The Compact Muon Solenoid Experiment

CMS Note

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February 2, 2005

Optically Isolated High Voltage Digital to Analog Converter*

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Abstract

We have designed, prototyped and characterized a High Voltage Digital to Analog Converter (HV-DAC) with a dynamic range of 600 Volts. When configured as a series voltage drop element in a High Voltage (HV) distribution system, the HV-DAC can be used in high energy physics experiments where individual high voltage control of many channels is needed. The design and performance of the HV-DAC and a prototype two-channel programmable HV distribution system are presented here.

1. Introduction

Digital to Analog Converters (DAC) can be used to provide digitally controlled analog output levels with a resolution that depends upon number of bits provided for digital control. The typical range of these devices is about few Volts. For devices that use high voltage DC supplies, often it is desirable to have a DAC which can have a large dynamic range (~500 Volts) so that their operating voltages can be controlled conveniently. We have designed such HV-DAC with a dynamic range of 600 Volts and tested its performance for accuracy and resolution over the entire dynamic range. This device can also be used as a programmable voltage drop unit between the input supply and the load enabling a variety of applications.

For example, many high energy physics experiments using detectors such as scintillation detectors, gaseous detectors etc. need high voltage either for the detection system itself or for the read out device to extract the signal. The number of such detectors is usually large, and often, they have to be operated at nearly the same efficiency or gain. These requirements lead to large variations in the operating voltage of each individual detector system, typically of the order of 500 Volts. It is impractical to use a separate HV supply for each channel as the cost involved is prohibitive. Instead, a programmable high voltage distribution system is used to supply the operating voltages for a group of detectors from a single power supply. Such systems are available commercially and they normally work on dc to dc conversion principle.

This requirement can also be fulfilled by using a HV-DAC. To demonstrate the application of HV-DAC as a voltage drop device, we have designed a two-channel prototype programmable HV distribution system with a dynamic range of 1900-2500 Volts. This is a cost effective design with good driving capacity (2 mA per channel) and has the flexibility to be used with different power supply voltages.

* Presented at ELECTRO-2005 Symposium held at BHU, Varanasi, India, Feb. 3-5, 2005

Our design is based on a HV-DAC connected in series as a variable voltage drop unit. The voltage drop in DAC is optically controlled by a 15-bit digital word and a maximum voltage drop of about 600 V is possible. A two-channel HV distribution system using the optical HV-DAC is schematically shown in Fig.-1.

Figure 1 Two channel HV Distribution System

2. Design Requirements

The basic design requirements are described in detail below:

- The main design requirement is to have a programmable high voltage drop with a dynamic range of about 600 V from the reference input voltage at load currents up to 2mA per channel, ie, for an input voltage of 2000 Volts, the output voltage range is 1400 to 2000 V.
- The gain of detector- readout systems is a sensitive function of high voltage. Therefore the HV-DAC design should have an output voltage resolution of 2 Volts or less.
- The number of HV channels in a typical high energy experiment may range from hundreds to thousands. Hence the system design has to be modular with a flexibility of scaling many such units.
- A flexible PC interface to each HV channel is necessary for automation.

3. High Voltage Digital to Analog Converter (HV -DAC)

The programmable high voltage drop between the common HV input and the load is achieved by using a HV-DAC unit in each of the HV channels.

3.1 Basic Principle of HV -DAC

A chain of zener diodes¹ of pre-selected breakdown voltages is connected serially between the input supply (V_{ref}) and the load (V_{out}) as shown in Fig. 2. A digitally controlled switch is connected across each of the zener diodes. The switch is used to activate (switch : OFF state) or deactivate (switch : ON state) each of the zener diode which will vary the voltage drop across the HV-DAC. If the breakdown voltages of the zener diodes in the chain are binary weighted ($V_{Z1}=1V$, $V_{Z2}=2V$, $V_{Z3}=4V$, $V_{Z4}=8V...$), then the desired drop across the HV-DAC can be obtained to an accuracy of 1 Volt by controlling the ON/OFF state of the switches.

3.2. Design of HV -DAC

The design details of the HV-DAC shown schematically in Fig.2 are explained below. As mentioned above, zener diodes are used as the basic voltage drop element. A photo transistor optocoupler is used as a switch across each of the zeners in the chain. This choice of switch provides good high voltage isolation of 7.5 KV to the control circuit. The HV-DAC zener chain contains 15 diodes with the breakdown voltages of the first seven

¹ Use of Zener diode as a passive voltage drop element, has been first demonstrated by John Doe of LBNL in 1970.

zeners (Z_1 to Z_7) approximately binary weighted (1,2,4...64 Volts). The subsequent 8 zeners (Z_8 - Z_{15}) are chosen to have the same breakdown voltage of approximately 64 Volts. The actual voltages of each zener in one of the HV-DAC chains that we have made are listed in the Table 1.

