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Low-Cost 4-20 mA Loop Calibrator

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Abstract

Instrument calibration is vital to a successful control system because signal inputs to the system controllers come from such instruments. This paper presents a method for actualizing a standard low-cost loop calibrator for the famous 4-20 mA electrical signaling scheme. The loop calibrator generates a linear current signal from 4 to 20 mA over a 250 Ω typical process instrument load for calibration. The realization of the loop calibrator relies on a voltage-to-current converter to build a constant current source. The voltage controlled constant current source is built from discrete components and an op-amp to keep the cost low. Results from simulations and the prototype demonstrate the performance of the 4-20 mA loop calibrator which utilizes a greatly reduced number of components. The cost of these components is approximately 34% of the least expensive calibrator sampled, though other production costs are not included. This conclusion reinforces the fact that loop calibrators can be cheaper.

Keywords

Instruments, Calibration, 4-20 mA Standard, Loop Calibrator

1. Introduction

In about the 1950s, current input became the preferred process control signal [1] therefore a new signaling standard was later in the same century introduced into the market known as the 4-20 mA current signaling standard. This standard had a striking resemblance to the 3-15 psi pneumatic signal, which was in use at that time. Out of the many standards available today for process signaling, the 4-20 mA still stands out as the most preferred because of its robust nature [2]. It is a reliable way of sending and receiving signals in process control on a single pair of cables carrying both instrument power and signal. It is equivalent to the 1 - 5 V [3]. The standard gave birth to many instruments; thus, the need for instrument calibrators for this standard.

2. Overview of 4-20 mA Loop Calibrators

These devices are used for optimizing control processes. They are also actively used in loop checks, function checks, calibration, maintenance and repair of process instruments like pressure, temperature, level and flow transmitters or sensors, which work with the 4-20 mA standard. Figure 1 shows a schematic of the 4-20 mA loop.

2.1. Properties

1) 20% Offset: Whether it is the 3 - 15 psi or 1 - 5 V or the 4-20 mA, all these share the property of 20% offset sometimes referred to as "live zero", which utilizes a measure of active measuring process value for the 0 points instead of an absolute zero value [5]. For the 4-20 mA, 4 mA is the 20% offset, and any loop current below this value is considered a dead zero and an alarm condition.

2) Robustness: It is ideal for transmitting data because of its high degree of immunity to electrical noise [3]. Though there are voltage drops across every process element and across less perfect terminations, the same current flows throughout the circuit because it's a series connection. See Figure 1.

3) Requirements: The interface requirement for this standard is simple. A pair of wire is required for interconnection. The wires can be added or removed without affecting the accuracy of the standard. This is a unique feature for analogue interfaces.

2.2. Cost of Loop Calibrators

Taking the mean of the prices will yield a value far above $200.00 per loop calibrator, and the mean of accuracy is 0.0258 mA. It is worth to note here that most of the loop calibrators mentioned in Table 1 perform more than just the basic loop calibrator function. They have some other functions incorporated at different levels of complexity with the loop calibrator function. Therefore, the basis of comparison here is restricted to the loop calibrator function.

Affordability of test equipment, can in a way, determines their availability. High prices reduce affordability and, in turn, the availability of such equipment. This leads us to the basis of this project. The aim here is to produce a standard, low-cost loop calibrator that can perform all the essential functions of a calibrator while remaining very affordable. The loop calibrator should cost less than $70.00 with an accuracy ±0.01 mA. Other specifications are a minimum load 0 Ω,

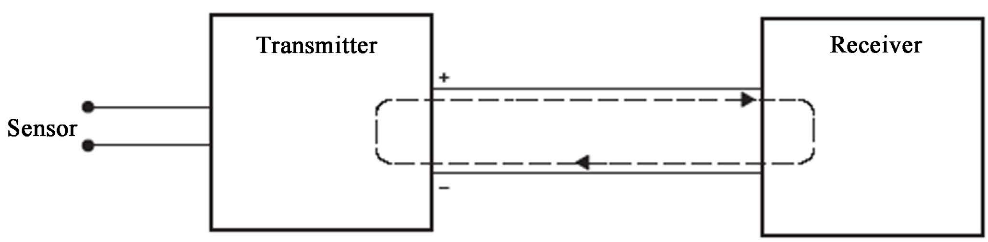

Figure 1. 4-20 mA current loop interface [4].

