Yokto (10^{-24}V) Instrumentation Amplifier

Neha Srivastava[1], Ahmad Shadab[2]
Dept. of Electronics & Communication Engg.
B. N. College of Engineering & Technology
Lucknow, U.P. – 226021, India
e-mail: [1]neha.sri.56@gmail.com,
[2]ahmadshadab.aec@gmail.com,

Gaurav Shukla
Dept. of Electronics & Comm. Engg.
Saroj Institute of Technology & Management
Lucknow, U.P. – 226002, India
e-mail: grv.shukla2011@gmail.com

Abstract—**Operational amplifiers (op-amps) are the building blocks for analog signal conditioning circuits and in particular, instrumentation amplifiers. Op-amps amplify electrical signals such as the small voltages coming from instrumentation sensors. The gain is controlled by external components, provided the amplifiers are operated within reasonable boundaries. The op-amp is a differential amplifier, allow us to not only amplify very small sensor signals but also to add or subtract offset voltages and to electrically isolate (buffer) sensors from the rest of system. The analysis in this paper will be based largely on ideal amplifiers. External components such as resistors are used to feed the output back to the input and thus to reduce the ideal infinite gain to any desired gain. In this paper, we present the amplification of Yokto level signal (10^{-24}V) to the saturation level of op-amp with the help of cascaded structure of instrumentation amplifier. We can say, this is the cascaded or Yokto instrumentation amplifier. This structure of instrumentation amplifier with order five, amplifies the signal level upto 490dB at normal condition of components. At the critical values of all the components, the gain will be approximately 630dB. The gain level is also increased by the increment in the order of the instrumentation amplifier. This paper presents the artificial neural networks (ANNs) implementation of cascaded instrumentation amplifier.**

Keywords- Operational Amplifier, Differential Amplifier, Instrumentation Amplifier, Cascaded Structure, Ideal Gain, Artificial Neural Network.

I. INTRODUCTION

With the increase in need to have a device which not only read a signal from a sensor but also to subtract one voltage level from another and amplify the difference significantly, instrumentation amplifier comes into existence. It is one of the most versatile signal processing amplifiers. An instrumentation amplifier is used for precision amplification of differential DC or AC signals while rejecting large values of common mode noise. To understand the circuit and working of instrumentation amplifier properly one should have a thorough knowledge of op-amp in general and differential amplifier is specific because it is a modification of differential amplifier.

The operational amplifier [1], [2] was coined in the 1940's to consign to a special kind of amplifier that, by appropriate selection of external components, can be configured to perform many type of mathematical operation. Near the beginning op-amps where made from vacuum tubes consuming a lot of space and energy. Presently, op-amps where made smaller by implementing them with transistors in integrated circuits (IC), highly proficient and cost effective, also amplify small electrical signals coming from instrumentation sensors. The amount of gain is controlled by external components, provided the amplifiers are operated within reasonable boundaries. They are easy to configure for many applications & very reliable. In true sense op-amp is a differential amplifier. It amplifies the difference between its two inputs. It allows us to not only amplify very small sensor signals but also to add or subtract offset voltages and to electrically isolate sensors from the rest of system, but it also has certain limitation which become basis for the development of instrument amplifier.

The limitations with the differential amplifier are as follows:

- The rejection of the common voltage at the inverting and non-inverting terminals is very much dependent on the external resistors. If there is any mismatch or a variation in these resistors the rejection of the common mode voltage will not be complete.
- The gain of the circuit is not easy to adjust. To adjust the gain two or more resistors need to be varied. While keeping their ratio exactly matched, this is almost impossible to achieve.
- The input impedance of two input terminals is finite. So, the two sources that provide the voltages to be subtracted will have to come from two identical and almost ideal sources. A balance between the two input sources of a very high degree is required.

To overcome the above limitations of differential amplifier certain modifications were made and instrumentation amplifier comes into existence.