Zener	Measured Vz Volts	Zener	Measured Vz Volts
Z_1	1.5	Z_9	58.9
Z_2	1.7	Z_{10}	59.6
Z_3	2.7	Z_{11}	59.0
Z_4	9.1	Z_{12}	58.8
Z_5	14.8	Z_{13}	61.5
Z_6	32.4	Z_{14}	61.8
Z_7	58.1	Z_{15}	62.2
Z_8	59.0		

Table 1: Breakdown Voltage of each zener diode in the chain

This chain of zeners ensures a dynamic range of about 600 Volts. Instead of increasing the zener voltages in a binary weighted manner beyond Z_7 , we have chosen to keep voltages of Z_7 - Z_{15} equal (~64 Volts) in order to avoid high jumps in the output voltage across the load while setting the drop across HV-DAC. The drop across the HV-DAC is generated by downloading the appropriate 15-bit control word to the control buffer. Each optocoupler is driven by the state of the corresponding bit, which in turn activates or deactivates that particular zener diode. A simple isolated digital interface was designed to communicate with the control buffer of each HV-DAC. The design has provision for a buffered low voltage sample of the output high voltage for monitoring purposes.

Figure 2 Schematic of HV-DAC

4. Enhanced Parallel Port (EPP) interface

We have chosen the printer port of a PC in EPP mode as the media to control and monitor the output voltages in our HV distribution system. The PC communicates to our EPP interface using standard EPP protocol [1]. The EPP protocol has a typical transfer rate of the order of 500KB/s to 2 MB/s. This is achieved by allowing the hardware contained in the port to generate handshaking, strobing etc, rather than having the software to do it, which was the case with the Centronics standard. EPP port provides bi-directional control of all the peripherals. The EPP interface designed for our application has two independent 16 bit I/O ports (two 8bit ports) connected to each of the two HV-DACs in our prototype HV distribution system. Figure-3 shows the block diagram of the interface. The bit pattern for a given voltage drop is downloaded to the I/O port which drives the control buffer of the HV-DAC to get the desired output voltage. These latched bit patterns can be read back from the I/O ports for confirmation.

Figure 3 EPP Interface

5. Software

User interactive programs have been developed in C-language to perform different tasks needed to regulate the output voltage of each HV channel. These tasks are identified and described below.

5.1 Read/Write Operation

A utility was developed to establish communications between the PC and each HV channel. First the HV channel is selected and then a 15-bit word is written into the buffer of HV-DAC of selected channel. Then the latched word is read back for validation. This utility was developed using the EPP protocol.

5.2 Computation of the control word

After the user inputs the common supply high voltage applied to the reference input of HV-DAC [Fig.1] and the desired output load voltage for a selected channel, the drop ($V_{in} - V_{load}$) across the HV-DAC can be determined. If the zeners had exact binary weighted breakdown voltages, then it is straight forward to compute the control word that generates the desired drop with an accuracy of 1 volt. But, as can be seen from Table 1, the actual breakdown voltages of the zeners are quite different from the ideal binary weighted voltages. To achieve 1 Volt resolution, the voltage drops corresponding to all 2^{15} zener combinations are computed and stored in an array. Then we loop through each of these values and select the bit pattern giving the closest value to the desired output.

Once the bit pattern is obtained, the control word could be loaded into the HV-DAC in one write cycle. But this results in a big instantaneous change in the output voltage which may not be desirable in many applications. In order to avoid this situation, the computed bit pattern is compared bit-by-bit with the existing latched control word. Whenever there is change in a bit, the current latched word is updated for that bit. This process is continued until all the 15 bits are compared and matched. In this way, the desired control word is loaded into the HV-DAC in not more than 15 write cycles ensuring a maximum change in the output voltage of no more than 64 Volts. A software delay is introduced between successive write cycles providing a settling time and smooth operation of detectors

6. Calibration

In order to compute the control word, it is important to know the breakdown voltage of each zener in the chain of HV-DAC accurately. They are obtained in the sites for the load of interest by measuring the change in the output voltage by shunting one zener at a time. The output voltage difference between successive shunting of zeners gives the breakdown voltage of that zener.

Once the zeners are calibrated, the expected output voltage across the load can be estimated for a given 15-bit word and the supply voltage (V_{in}). Comparison of the measured (V_o) and expected (V_e) voltages across the load showed differences ($V_o - V_e$) of few Volts (max. of 5 Volts) which were proportional to the drop across the HV-DAC ($V_{in} - V_e$). A detailed study of this was done as follows. The supply voltage was kept fixed at 2500 Volts, and the 15-bit word was computed and downloaded to get load voltages of 2500 to 1900 Volts in steps of ~50 Volts. Fig. 4 shows the plot of the differences between expected and observed voltages versus expected voltage.