Table 1. Cost of loop calibrators (online shops as at 14/08/2022).

S/N	Item	Price/Unit ($)	Accuracy (mA)
1	Fluke 705 Loop Calibrator	799.49	0.025
2	Martindale MARTEK300	407.20	0.100
3	CALOG LOOPII mA	695.34	0.010
4	PIE 334 and 334Plus	835.00	0.015
5	Altek 334A Process Loop	555.00	0.015
6	Voltcraft CC-421	148.28	0.048
7	GE Druck UPS-Ill	965.00	0.010
8	Additel 209/210 Series	731.00	0.015
9	Extech PRC10	365.90	0.010
10	Yokogawa CA71	1622.00	0.010

maximum load 400 Ω, resolution 0.01 mA or 0.1%, power input 18 - 32 Vdc, operating temperature 0 - 60˚C, storage temperature 10˚C - 70˚C, overload protection at 20 mA, ramp-based input, robust, efficient, portable and reliable.

Loop calibrators began with the work of a man called Edward Weston [6]. The inventions of Edward Weston in the late 1800 s became the foundation for electrical measurement or electrical signaling schemes of today's world. When electronics-enabled wiring came into existence, various companies introduced their standard instrumentation signals, causing confusion until the 4-20 mA range was used as the standard electronic instrument signal for transmitters and valves. This signal was eventually standardized as ANSI/ISA 50.00.1-1975 (R2012) [7]. "Compatibility of Analogue Signals for Electronic Industrial Process Instruments".

3. Why a Low-Cost 4-20 mA Loop Calibrator

3.1. Advances in Technology

In the wake of the rigorous research in this field, a significant breakthrough in technology might not mean so well for many traditional technologies, the 4-20 mA calibrator inclusive. For example, in [8] a wireless 4-20 mA simulator is considered. Nobody will want to invest large sums of money in an old traditional technology that could be perceived to be overtaken with modernization. It is, therefore, better to invest wisely in a low-cost traditional technology.

3.2. Affordability

Making affordable high-quality calibrators may help improve a company's share of the market considerably. The afore-mentioned, has the potential to raise sales of such a calibrator. This leads us to the next point, availability.

3.3. Availability

A low-cost calibrator could help improve the availability of the calibrator at its point of need. So many could be put to work while, reducing downtime and increasing productivity.

4. Calibrator Design

At the heart of the loop calibrator is its ability to provide constant current irrespective of the load as long as the load falls within the specified load range [9] [10]. This necessitated the design of a voltage-controlled current source (VCCS). In order to properly discuss the requirements, the loop calibrator is divided into two fundamental block components. See **Figure 2** below.

4.1. Constant Current Source

A simple current source setup from Horowitz & Hill, 2015 [11] is adopted. This current source would then become the basis for the loop calibrator design. This is how the circuit works. The voltage divider set up with $R1$ and $R2$ would determine V_{in}, which is the voltage at the non-inverting input of the op-amp.

Thus:

$$V_{in} = V_{cc}\frac{R2}{R1+R2} \tag{1}$$

This same voltage appears at the inverting input of the op-amp through the internal feedback mechanism of the op-amps [12]. With the inverting input connected to the emitter of the transistor Q_1, this then implies that the input voltage to the operational amplifier is equal to the collector voltage as seen in **Figure 3**.

$$V_{in} = V_e \tag{2}$$

Applying Ohm's law to **Figure 3**,

$$V \propto I \quad \text{thus:}$$

$$V = IR \tag{3}$$

Therefore, I_{out} for the circuit in **Figure 3** is given by,

$$I_{out} = \frac{V_{cc} - V_{in}}{R} \tag{4}$$

where the voltage across R, the shunt is given by,

$$V_s = V_{cc} - V_{in} \tag{5}$$

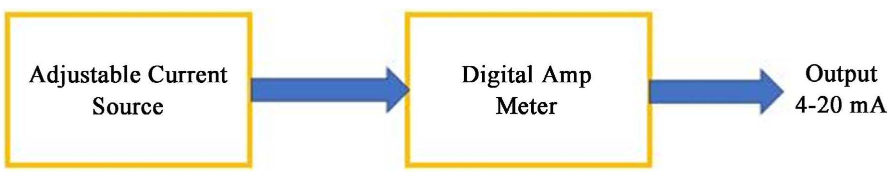

Figure 2. Block diagram of the 4-20 mA calibrator.

