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Design, Development and Simulation of Front-End Electronics for Nuclear Detectors: Preamplifier-Amplifier-Shaper-Discriminator

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ABSTRACT

Design, Development and Simulation of Front-end Electronics for nuclear detectors Preamplifier-Amplifier-Shaper-Discriminator has been presented in this article. The Nuclear Detector Signal Channel (NDSC) comprises of charge-sensitive preamplifier, single-stage gain amplifier, CR-RC shaping amplifier and integral discriminator. The charge-sensitive preamplifier feedback circuit has 1MΩ resistor and 10 pF capacitor that gives its decay time constant (τ) of 10 µs. The gain of amplifier used in this channel is 51. Shaping amplifier which is the combination of high pass and low pass filter with equal time constant ($\tau_1=\tau_2=\tau$) of 5 µs to increase the signal-to-noise ratio. Single ended or integral discriminator function is to eliminate the system noise and pulse height discrimination. The NDSC has been designed and verified in Proteus 7.7 simulation platform. And the simulation results have been presented to show the performance and characteristics of the channel.

KEYWORDS: *Nuclear Detector Signal Channel, Nuclear Pulse Processing, Preamplifier, Amplifier, Shaper and Discriminator*

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1. INTRODUCTION

In Nuclear Pulse Processing (NPP), both analogue and Digital Pulse Processing (DPP) systems, the common pulse shaping and processing goals are noise suppression to achieve high energy resolution, reduction of dead time to optimize throughput and reduction of ballistic deficit to improve resolution and reduce peak distortion [1]. Pulse signals from a radiation detector like a NaI(Tl) scintillation counter or a BF3 proportional counter are amplified by a pre-amplifier and a shaping amplifier fed to a free-running ADC [2]. In [3], a 16-channel integrated circuit readout electronics chip include a low-noise, variable gain, charge-sensitive preamplifier circuit, a 4-pole pulse shaper with variable peaking times and a stretcher circuit for use with a germanium strip detector. The integrated circuits are fabricated in a 1.2 micron n-well CMOS process. The signals coming from a multielement silicon drift detector are amplified by four voltage preamplifiers (VPA), each coupled to a detector channel. The preamplifier signal is fed to an analog section constituted by a custom-made 4-channel shaping amplifier with digitally selectable shaping time constant of 150 ns and 450 ns for high energy resolution elemental mapping, fast trigger signal(30 ns shaping time for pile-up rejection), and 4-channels peak-stretcher. The stretched signals are multiplexed to a single analog-to-digital converter (ADC) that provides the conversion of the peak amplitude into a digital word. A discriminator (DISCR_S) per shaping line allows the A/D conversion only for signals higher than a minimum threshold. A discriminator follows also the fast shaping line (DISCR_F) to provide a squared signal to the pile-up rejection logic implemented in the FPGA [4]. In the current research, the Nuclear Detector Signal Channel consisting of charge-sensitive preamplifier (feedback time constant 10 µs) uses a capacitor in place of the feedback resistor that avoids detector and stray capacitances by directly detecting the charge from the detector, single-stage gain amplifier (51) although this may be increased/decreased depending on the input signal amplitude and components value, CR-RC shaping amplifier which is the combination of high pass and low pass filter with equal time constant ($\tau_1=\tau_2=\tau$) of 5 µs to increase the signal-to-noise ratio and integral discriminator converts the CR-RC shaping amplifier output into logic pulses which eliminates the system noise as well as pulse height discrimination has been presented. The channel has been designed and simulated in Proteus 7.7 simulation platform.

2. Materials and Method

2.1. Block Diagram

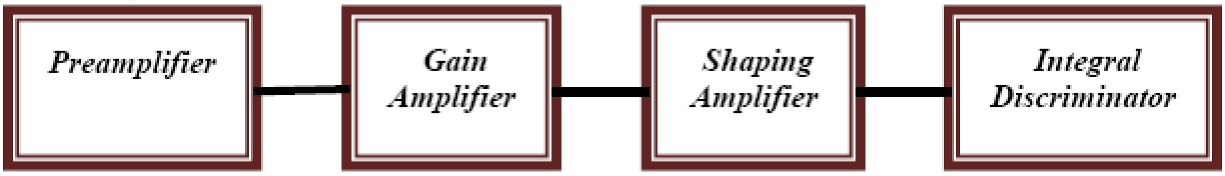

Fig.1: Block Diagram of the Proposed Nuclear Detector Signal Channel

2.2. Circuit Diagram

Complete simulation model of the nuclear detector front end electronics consisting of preamplifier-amplifier-shaper-discriminator has been shown in fig.2. The description of individual module has been provided below:

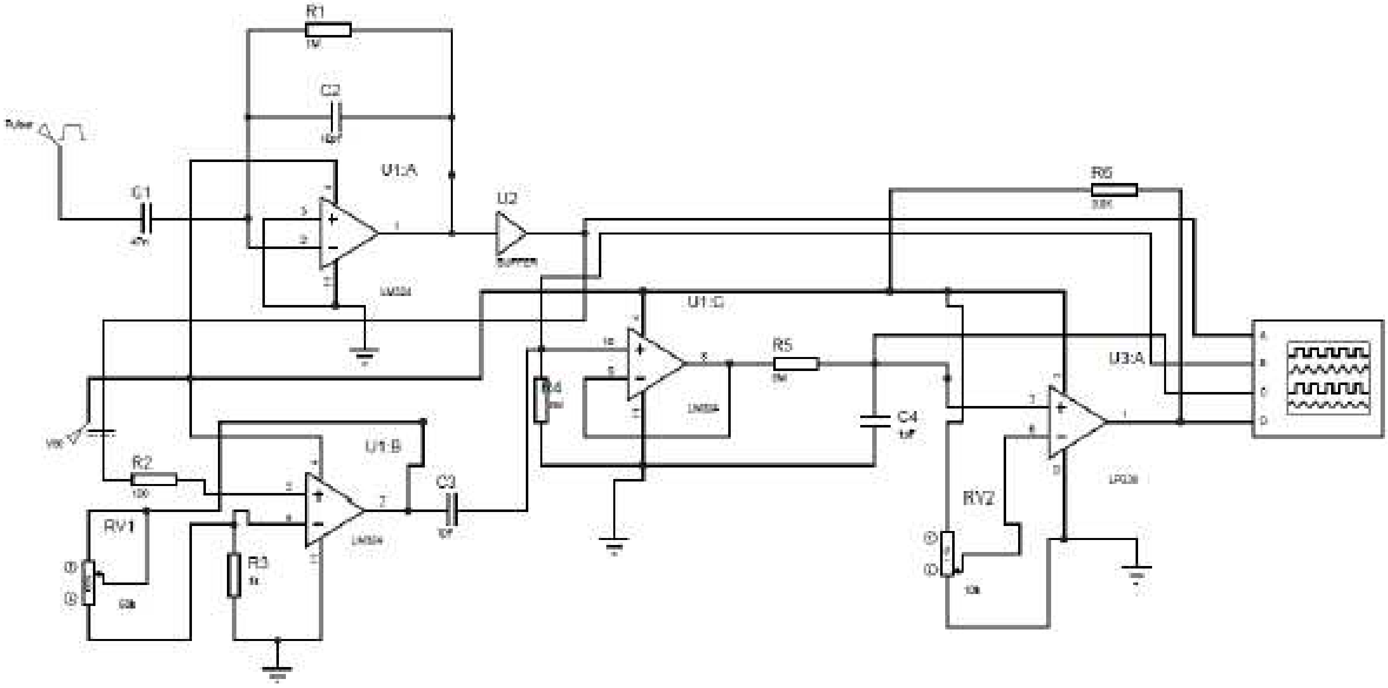

Fig.2: Complete Simulation Model of the Proposed Nuclear Detector Signal Channel.

2.2.1: Low Voltage Power Supply: A power supply must provide stable and ripple-free DC output voltage independent of line and load variations [5, 6]. Therefore, the low voltage power supply is essential for the channel and a built-in 5V DC power supply has been used in Proteus 7.7 simulation platform.

2.2.2: Preamplifier Circuit: The channel comprises of charge-sensitive preamplifier that avoids detector and stray capacitances by directly detecting the charge from the detector. The charge sensitive preamplifier uses a capacitor in place of the feedback resistor. This module has op amp U1: A, feedback resistor R1 and feedback capacitor C2.The input capacitance of this circuit is Ci, where A is the open-loop gain of the op-amp (operational amplifier).

