DEVELOPMENT OF A DIGITAL AMPLIFIER FOR NUCLEAR RADIATION DETECTORS

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Abstract

Many types of radiation sensors, including solid-state diodes, ion chambers, fission chambers, and self-powered detectors, give a signal consisting of a current or charge proportional to the incident radiation. The output signal is traditionally amplified by a current-to-voltage amplifier, and processed downstream by various analogue signal conversion and processing steps before digitization for display or for use in a control, safety, or monitoring system. The present work describes the development of a “digital amplifier” system, capable of directly digitizing the small current or charge output signal from radiation sensors, so that all downstream signal processing, display, and decision-making can be accomplished digitally. The size, simplicity, accuracy, robustness, and self-checking capability of the digital amplifier make it suitable for use in modern nuclear power plant instrumentation and control systems.

1. Introduction

A variety of radiation sensors are used in the nuclear industry. The following radiation detectors are of particular interest from the standpoint of a compact current measurement sensor: Ion Chamber, In-Core Flux detector, Fission Chamber, and Semiconductor Sensor. All of these sensors have very high output impedance and generate currents in the nano-amp to micro-amp range, making readout of the sensor challenging.

2. Smart Sensors

In the field of instrumentation, there is a trend toward sensor interfaces which can be placed in close proximity to the actual sensor, directly digitize the sensor signal, and are capable of (at least) limited local processing of the signal. Such devices are often called ‘smart sensors’ and can offer advantages over the standard practice of cabling analog signals directly to a digitizer at a central control or monitoring system, which may be a considerable distance from the sensor. Some of the general advantages offered by the smart sensor [1] concept are given below:

- Digitization occurs close to the actual sensor. This avoids transmitting analog signals over long cables which can cause a loss in signal to noise ratio, reducing the accuracy of the final reading.

- Smart sensors, because of their on-board processing capabilities, can support a variety of useful features, such as:
    - Self calibration or calibration based on externally supplied data
    - Signal processing such as non-linearity correction or filtering
    - Self diagnostics
    - Smart sensors can be designed to support networking, both wired and wireless. This allows sensor networks to be employed. This could save on the amount and cost of cabling.

For radiation sensors/detectors, the requirements of the smart sensor device are as follows:

- The device must measure the low currents produced by the radiation sensors with enough resolution to make use of the full dynamic range of the sensor.
- The device must not introduce excessive noise into the reading, again to preserve the dynamic range of the sensor
- The device must be able to communicate the digitized current value via a standard industrial protocol
- The device must be in-expensive and easy to deploy

The device must support self-test and self-diagnostic capabilities, and be capable of communicating out-of-normal conditions via its communications link.

3. Digital Amplifier

The goal of this work is to develop a small and inexpensive current measuring device to read out the current from a radiation sensor, digitize this current, perform any necessary processing on the digitized data and then transmit the final measurement to a control or monitoring system. Thus, we are seeking to develop a smart sensor for nuclear radiation measurement applications.

A prototype of the system was built and tested at AECL. The most challenging aspect of the system is the measurement of the very small currents produced by radiation sensors. A typical way this is done is shown in Figure 1. Here a high impedance operational amplifier is used with a large value resistor to form a trans-impedance amplifier, or current to voltage converter. Although this method is reliable and proven, it is difficult to design and construct due to leakage, component tolerance, and noise issues. It also has no inherent self-test and calibration abilities, such functionality would have to be designed around it, adding further to the design complexity.

In order to decrease design effort and increase system reliability and features, an off-the-shelf IC by Texas Instruments is used to measure and digitize the current (the DDC112 originally produced by Burr Brown [2]). This IC was designed as a photo diode digitizer for medical imaging devices, so it is a very good candidate for low current radiation sensor applications.

The IC also supports self-diagnostic features and programmable resolution. Rather than the trans-impedance principle, the IC uses capacitive charge integration (charge to voltage conversion) to measure the current. The IC greatly simplifies the design of the smart sensor and will allow it to be much smaller in size and have a much lower component count, which improves overall reliability and production cost. Figure 2 shows a block diagram of the prototype system.