We see a linear dependence of $(V_o - V_e)$ on V_e which is due to the corresponding change in load current. We fit a straight line and obtain the slope (p_1) and intercept (p_0) of the fit. These fitted parameters are used to compensate the load current effect proportional to V_e and improve the agreement between the measured load voltage and the actual desired voltage. The load current dependency of total breakdown voltage of zener chain is studied in detail and explained in section 8.

For a given supply voltage (V_{in}) and the desired load voltage (V_e), we obtain the voltage offset using the fitted parameters p_0 and p_1 as,

$$V_{\text{offset}} = p_0 + p_1 * V_e \quad \dots\dots 1$$

Then, the desired V_e is increased by the estimated offset voltage (Eq.1) and the control word is determined for this enhanced voltage ($V_e = V_e + V_{\text{offset}}$). With this correction, the agreement between desired and measured voltage improves significantly and is shown in Figure 4 below:

Figure 4 Response of two HV channels

All the measurements were made manually using a $4\frac{1}{2}$ digit high voltage meter.

7. Linearity and Resolution

We have made two HV-DAC units and tested their performance. After calibrating the zener chains, we operated them with a reference voltage of 600 Volts. The control word was computed with the offset corrections described above for different voltages (0, 50, ... 600V) in steps of 50 Volts and downloaded into the HV-DAC buffers. The output voltage was measured at each setting and compared with expected voltage corresponding to that control word. As can be seen from Fig.-5, we get good linear response between set and measured voltage with a slope of 0.997 demonstrating excellent linearity.

Figure 5 Linearity of HV-DAC

We have used these HV-DACs in a HV distribution system as shown in Fig.1. It is important to see how

accurately the load voltage can be set w.r.t. the desired voltage. We operated this system in the range of 1900-2500 Volts taking both uncorrected and offset corrected data. The histograms of the differences between expected and observed voltages combined for both the channels are shown in Figure 6. It can be seen that the precision (after correction) is about 0.5 Volts and the resolution is less than 0.3 Volts.

Figure 6 Accuracy and Resolution of programmable HV channels

8. Stability

To study the effect of load current and temperature on Zener breakdown voltages, we made a Zener chain consisting of 10 Zeners (without opto-switches) of approximately 62 Volts each resulting in a total drop of about 630 Volts.

8.1 Load current effect

The Zener chain is connected between the variable HV supply and a fixed resistive load (1.7M Ω). The output voltage across the resistive load is measured each time by varying the input supply voltage resulting in change in load current. Total breakdown voltage ($V_{in}-V_{out}$) of the Zener chain at different load current is plotted in fig. 7. We observe linear dependence of the break down voltage on load current.

Figure 7 Effect of Load Current on Zener Chain

8.2 Temperature Effect

Effect of this on the breakdown voltage of a Zener chain is studied in detail by placing the zener chain inside a incubator having a temperature range from room temperature to 50°C with an arrangement to measure the load voltage and ambient temperature inside the incubator with an accuracy of 0.1°C. The input supply voltage is set to get load current of approximately 0.5 mA. The load voltage was measured over a wide range of temperature (20°-50° C). This test was repeated for different values of load current. The variation in total break down

voltage with temperature at different current settings is shown in Fig.8. The plots for different load currents show a linear dependence of breakdown voltage with temperature having a similar slope of 0.52 ± 0.02 Volts / $^{\circ}\text{C}$.

Using these studies, effect of load current and temperature on breakdown voltage can be appropriately parameterised and used in programmable HV distribution system for computing bit pattern to get the desired output voltage more accurately.

Figure 8 Effect of ambient temperature on breakdown voltage of zener chain

9. Summary

We have designed a HV-DAC with a dynamic range of 600 Volts having an accuracy of 0.5 Volts. This system can be used to regulate high voltage in a programmable manner in a variety of detection and readout applications in high energy physics experiments. A prototype HV distribution system was developed for 2 channels. It meets all the design specifications. The design is also quite cost effective, and has a good driving capacity up to 2 mA, per channel with the flexibility of scaling so as to make a distribution system for a large number of channels. Load current and ambient temperature effects on zener voltage has been characterized quite accurately and they can be used in programmable HV channels to calculate bit pattern more accurately.

One of the sub-detector (HF) in CMS HCAL detector uses PMT as readout element. Many PMTs are bunched as per their gain and same HV is applied to all tubes in each bunch. For the consideration of CMS HCAL, we propose the present scheme as an alternate cost effective solution to have a programmable control of high voltages of these bunches.

10. Acknowledgement

We thank D. Green and A. Skuja for their encouragement. We thank John Elias for many useful discussions and suggestions that have helped in improving the work presented in this note.

Also, we thank A.I. D'Souza, S.R. Joshi, B.K. Nagesh, P.M. Pathare, S. K. Rao, L.V. Reddy, B. Satyanarayana and P.V. Sudersanan for their help at various stages.

11. References

1. IEEE1284 standard released in 1994