If the op-amp gain is high enough that, the external (detector and stray) capacitance can be neglected.

$$A >> (Ci + Cf) / Cf$$

$$Vout = -AVin$$

$$Vout = -A \frac{Q}{Ci + (A+1)/Cf} \quad (1)$$

$$Vout \cong -\frac{Q}{Cf}$$

And the charge gain $$G_c = \frac{V_{out}}{Q_s}(=\frac{1}{C_f}) \qquad (2)$$

Typical R1 is of order 1 to 100 MΩ combined with C2 of 1pF, this leads to $\tau = 1 \sim 100$ µs [7]. Here, R1 is of only 1MΩ combined with C2 of 10 pF, which yields $\tau = 10$ µs. The charge gain G_c for the charge sensitive preamplifier in the proposed nuclear detector signal channel is 0.1V/pC.

2.2.3: Gain amplifier: The gain amplifier, amplifies the preamplifier output signal into 51 times although this may be increased/decreased depending on the input signal amplitude and components value, consists of R2, R3, RV1 and op amp U1:B. The gain amplifier circuit has been designed with the LM324 series consists of four independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages [8, 9].

$$V_{out} = (1+\frac{RV_1}{R_3})\,V_{in} \qquad (3)$$

2.2.4: Shaping amplifier Circuit: The shaping amplifier which is the combination of high pass and low pass filter with equal time constant ($\tau_1=\tau_2=\tau$) of 5 µs to increase the signal-to-noise ratio. The CR-RC shaping amplifier comprises of C3, R4, R5, C4 and U1:C. The noise contribution can be minimized by choosing an appropriate shaping time constant. At short time constants the series noise, thermal noise in the channel of the input FET, is dominant. At long shaping time constants the parallel noise viz. leakage currents, resistor thermal noise component dominates and removes DC offsets and baseline fluctuation [10].

The general solution of the response of the combined network to a step voltage of amplitude E at t=0 is

$$Eout = \frac{E\tau_1}{\tau_1-\tau_2}\left(e^{-\frac{t}{\tau_1}} - e^{-\frac{t}{\tau_2}}\right) \qquad (4)$$

Where τ1 and τ2 are time constants of the differentiating and integrating networks, respectively.

In nuclear pulse amplifiers, CR-RC shaping is most often carried out using equal differentiating and integration time constants. In that event, a particular solution for this case

$$Eout = E\frac{t}{\underset{3}{\tau}}e^{-\frac{t}{\tau}} \qquad (5)$$

2.2.5: Discriminator Circuit: Single ended or integral discriminator converts the CR-RC shaping amplifier output into logic pulses constituents are multi-turn potentiometer RV2, pull-up resistor R6 and comparator U3:A.

It also eliminates the system noise as well as pulse height discrimination. The discriminator circuit selects the minimum pulse height. When the input pulse exceeds the discriminator preset level, the discriminator generates an output pulse. The discriminator input is normally an amplified and shaped detector signal. This signal is an analog signal because the amplitude is proportional to the energy of the incident particle [12].

2.3. Results and Discussions

Nuclear pulse processing (NPP) deliver improvements in the quantity, quality and reliability of data for laboratory and research based nuclear spectroscopy systems, providing end users with data with a higher degree of accuracy and confidence to support their findings and conclusions, and the development and deployment of handheld instruments and field based instruments for remote and unattended operations [1].