ANNs can solve great variety of problems in areas of pattern recognition, image processing and medical diagnostic. The biologically inspired ANNs are parallel and distributed information processing systems. This system requires the massive parallel computation. Thus, the high speed operation in real time applications can be achieved only if the networks are implemented using parallel

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hardware architecture. Implementation of ANNs falls into two categories: Software implementation and hardware implementation. ANNs are implemented in software, and are trained and simulated on general-purpose sequential computers for emulating a wide range of neural networks models. Software implementations offer flexibility. However hardware implementations are essential for applicability and for taking the advantage of ANN's inherent parallelism. Specific-purpose fixed hardware implementations i.e. VLSI implementations of ANNs provide high speed in real time applications and compactness [3]. However, they lack flexibility for structural modification and are prohibitively costly. Therefore, the cascaded instrumentation amplifier is implemented by the ANNs.

II. INSTRUMENTATION AMPLIFIER

An instrumentation amplifier [4] is a unique combination of commonly used differential inputs of any op-amp and an additional resistor R_{gain} which introduce control on gain of amplifier. Some other additional characteristics included in instrumentation amplifier are very low DC offset, low drift, low noise, very high open-loop gain, very high common-mode rejection ratio, and very high input impedance. It provides us great accuracy and stability of the circuit. Instrumentation amplifier offer a unique combination of differential inputs, high input impedance and excellent precision and noise specifications. Using both zero-drift and traditional topologies, linear technology's instrumentation amplifiers feature high precision, low drift and excellent power supply rejection ratio and common mode rejection ratio (CMRR) [5].

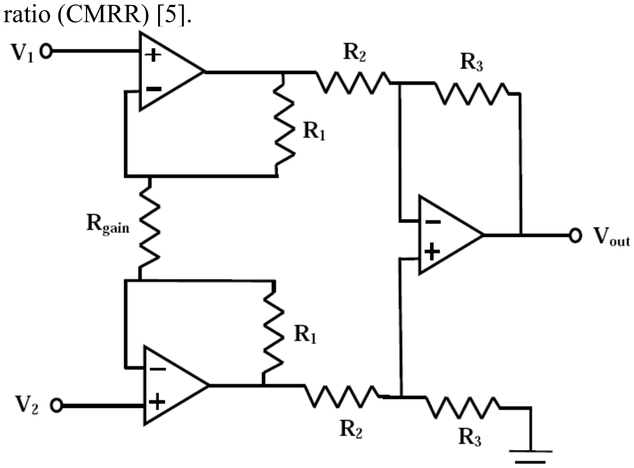

Figure 1. Instrumentation amplifier [1].

Like all linear technology devices, instrumentation amplifiers are unique in offering fully specified, tested and guaranteed performance for key parameters over the full operating temperature range, enabling high reliability designs [6]. These instrumentation amplifiers use an external resistor to set the gain. An instrumentation amplifier is a category of differential amplifier that has been united with input buffers, which remove the need for the matching of input impedance and thus make the amplifier appropriate for use in measurement and test equipments. Although, the instrumentation amplifier is usually shown schematically identical to a standard op-amp, the instrumentation amplifier is almost always internally composed of three op-amps shown in Figure 1. These are arranged so that there is one op-amp to buffer each input and one to produce the desired output with adequate impedance matching for the function.

The most commonly used instrumentation amplifier circuit is shown in the Figure 1. The gain of the circuit is,

$$\frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2} \tag{1}$$

The standard differential amplifier [7] circuit demonstrates along with the resistors R_2 and R_3, with gain R_3/R_2 and differential input resistance $2R_2$. The two amplifiers before the differential amplifier are the buffers. When R_{gain} is open circuited, they are simple unity gain buffers; the circuit will work in that condition, with gain simply equal to R_3/R_2 and high input impedance due to buffers. The buffer gain could be increased by putting resistors between the buffer inverting inputs and ground to shunt away some of the negative feedback; however, the single resistor R_{gain} between the two inverting inputs is a much more well-designed method. It increases the differential-mode gain of the buffer pair while leaving the common-mode gain equal to 1. The CMRR is increases of the instrumentation amplifier and also enables the buffers to hold larger common-mode signals without clipping than would be the case if they were separate and had the same gain. Another benefit of the method is that it increases the gain using a resistor relatively than a pair, thus avoiding a resistor-matching problem and very conveniently allowing the changed gain of the circuit by changing the value of a resistor.