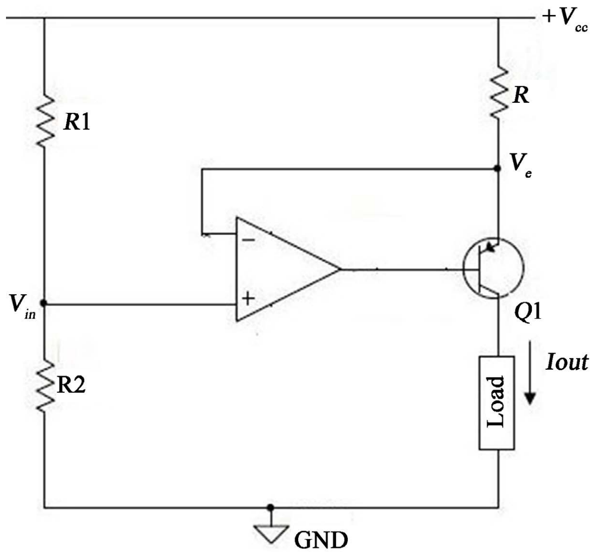

Figure 3. A current source circuit with load to the ground [11].

4.2. Voltage to Current Converter

Constant current sources are referred to as current generators which are expected to supply constant current. It is worth noting that every current source can supply constant current only over a given range of load resistances in as much as the circuit's current supply is not dependent on the load but on internal conditions [13] [14].

4.3. Bipolar Junction Transistor (BJT)

The PNP BJT type is put to use here because they are better associated with current sourcing.

$$\text{Where, } I_c = I_e - I_b \tag{6}$$

$$\alpha = \frac{I_c}{I_e} \text{ (Common – Base Gain), Therefore, } I_c = \alpha I_e$$

$$\text{Also, } \beta = \frac{I_b}{I_c}\text{, Common – Emitter Gain.} \tag{7}$$

$$\text{Therefore, } I_b = \beta I_c \tag{8}$$

The parameter α is usually close to unity therefore, $I_c = I_e$ approximately.

The range or limit of load resistances over which the loop calibrator behaves very well is determined by the transistor properties and is called the transistor's output compliance. The transistor connection, as shown in Figure 4, operates very well in its output compliance only if it remains in the active region and not in its cut-off nor saturation region. For the transistor to remain in the active region then, these conditions must be true,

$$I_b > 0, V_{CE} < -0.2\text{ V and } V_{BE} > 0.7\text{ V}$$

For the saturation region,

$$I_b > 0, V_{CE} < -0.2\text{ V and } \beta I_b > I_c > 0$$

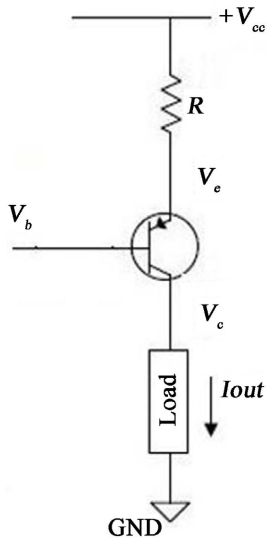

Figure 4. The basic concept of a PNP transistor current source [11].

And for the cut-off region,

$$V_{BC} > -0.5\text{ V and } V_{BE} > -0.5\text{ V}$$

When the load increases (increase in R_L), V also increases proportionately as,

$$V_c = R_l * I_{out} \quad \text{(Ohms Law)} \tag{9}$$

At maximum I_{out}, when V_c increases with an increase in R_L to a point where,

$$V_e \sim V_c + V_{CE} \tag{10}$$

The transistor is said to be at the edge of saturation and that, determines the maximum load ($R_L max$) that can be obtained for the constant current source or generator to remain in the given output compliance. At that point, the transistor begins to go into saturation. Any further increase in R_L will not cause any increase in V_c as the maximum voltage at the collector is attained,

$$V_c max = R_L max * I_{out} max \text{, from (9).}$$

Therefore, increasing the load R_L at $V_c max$ will cause the I_{out} to reduce as shown in Equation (11) below.

$$I_{out} = \frac{V_c max}{R_L} \tag{11}$$

where $V_c max$ becomes constant then I_{out} varies inversely proportional to R_L.

$$\text{Thus, } V_c = \text{constant}, \quad I_{out} \propto \frac{1}{R_L} \tag{12}$$

Therefore, if R_L becomes sufficiently large enough, I_{out} becomes negligible at constant V_c ($V_c max$). To illustrate this, if $I_{out} max$ is 25 mA and $V_c max$ is 5 V.