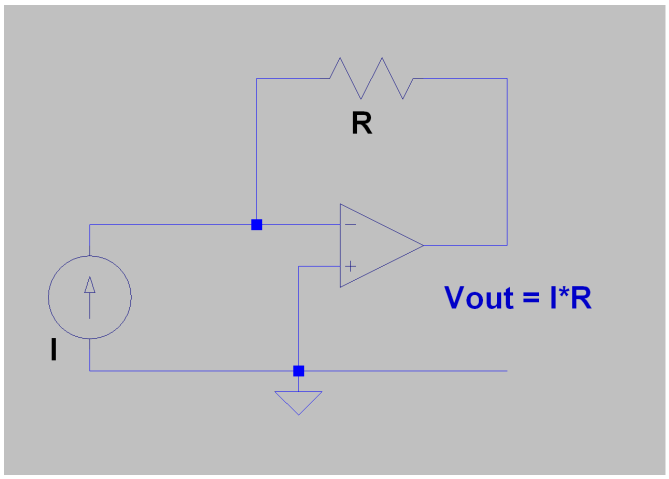

Figure 1 Regular Small Current Amplifier

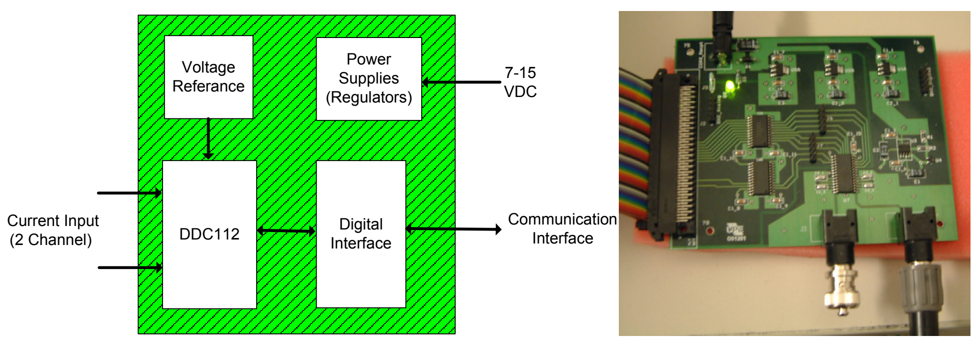

Figure 2 Digital Amplifier Prototype

3.1 Prototype system testing

The prototype system was tested to ensure that it could indeed measure current at the levels necessary for a radiation sensor system. A block diagram of the testing system is shown in Figure 3.

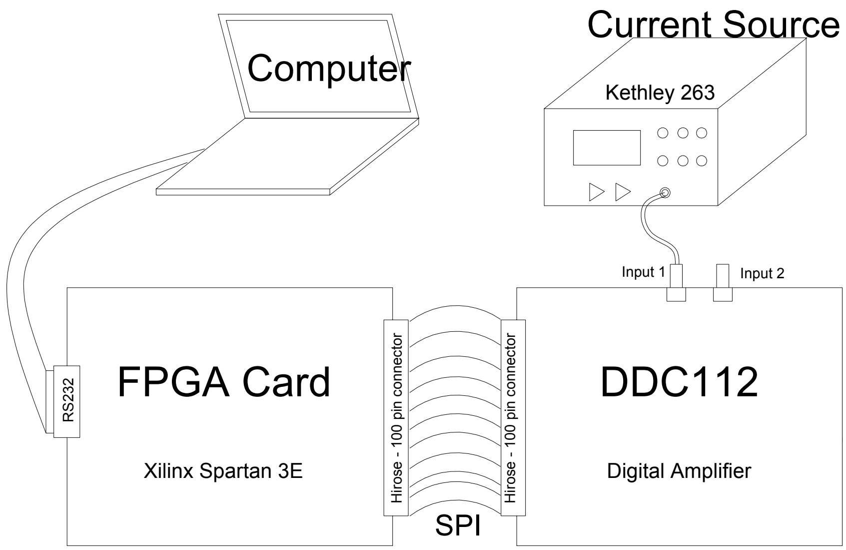

Figure 3 Block Diagram of Testing System

The purpose of this testing is to understand the digital amplifier working range and the accuracy of the reading. A Kethley 263 calibration source was used. A field programmable gate array (FPGA) card was configured to allow the computer to communicate with, and acquire data from the test board.

