counts. Taking log2, this comes to almost 15bit resolution, which is fine in most cases. If the exposure time is

1ms, the 2MHz V2F delivers 2000 counts, and hence has 11 bits of resolution. One can see that for shorter and shorter exposure times, the resolution of the V2F gets worse. If the V2F delivers a 50MHz frequency, we have almost 16bits resolution for a 1ms exposure. This allows precise measurement of energy deposited on a sample for short exposure times, speeding up the process of data gathering, and reducing sample damage.

2. Algorithm for V2F

The APS detector group designed a custom V2F circuit using a commercial high-quality analog to digital converter (ADC) and field programmable gate array (FPGA). The voltage fed into the APS V2F instrument is first processed with an analog amplifier, and then digitized with the ADC. The digital signal is sent to the FPGA which generates a pulse train based on the digitized voltage. A diagram of the V2F algorithm is shown in figure 1.
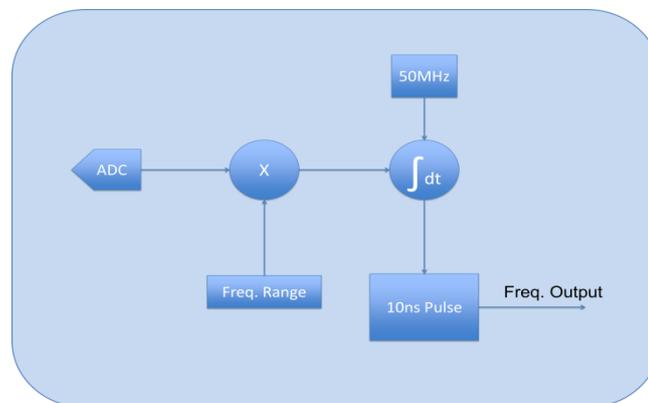

Figure 1. Algorithm for APS V2F convertor. Digitized input voltage is converted to pulse train in FPGA.

The digitized voltage is multiplied by a constant determining the output frequency range. This product is considered to be a fraction, that is, a number between 0.0 and 1.0, represented by a 32 bit binary number. The product is then integrated in a digital integrator clocked by a 50MHz system clock. When the running sum in the digital integrator reaches 1.0, the integrator overflows. On overflow, the integrator drops the integer part of its value. For example, if the sum of the integrator reaches 1.1, then the 1 is subtracted and the result stored in the integrator is 0.1. Each overflow causes a 10ns pulse to be generated. The 10ns pulse is timed by an internally generated 100MHz clock in the FPGA. The series of these pulses comprises the frequency output of the instrument.

The beauty of this algorithm is its simplicity and its ability to generate frequencies only limited by the system clock. For example, using a 100MHz system clock would allow the V2F to generate 100MHz frequencies with the same performance in terms of linearity and accuracy, as these parameters are limited by the quality of the input amplifier and ADC. This algorithm was based on an invention described in [3,4].

3. The APS Instrument

3.1. High Level Description of Instrument

The APS V2F converter is built as a NIM instrument because virtually every APS beam line has NIM crates. The NIM power supplies are low noise, and lend themselves to powering analog instrumentation. The APS instrument features four V2F channels, with four voltage inputs and four

frequency outputs, all independently configurable. The inputs and outputs on the instrument appear as BNC connectors on the front panel. The instrument is configured with a knob and pushbutton switch that control a series of menus displayed on a liquid crystal display (LCD). Each channel can be configured to five frequency ranges: 0MHz (disabled), 2MHz, 10MHz, 25MHz, and 50MHz. The voltage input ranges from 0V to +10V, corresponding to 0MHz to 50MHz in the highest frequency range. On power-up, the 50MHz range is by default set, and the instrument can be used without tweaking any settings. The instrument has an extra BNC to be used in the future. A photograph of the V2F instrument is shown in figure 2.

Figure 2. APS Voltage to Frequency Converter.

3.2. Frequency Noise

The output signal of the V2F instrument is not a constant frequency. The V2F algorithm does not assure a constant output frequency, but that a certain number of pulses are generated in a given amount of time. Because the output of the V2F is generally connected to digital pulse counter, only the number of pulses in a given time matter in synchrotron experiments. One can think of the V2F as generating an exact frequency plus frequency noise. A figure showing the output signal of the V2F at different frequencies is shown in figure 3.
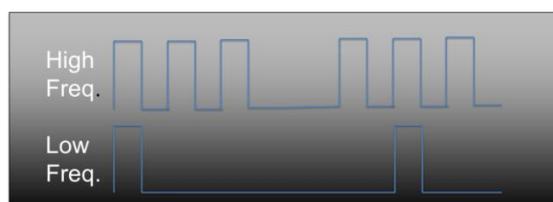
Figure 3. High and low frequency outputs from V2F.

3.3. Calibration and Specifications

The instrument is calibrated by supplying a DC voltage of 9V with a voltage standard and adjusting the output frequency to 45MHz. This calibration removes errors in the input amplifier gain. The calibration is stored in the FPGA firmware as a gain factor applied to the digitized voltage. Because connecting two instruments can cause small DC offsets due to amplifier bias and grounding problems, the V2F has the ability to zero the frequency to cancel DC offsets. Because the on-board crystal

oscillator can drift with temperature, changing the output frequency, a digital thermometer is included on the instrument, but is currently not used in the calibration. A future firmware revision may include the effects of temperature in the calibration.

The APS instrument can be constructed with either a Linear Technology LTC2400 24-bit converter with a 15Hz sample rate, or a Burr Brown ADS8320 16-bit converter with 100 kHz sample rate, depending on the application [5, 6]. Separate firmware and calibration exists for either converter. The slow 24-bit converter used for slowly varying signals, while the faster 16-bit converter can be used in fly scans, in which a detector signal quickly varies as a sample is rotated on a motor stage.

Table 1. Specifications

Spec	Value
ADC Bits	16 or 24
ADC Linearity (24 bit)	30ppm, integral 2ppm, differential
Sample Rate	15Hz, 24bit 100kHz, 16bit
Pulse Output	10ns, TTL
Freq. Ranges	2,10,25,50MHz
Voltage Range	0V-10V

4. Conclusion and Acknowledgements

The V2F Instrument has been in use at Sector 12-ID at APS since 2011. A second instrument resides in the APS detector pool and is currently configured in the faster 16 bit mode. The APS detector group is redesigning the analog portion of the V2F to allow both positive and negative voltages to make the instrument more useful for beam lines. The authors would like to acknowledge Byeongdu Lee and Soenke Seifert for testing the instrument at APS Sector 12. Also, it should be noted that after the APS V2F was designed, a commercial 100MHz V2F instrument was offered by Quantum Detectors [7].Use of the Advanced Photon Source, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Argonne National Laboratory, was supported by the U.S. DOE under Contract No. DE-AC02-06CH11357.

5. References

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