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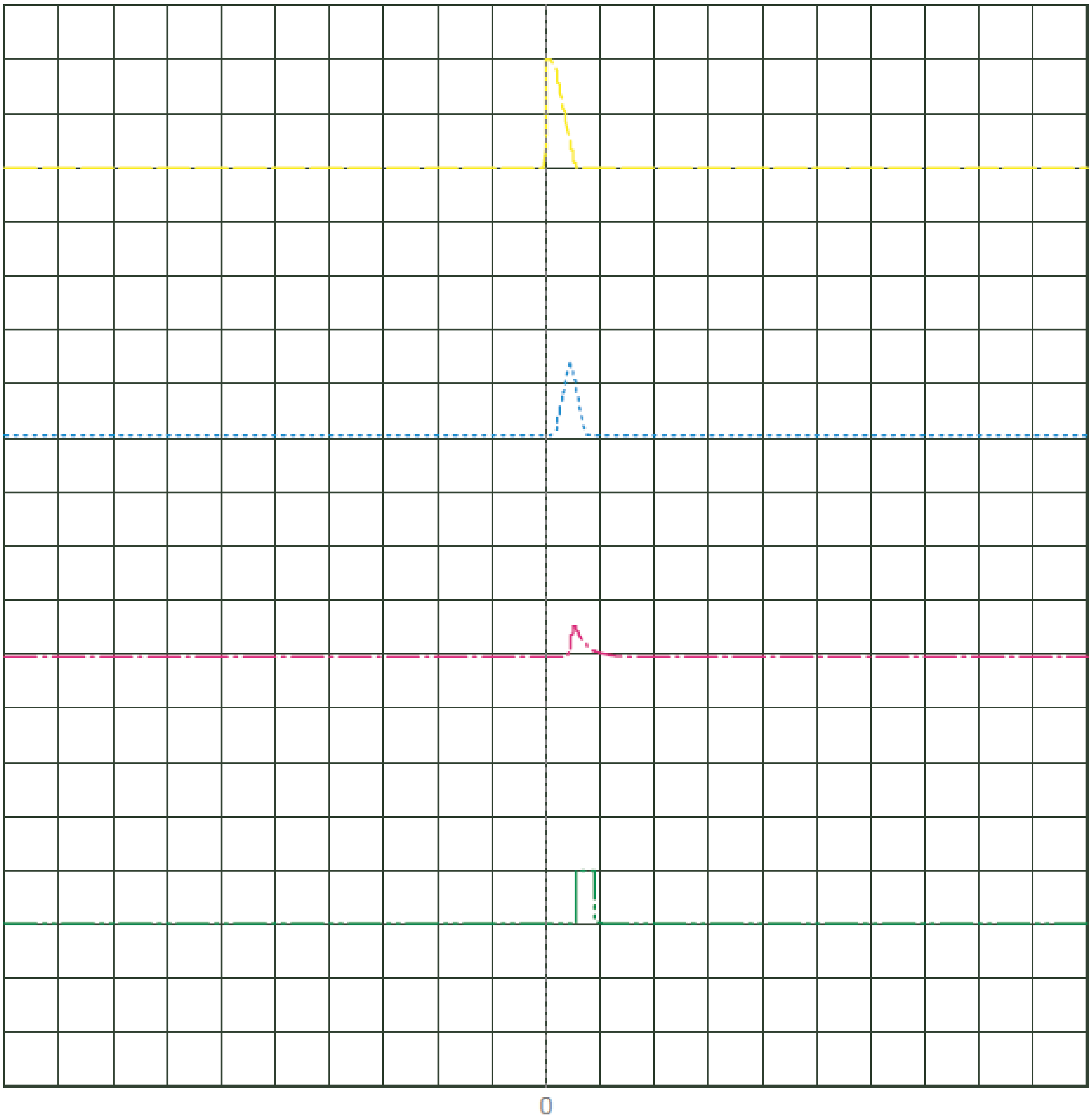
DSO Output