The testing result is summarized in Table 1. The 'gain', or sensitivity of the amplifier is set by selecting one of the 8 internal capacitors. Selecting a smaller capacitor increases the gain because if the fundamental relationship between charge and voltage in a capacitor (Voltage = Charge/Capacitance). Thus lowering the capacitance increases the voltage for a given amount of injected charge, leading to higher sensitivity in the reading. By the same token, a smaller capacitor also allows a higher sampling rate since the capacitor will be charged (and the voltage increased) more rapidly for a given level of measured current (shorter integration time). For each current, all gain settings (capacitor values) were tested except the gain(s) which required integration time out of specification; and for each of gain, the integration time from 10% of saturation to 110% of saturation were tested. However, the mean values in Table 1 cover only from 10% to 90% of saturation time, because the saturated readings are not correct. The data also highlights how the capacitor or gain must be selected appropriately for the magnitude of current being measured. Too high a capacitance will produce too little voltage for a proper measurement by the internal converter (ADC). Too low a capacitance could lead to capacitor saturation. This is why some of the fields are blank in the chart, the capacitance value (and thus integration time) of the amplifier must be chosen optimally for the expected range of currents to be measured.

Table 1
Testing Result of DDC112 Digital Amplifier

Injected	Mean Reading (nA) (cover 10% - 90% integration time)								
current	Gain 1	Gain 2	Gain 3	Gain 4	Gain 5	Gain 6	Gain 7	Gain 00	Max. Error
(nA)	(12.5 pF)	(25 pF)	(37.5 pF)	(50 pF)	(62.5 pF)	(75 pF)	(87.5 pF)	(270 pF)	(Internal)
1 pA 0.001	0.0011							External	10.00%
0.005	0.004546							Capacitor	-9.08%
0.01	0.009617	0.009637							-3.83%
0.02	0.019685	0.019689	0.019745						-1.27%
0.05	0.049751	0.049776	0.049841	0.049779					-0.50%
0.1	0.099868	0.100002	0.100011	0.099981	0.100032	0.100018			-0.13%
0.2	0.199955	0.200192	0.200163	0.200222	0.200237	0.200231	0.200258	0.196941	0.13%
0.5	0.500697	0.500665	0.500461	0.500786	0.500697	0.500818	0.500763	0.492807	0.16%
1 nA 1	1.000817	1.001614	1.001091	1.001886	1.001587	1.001841	1.001674	0.986126	0.16%
2	2.00213	2.003653	2.003247	2.003988	2.003717	2.003547	2.003357	1.972333	0.20%
5	5.004826	5.007405	5.006581	5.009462	5.009026	5.010101	5.009192	4.93185	0.19%
10	10.0072	10.01428	10.01309	10.01896	10.0168	10.0179	10.0169	9.868357	0.19%
20	20.0132	20.03676	20.02789	20.04452	20.03835	20.04195	20.03861	19.72342	0.22%
50	49.80618	50.08811	50.08821	50.1006	50.10246	50.1004	50.09238	49.31401	-0.39%
100	100.0405	100.2048	100.1734	100.2326	100.2041	100.1953	100.1757	98.71591	0.23%
200	199.8454	200.3178	200.2685	200.4348	200.3719	200.3957	200.3851	197.4146	0.22%
500			500.8834	501.1292	500.9663	501.0409	500.9788	493.279	0.23%
1 uA 1000						1002.162	1001.924	984.6875	0.22%
2000								1965.7	
5000								4927.526	

Without any calibration of the capacitors, the maximum error of the readings varied from –0.5% to 0.23% with current from 50 pA to 1 uA. When the current is less than 20 pA, the error gets larger, up to 10% at 1 pA. However, it should be noted that: first, the capacitance of the internal and external capacitor was not calibrated; and second, there was about 0.4pA leakage with the PCB board sitting on a foam pad.

3.2 Final system design

The final system is still under development, but a generic block diagram is shown in Figure 2. The processing element can be either microprocessor, or FPGA based, each having an advantage in certain areas such as flexibility, cost and software design/validation effort. In the final implementation, the system should provide self-test and self-diagnostic capabilities, such as IV curves and Time Domain Reflectometry [3]. The communications protocol is still under consideration, with the possibility that several different systems will be designed with a common core and different communications subsystems to address different deployment strategies.

The Texas Instruments IC is available with a number of different channel count configurations. Devices that can support up to 32 current inputs are being investigated to determine whether multiple sensor capable devices offer any advantage in this application.