An instrumentation amplifier can also be built with two op-amps to save on cost and increase CMRR, but the gain must be higher than +6dB. Instrumentation amplifiers can be built with used components in an IC. Instrumentation amplifier without feedback is the high input impedance differential amplifier designed. This allows lesser number of amplifiers, reduced thermal noise and increased bandwidth. Very high input impedance, high CMRR, low DC offset, low-noise measurements, is made by adding a non-inverting buffer to each input of the differential amplifier to increase the input impedance.

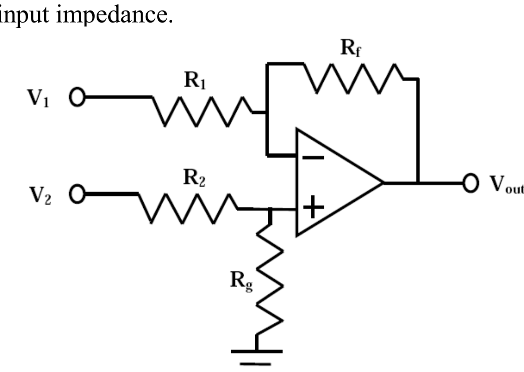

Figure 2. Differential amplifier.

Figure 2 is used for finding the difference of two voltages each multiplied by some constant (determined by the resistors) is also known as differential amplifier.

$$V_{out} = \left(\frac{R_f + R_1}{R_g + R_2}\right)\frac{R_g}{R_1}V_2 - \frac{R_f}{R_1}V_1 \quad (2)$$

The input impedance of the differential amplifier is approximately R_1+R_2. For common mode rejection, anything done to one input must be done to the other. The addition of a compensation capacitor in parallel with R_f, must be balanced by an equivalent capacitor in parallel with R_g.

III. Cascaded Instrumentation Amplifier

The cascaded instrumentation amplifier is shown in Figure 3. The cascaded form is designed with the help of an additional part of the instrumentation amplifier i.e. known as electronically isolated (buffer) circuit, shown in Figure 4. The need of cascaded instrumentation amplifier to provides the very high gain by the use of small values of components. The output voltage for the cascaded instrumentation amplifier is,

$$\frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)\left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2} = \left(1 + \frac{2R_1}{R_{gain}}\right)^2 \frac{R_3}{R_2} \quad (3)$$

If, the number of stages is N, the output voltage for cascaded instrumentation amplifier is,

$$\frac{V_{out}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{gain}}\right)^N \frac{R_3}{R_2} \quad (4)$$

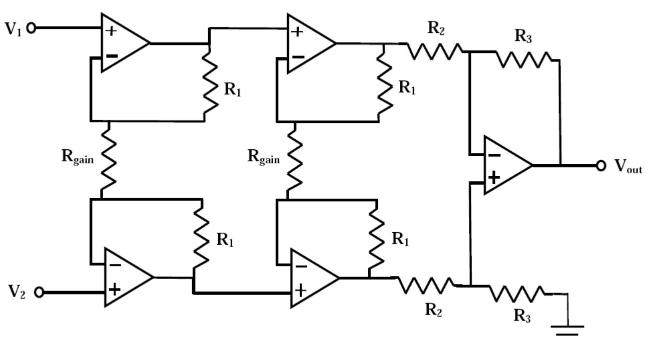

Figure 3. Cascaded instrumentation amplifier.

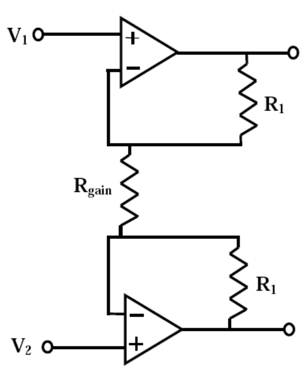

Figure 4. Additional part for the cascaded instrumentation amplifier.