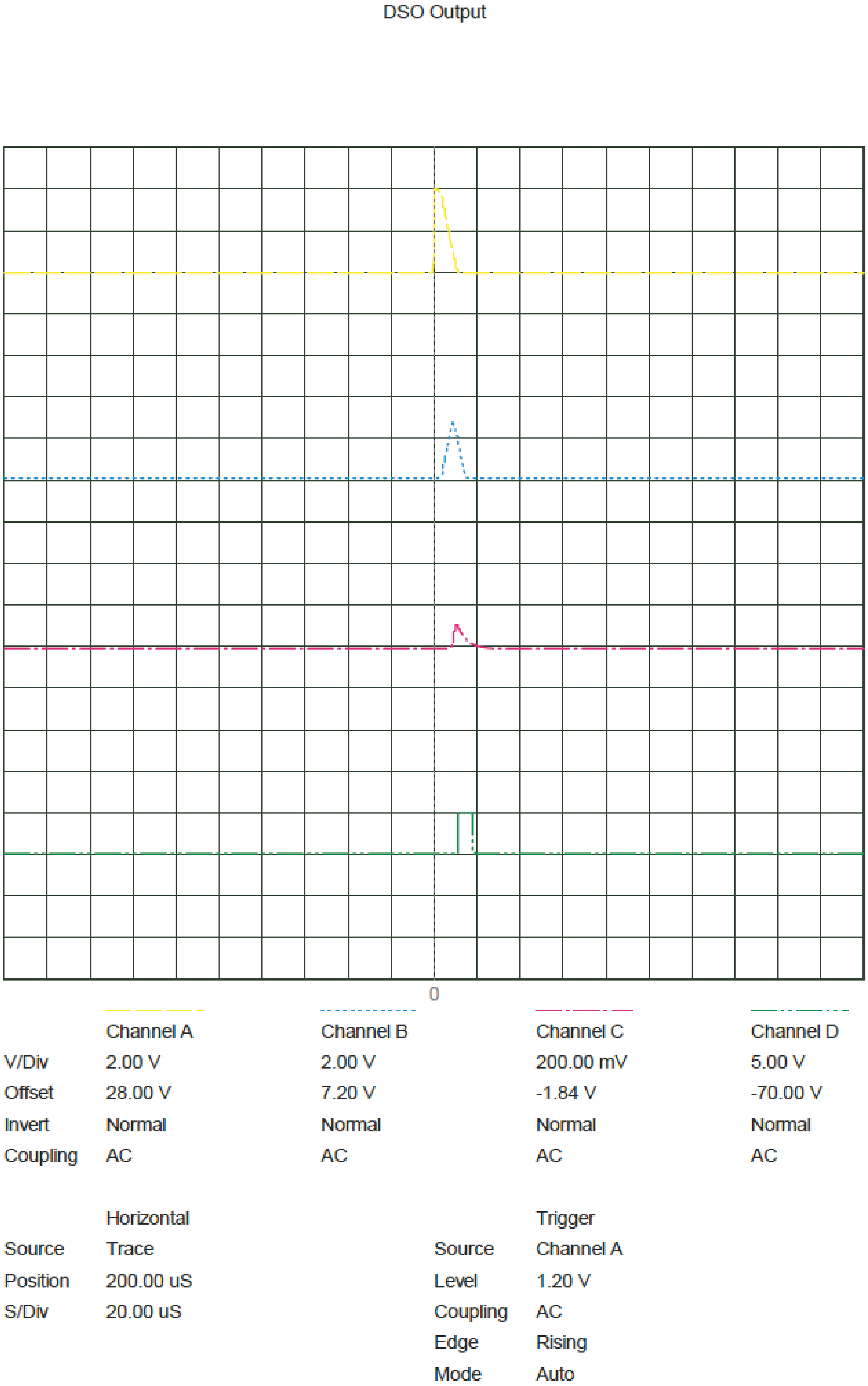


	Channel A	Channel B	Channel C	Channel D
V/Div	2.00 V	2.00 V	200.00 mV	5.00 V
Offset	28.00 V	7.20 V	-1.84 V	-70.00 V
Invert	Normal	Normal	Normal	Normal
Coupling	AC	AC	AC	AC

	Horizontal		Trigger
Source	Trace	Source	Channel A
Position	200.00 uS	Level	1.20 V
S/Div	20.00 uS	Coupling	AC
		Edge	Rising
		Mode	Auto

Fig.3: Shows the of the Proposed Nuclear Detector Signal Channel Charge Sensitive Preamplifier, Gain Amplifier, Shaping Amplifier and Discriminator output waveforms for 100Hz.

Therefore, fig.3, 4 and 5 shows proposed nuclear detector signal channel (NDSC) charge sensitive preamplifier, gain amplifier, shaping amplifier and discriminator output waveforms for different pulse/sec situations as 100Hz, 1 KHz and 10 KHz respectively.