4. Example Applications

4.1 Diode-based gamma radiation sensor

A silicon diode based sensor for measuring high gamma radiation field was developed at Chalk River Laboratories, Atomic Energy of Canada Limited (AECL). The sensor produces a current when exposed to a gamma field. The sensitivity is about 0.3 pA/(Rad/hr). Silicon (Si) p-n junction diodes operating in current mode are used for high exposure rate gamma fields. The total charge generated by a Si p-n junction diode is known to be proportional to the ionization energy deposited in the diode depletion region [4]. Since radiation dose is by definition equal to the ionization energy deposited, the total charge is a direct measure of the radiation dose. After some experimentation, a small Si p-n diode, operating in current mode was chosen as the sensor for our applications. A variety of small, inexpensive Si diodes are readily commercially available because of their extensive use in electronic circuits. Unlike an ionisation chamber, a Si diode does not require high voltage for operation, which considerably simplifies the electrical connections and signal amplification.

4.1.1 Original diode-based radiation sensor readout system

The readout system originally consisted of an analog current-to-voltage amplifier, (a FEMTO current-to-voltage amplifiers was used, which was capable of amplifying the 10^{-3}~10^{-11} A diode output current.), a National Instruments Data Acquisition (DAQ) Box, and a laptop computer. The laptop was used to retrieve the data from the DAQ box for storage on the hard drive. The major drawback for this readout system is the analog amplifier, which is large and needs to be zeroed before use. A photo of the original readout system is shown in Figure 4. The most-left blue box is the analog current-to-voltage amplifier, which is fed by the output of the sensor. The output from the amplifier is a voltage, which is sampled by the middle blue box containing the Data Acquisition (DAQ) box (NI 6259). A laptop computer is used to retrieve the data from the DAQ box and store the values on the hard drive. This system had been used in many applications at Chalk River Laboratories of AECL [5].

Figure 4 Original System

4.1.2 Benefits of using a digital amplifier based readout system

To overcome the drawbacks of the original system, it would be desirable to make the readout system low cost, compact, and more intelligent. The digital amplifier was developed to address these issues. The new system digitizes the radiation sensor output signal directly, and thus eliminates the previously required analog signal processing. This improves the overall performance of the readout system.

4.2 Applications in nuclear power plants

In a nuclear power plant, the output signal from the radiation sensors are traditionally amplified by a current-to-voltage amplifier, and processed downstream by various analog signal conversion and processing steps before digitization for display or for use in a control, safety, or monitoring system. Compared to digital systems, the analog instruments are more prone to noise and interference, have little or no 'intelligence', are large, and require significant cabling to transfer the signal. In addition to these technical drawbacks, the issue of obsolescence of equipment and components is becoming a serious one in existing stations. Often, no spare parts are available; and there is lack of expertise to repair the old analog equipment. Going to a digital system is an attractive alternative, which can help to alleviate these issues.

One promising application in CANDU reactors is neutron flux detector instrumentation. There are hundreds of neutron flux detectors in CANDU reactors for flux mapping and safe shutdown systems. The existing system locates the amplifiers in the instrument room. The digital amplifier can be located in the same position or outside the reactor. With the digital amplifier outside the reactor (near the detector possibly), a lower amount of electrical noise will be coupled into the small current signals. The amplifier must be tested for environment qualification.

If the digital amplifiers are located near the detector, the transmission system could deploy a digital network. Digital communication requires much less cabling comparing to analog signals. All the sensor output could be transmitted in one digital network, instead of hundreds of single wires. The penetration through the containment boundary could be reduced significantly.

Existing nuclear power plants have various instrumentation systems. To retrofit the new design into the existing system, a detail analysis has to be done to figure out where and how the digital amplifier be integrated into the existing system. There is no general solution that could satisfy all plants.

5. Conclusion

The developed digital amplifier is able to directly digitize the small current signals from nuclear radiation sensors. Thus, eliminating the complicated analog signal processing. This results in a simplified signal transmission system. If the digital amplifier is used for neutron flux detector, enhanced safety and low cost can be achieved.

However, how to incorporate the digital amplifier into existing nuclear power plant is a major issue to solve. There is still a long way to go for addressing qualification, environmental, and retrofitting issues.

6. References

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