All the parameters, V_{out}, V_1, V_2, R_1, R_2, R_3 and R_{gain} are shown Figure 3. If, we increase the number of stages, the gain of the cascaded instrumentation amplifier definitely increased with very high rate. Therefore, the cascaded instrumentation amplifier concludes that, we can amplify very low level input signals. The cascaded instrumentation amplifier provides a very high gain. Therefore, it can be used in different applications as medical instruments, data acquisition systems, electronic measuring instruments, etc but the most important application is noise amplification.

IV. Artificial Neural Network Implementation of Cascaded Instrumentation Amplifier

The concept of ANNs is emerged from the principles of brain that are adapted to digital computers. The works of ANNs were the models of neurons in brain using mathematics rule. These works show that each neuron in ANNs take some information as an input from another neuron or from an external input. This information is propagated as an output that are computed as weighted sum of inputs and applied as non-linear function [3]. Architectural ANNs parameters such as number of inputs per neuron and each neuron's conductivity change remarkably from application to application. Thus, for special purpose network architectures parameters must be carefully balanced for efficient implementation. It is apparent that there are three kinds of parallelism to explain within ANNs when carefully exanimate to the data flow and structure of ANNs. The first is spatial parallelism i.e. every neuron in the same layer runs simultaneously. The second is algorithmic parallelism that is related to the formulation of the algorithm itself. In addition, computation on successive layers can be pipelined [8]. In the neural network implementation of cascaded instrumentation amplifier, the multilayer neural network is used.

A. *Multilayer Neural Networks*

The multilayer feedforward neural network is the workhorse of the Neural Network. It can be used for both function fitting and pattern recognition problems. With the addition of a tapped delay line, it can also be used for prediction problems. It illustrates the basic procedures for designing any neural network. The work flow for the general neural network design process has seven primary steps:

- Collect data
- Create the network
- Configure the network
- Initialize the weights and biases
- Train the network
- Validate the network (post-training analysis)
- Use the network

B. *Multilayer Neural Network Architecture*

An elementary neuron with *R* inputs is shown in Figure 5. Each input is weighted with an appropriate *w*. The sum of the weighted inputs and the bias forms the input to the transfer function *f*. Neurons can use any differentiable transfer function *f* to generate their output.

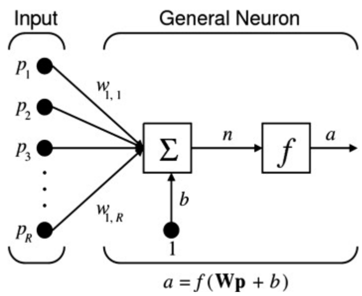

Figure 5. Elementry neuron.

The multilayer networks are used many types of neuron models or transfer functions as logsig, tansig & purelin etc. The function logsig generates outputs between 0 and 1 as the neuron's net input goes from negative to positive infinity. Alternatively, multilayer networks can use the tan-sigmoid transfer function tansig. Sigmoid output neurons are often used for pattern recognition problems, while linear output neurons are used for function fitting problems. All the three transfer functions are the most commonly used transfer functions for multilayer networks, but other differentiable transfer functions can be created and used if desired.

A single-layer network of S logsig neurons having R inputs is shown in Figure 6 in full detail on the left and with a layer diagram on the right.

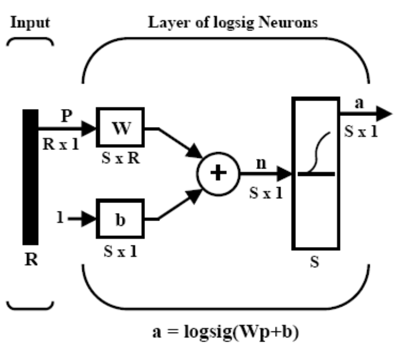

Figure 6. Single-layer neural network.

Feedforward networks often have one or more hidden layers of sigmoid neurons followed by an output layer of linear neurons. Multiple layers of neurons with nonlinear transfer functions allow the network to learn nonlinear relationships between input and output vectors. The linear output layer is most often used for function fitting problems. On the other hand, if you want to constrain the outputs of a network, then the output layer should use a sigmoid transfer function.