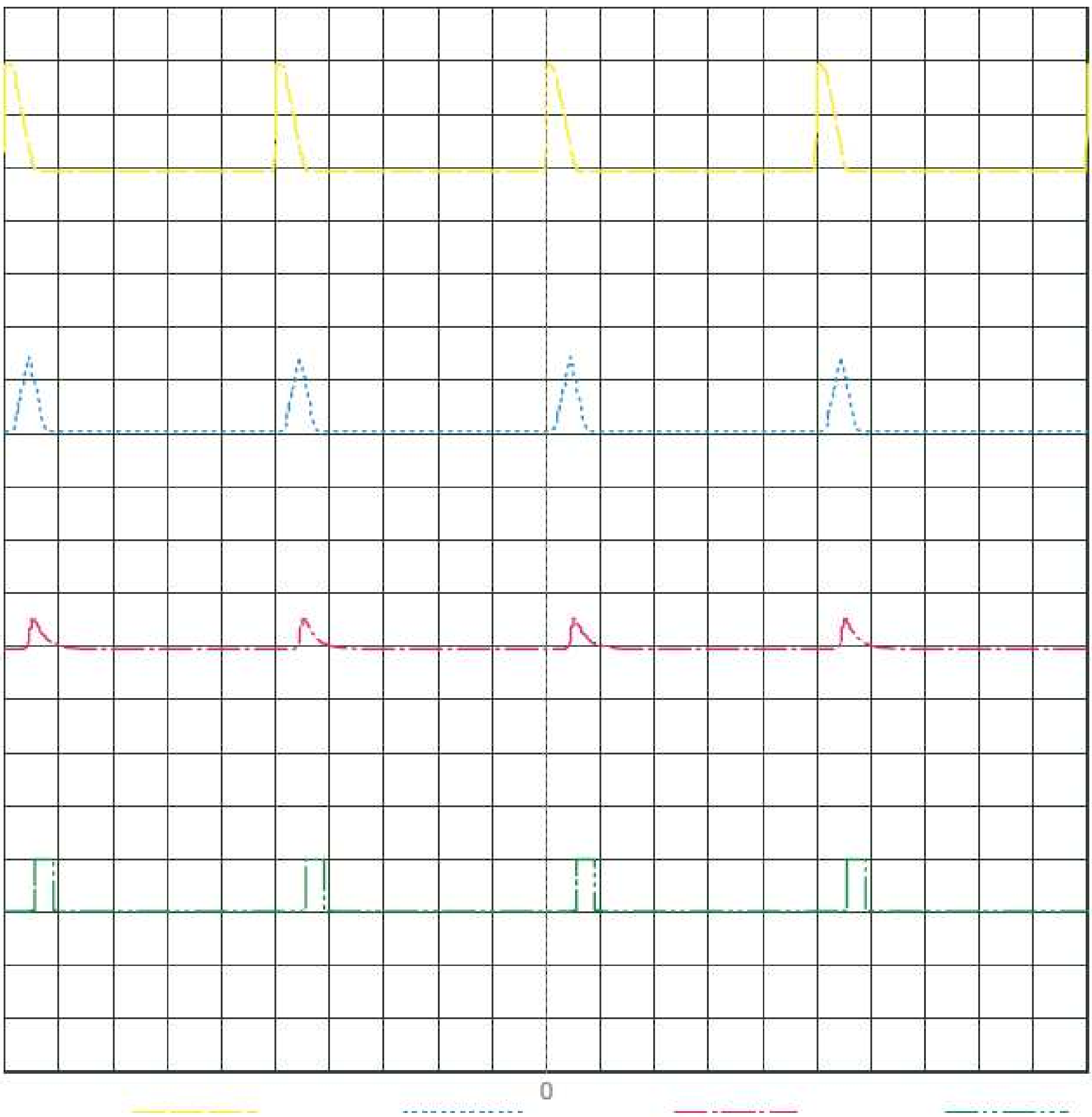
	Channel A	Channel B	Channel C	Channel D
V/Div	2.00 V	2.00 V	200.00 mV	5.00 V
Offset	28.00 V	7.20 V	-1.84 V	-70.00 V
Invert	Normal	Normal	Normal	Normal
Coupling	AC	AC	AC	AC

	Horizontal
Source	Trace
Position	200.00 uS
S/Div	20.00 uS

	Trigger
Source	Channel A
Level	1.20 V
Coupling	AC
Edge	Rising
Mode	Auto

Fig.4: Shows the of the Proposed Nuclear Detector Signal Channel Charge Sensitive Preamplifier, Gain Amplifier, Shaping Amplifier and Discriminator output waveforms in case of 1KHz.