This is the case when the network is used for pattern recognition problems. As in Network Objects, Data, and Training Styles for multiple-layer networks the layer number determines the superscript on the weight matrix. The appropriate notation is used in the two-layer tansig/purelin network shown in Figure 7. This network can be used as a general function approximator. It can approximate any function with a finite number of discontinuities arbitrarily well, given sufficient neurons in the hidden layer.

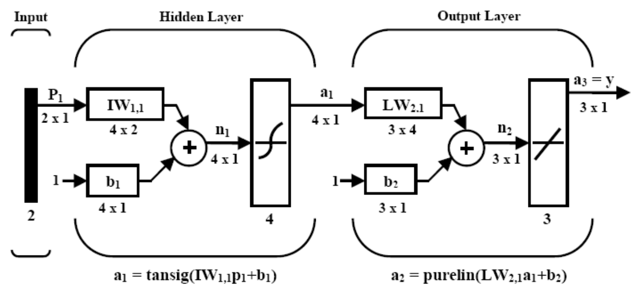

Figure 7. Multi-layer network: two layer tansig/purelin network.

V. SIMULATION OF CASCADED INSTRUMENTATION AMPLIFIER

A. *Simulation without neural network using MATLAB*

In Figure 3, the cascaded instrumentation amplifier is shown. For the general structure of cascaded instrumentation amplifier, we can use the N number of stages of the additional part of instrumentation amplifier. In equation (4), the general formula of gain for the N stages of instrumentation amplifier is given. According to that, Table I represent the typical values of gain and Table II maximum input voltage for the saturation level of cascaded instrumentation amplifier at the different ratios of resistances R_3/R_2 and R_1/R_{gain}.

The graphical representation of gain in dB is shown in Figure 8 at the different ratios of resistances. Simulation is done through MATLAB simulation software [9], [10]. Here, the maximum gain level is 490dB at R_3/R_2=1k and R_1/R_{gain}=10k for ideal case upto 5 stages of cascaded instrumentation amplifier. It can be increases, if we increase the number of stages. The gain level 490dB for five stages at the normal values of the components, at the critical values of components it will be approximately 630dB.

Figure 9 presents, the graphical representation of maximum input signal w.r.t. maximum input of zero order instrumentation amplifier for the cascaded instrumentation amplifier. The maximum input level is decreased by 430dB. The gain for the fifth order of the cascaded instrumentation amplifier is approximately 3.2×10^{24} and the maximum input voltage for saturation level is 4.686×10^{-24}V. Therefore, this paper concludes that the fifth order cascaded instrumentation amplifier is ideally used as a Yokto (10^{-24}V) instrumentation amplifier.

TABLE I. GAIN (IN DB) OF CASCADED INSTRUMENTATION AMPLIFIER.

No. of stages	Gain (In dB)				
	R_3/R_2= R_1/R_{gain} =1	R_3/R_2= R_1/R_{gain} =10	R_3/R_2= R_1/R_{gain} =100	R_3/R_2= R_1/R_{gain} =1k	R_3/R_2=1k & R_1/R_{gain} =10k
0	0	20	40	60	60
1	9.5424	46.4443	86.0639	126.0249	146.0210
2	19.0848	72.8887	132.1278	192.0498	232.0420
3	28.6272	99.3331	178.1917	258.0748	318.0631
4	38.1697	125.7775	224.2556	324.0997	404.0841
5	47.7121	152.2219	270.3196	390.1247	490.1051

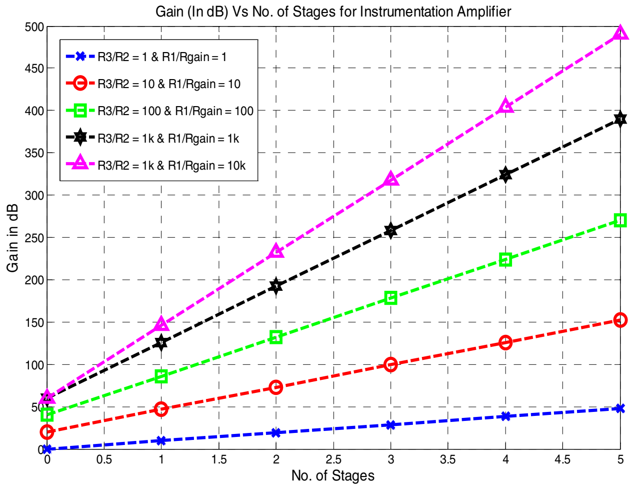

Figure 8. Cascaded instrumentation amplifier gain (in dB) at different values of R_3/R_2 and R_1/R_{gain}.

TABLE II. MAXIMUM INPUT VOLTAGE FOR SATURATION LEVEL OF CASCADED INSTRUMENTATION AMPLIFIER.

No. of stages	Maximum input voltage for saturation level (in Volt)				
	$R_3/R_2 = R_1/R_{gain} = 1$	$R_3/R_2 = R_1/R_{gain} = 10$	$R_3/R_2 = R_1/R_{gain} = 100$	$R_3/R_2 = R_1/R_{gain} = 1k$	$R_3/R_2 = 1k$ & $R_1/R_{gain} = 10k$
0	15	1.5	0.15	0.015	0.015
1	5	0.0714	0.0007	7.496E-06	7.499E-07
2	1.6667	0.0034	3.712E-06	3.746E-09	3.749E-11
3	0.5556	0.0001	1.847E-08	1.872E-12	1.874E-15
4	0.1851	7.712E-06	9.189E-11	9.356E-16	9.373E-20
5	0.0617	3.672E-07	4.572E-13	4.675E-19	4.686E-24

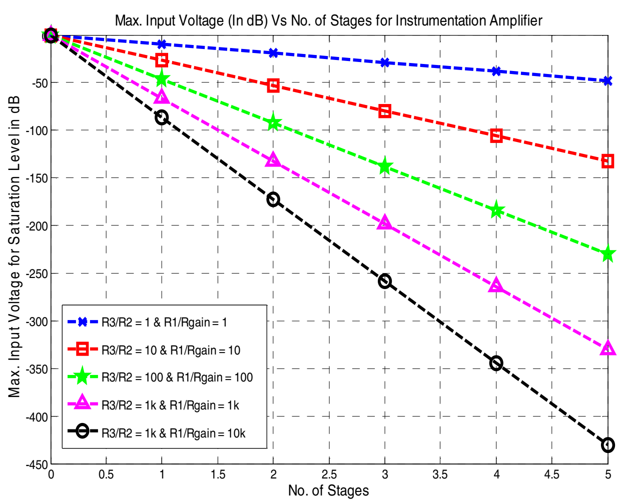

Figure 9. Cascaded instrumentation amplifier maximum input (in dB) w.r.t. zero order instrumentation amplifier at different values of R_3/R_2 and R_1/R_{gain}.

B. *Simulation with neural network using MATLAB*

The neural network is implemented for the five stage cascaded instrumentation amplifier. The two layer network is used for the instrumentation amplifier. For the training of network with above condition we get the trained network for the ratios of resistances upto 1000, mean square error (*mse*) upto 10^{-3}, and simulation training time is approximately 1.59s.

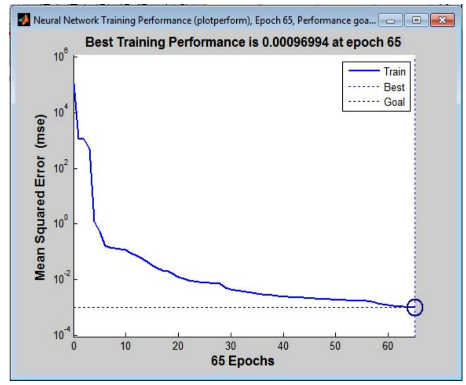

Figure 10. Training performance of neural network.