DSO Output



	Channel A	Channel B	Channel C	Channel D
V/Div	2.00 V	2.00 V	200.00 mV	5.00 V
Offset	28.00 V	7.20 V	-1.84 V	-70.00 V
Invert	Normal	Normal	Normal	Normal
Coupling	AC	AC	AC	AC

	Horizontal
Source	Trace
Position	200.00 uS
S/Div	20.00 uS

	Trigger
Source	Channel A
Level	1.20 V
Coupling	AC
Edge	Rising
Mode	Auto

Fig.5: Shows the output waveforms of the Proposed Nuclear Detector Signal Channel Charge Sensitive Preamplifier, Gain Amplifier, Shaping Amplifier and Discriminator for 10KHz.

Pulse generator properties were analog pulse type current source amplitude 300µA, rise time 400ns, fall time 400ns, pulse width 500ns, both positive and negative overshoot were 0.00%, frequency ranges from 100Hz to 10 KHz in proteus 7.7 simulation platform.

Fig.3, 4 and 5 shows proposed nuclear detector signal channel charge sensitive preamplifier, gain amplifier, shaping amplifier and discriminator output waveforms characteristics data. From these figures, first of all, it has been observed that for an analog pulse type current source amplitude 300µA input to charge sensitive preamplifier from a pulse generator in proteus 7.7 simulation platform output was 4V fixed. Over all, 100Hz, 1 KHz and 10 KHz pulse/sec situations output amplitude for all cases was quite appreciable.

The preamplifier outputs electrical pulses 4V, rise time 1 µs which were input into an amplifier module which yielded 3V though it has 51 times amplification. The fall time for the input signal was 1 µs, that of output pulse was 12 µs. The pulse width of the amplifier output was 5µs, almost all cases that of input signal was 10µs .The positive and negative overshoot for both the cases has been recorded as 0.00%. Finally, the gain for the amplifier was 51 times although this may be increased/decreased depending on the input signal amplitude and components value.

Then the 3V input has fast rise time 6µs, the corresponding values for the shaping amplifier output were 100mV, 2µs has been observed. Thereafter, the fall time for the input signal was 6 µs that of output pulse was 6µs.The pulse width of the shaping amplifier output was 8µs, almost all cases that of input signal was 10µs .The positive and negative overshoot for both the cases has been recorded as 0.00%. Finally, the gain for the shaping amplifier has been observed as 0.033 for all 100Hz, 1 KHz and 10 KHz pulse/sec situations.

Fig.3, 4 and 5 shows the functionality testing data for discriminator in the proposed nuclear detector signal channel (NDSC). From these waveform graphs, it has been observed that discriminator output pulse amplitudes for all 100Hz, 1 KHz and 10 KHz pulse/sec situations approach to supply voltage. While the supply voltage was 5.0V, the output logic pulse amplitude has been observed as 5.0V. The rise time and fall time for the logic pulses has similar pattern. And the discriminator outputs have large pulse width as seen 6µs. There were no positive or negative overshoot.

The selected operational amplifier LM324 is low-cost, short circuited protected outputs, single supply operation and four amplifiers per package [9]. The LM339 consists of four independent precision voltage comparators, with an offset voltage specification as low as 20mV max for each comparator, which were designed specifically to operate from a single supply over a wide range of voltages [13]. Therefore, the channel can be used with prototype nuclear instruments/MCA/ nuclear imaging applications successfully.

3. Conclusion

Nuclear Detector Signal Channel (NDSC) comprises of Preamplifier-Amplifier-Shaper-Discriminator for prototype Nuclear Instruments/MCA/ Nuclear Imaging has been presented in this research. Circuit description, functional description and related mathematical formulae for these modules have been provided elaborately. Waveforms of the proposed NDSC under various pulse/sec (100 Hz, 1 KHz & 10 KHz) situations also have been presented. The channel has been tested repeatedly. Its performance was found satisfactory.

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