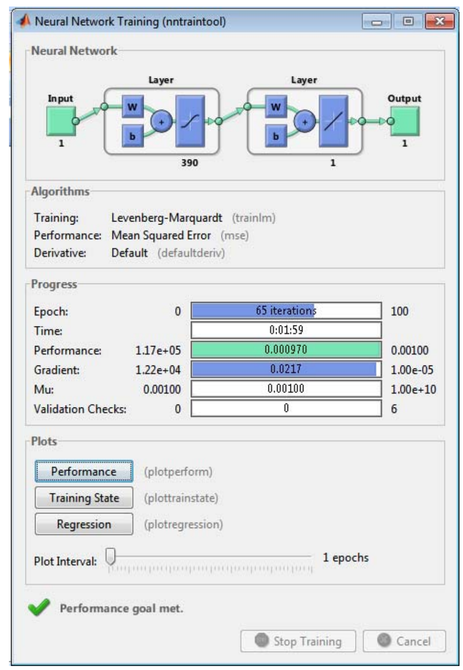

Figure 11. Neural network training tool status.

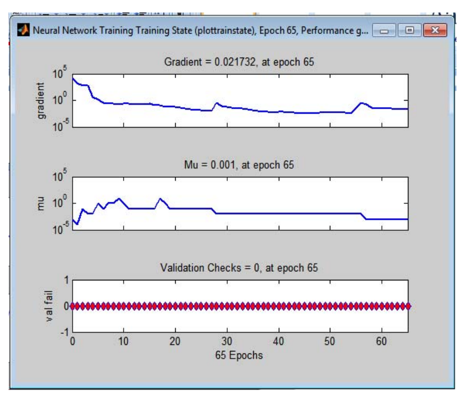

Figure 12. Neural network training states.

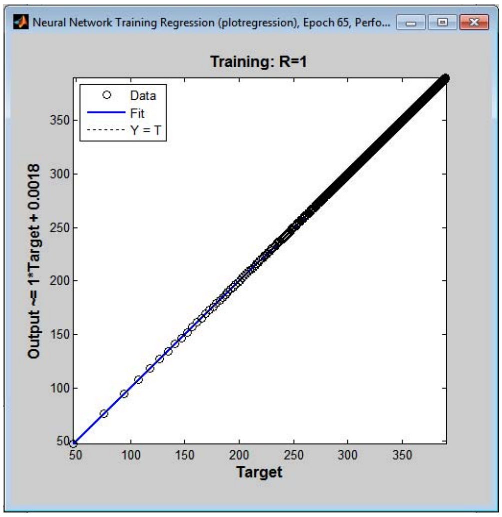

Figure 13. Neural network regression.

The training time will be lesser if the ratio of resistances is small and also the order of the cascaded instrumentation amplifier is less. The goal is met at 65 epochs i.e. *mse* of 10^{-3} which is shown in Figure 10. The training network status shown in Figure 11 and also their graphical representation are shown in Figures 12 & 13, presents the training status & regression of neural network.

VI. CONCLUSION

Many research works are present in the field of analog electronics as operational and instrumentation amplifier as well as neural network but it is the strong effort in this field. Op-amps are the base for analog signal processing and conditioning circuits. Op-amps also amplify the small voltage signals by the instrumentation amplifiers. They are easy to configure for many applications, cost effective and reliable. The instrumentation amplifier amplify very small signals and also subtract offset voltages and to electrically isolate sensors from the rest of system.

This paper concludes that the cascaded instrumentation amplifier is implemented and also used for the amplification of very low i.e. Yokto (10^{-24}V) level signals. Therefore it can be easily amplify the very low level signals and used in many applications like medical instruments, data acquisition systems, physical quantity measuring instruments, etc. But, the most important application is noise amplification because the level of noise signal is approximately 10^{-12}V.

Here, the five stages cascaded instrumentation amplifier is also implemented on neural network and we can set their minimal *mse*. The structure of the network is similar for any stage of instrumentation amplifier; power consumption at higher stage will be lesser than cascaded instrumentation amplifier using op-amps. So, it gives the better performance w.r.t. cascaded instrumentation amplifier using op-amps.

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