Then, $R_L max = 200\ \Omega$.

This implies that from 0 to 200 Ω, $I_{out} max$ of 25 mA will be obtained as the conditions hold true.

For R_L = 250 Ω, 300 Ω, 350 Ω, 400 Ω, etc.

As R_L increases by 50 Ω from 250 Ω to 400 Ω, I_{out} is 11.1 mA, 10.0 mA, 9.09 mA, 8.33 mA respectively.

4.4. Power Supply

LM7812 [15] is used because of its steady voltage output and current generation capabilities. That makes it suitable for this project. DC power supply Constant Current (CC) mode is preferred here, which is energized by two 9-volts lithium type PP3 batteries.

Voltage Range: A shunt of 100 Ohms is chosen to deliver current to the load. Specific voltage drops across the shunt were required to deliver a minimum current of 4 mA and a maximum current of 20 mA to the load.

V_{cc} = 12 V (Output from voltage regulator)

Shunt Resistor, R_s = 100 Ω.

Potential Difference across R_s, = $V_{cc} - V_e$.

From (3), $I_s = (V_{cc} - V_e)/R_s$,

Therefore,

$$V_e = V_{cc} - IR_s \tag{13}$$

For $I = 4 \text{ mA}$,

$$V_e = 11.6 \text{ V}$$

For $I = 20 \text{ mA}$,

$$V_e = 10.0 \text{ V}$$

Therefore, the required range of voltage drop across the shunt to produce 4-20 mA is 0.4 - 2.0 V respectively and the corresponding voltages at point V_e are 11.6 and 10.0 V.

A voltage divider to deliver the required voltage is shown below in Figure 5.

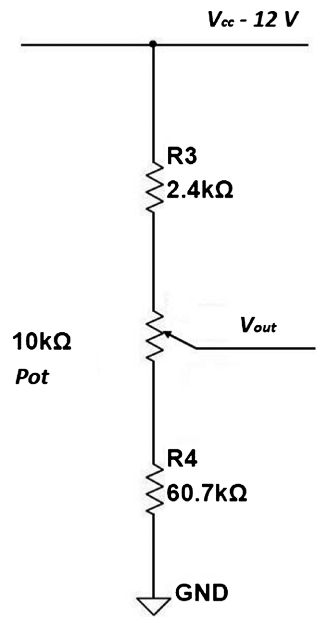

Figure 5. The designed voltage divider [16].

Voltage divider rule for Figure 5 is given in Equation (14).

$$V_{out} = \frac{R4}{R3 + R4} \times V_{cc} \tag{14}$$

The output voltage obtained when the 10 kΩ potential divider is at its minimum will be equal to,

$$V_{out} = 11.6 \text{ V},$$

therefore,

$$V_{cc} - V_{out} = 0.4 \text{ V}$$

When the 10 kΩ potentiometer is set to its minimum 0 Ω, the voltage drop produced is equal to the PD needed across the shunt to produce the desired minimum current of 4 mA.

$$V_{out} = 9.96 \text{ V},$$

Therefore,

$$V_{cc} - V_{out} = 2.04 \text{ V}$$

When the 10 kΩ potentiometer is set to its maximum 10 kΩ, the voltage drop produced is equal to the PD needed across the shunt to produce the desired maximum current of approximately 20 mA. As the 10 kΩ potentiometer goes from 0% - 100% (0 - 10 kΩ), the V_{out} produced is proportional to the voltage drop needed across the shunt to produce a current from 4-20 mA.

4.5. Design Simulation

Simulations with software tools like Multisim as seen in Figure 6 and Circuit wizard were carried out. A computer model was designed to mimic the real loop

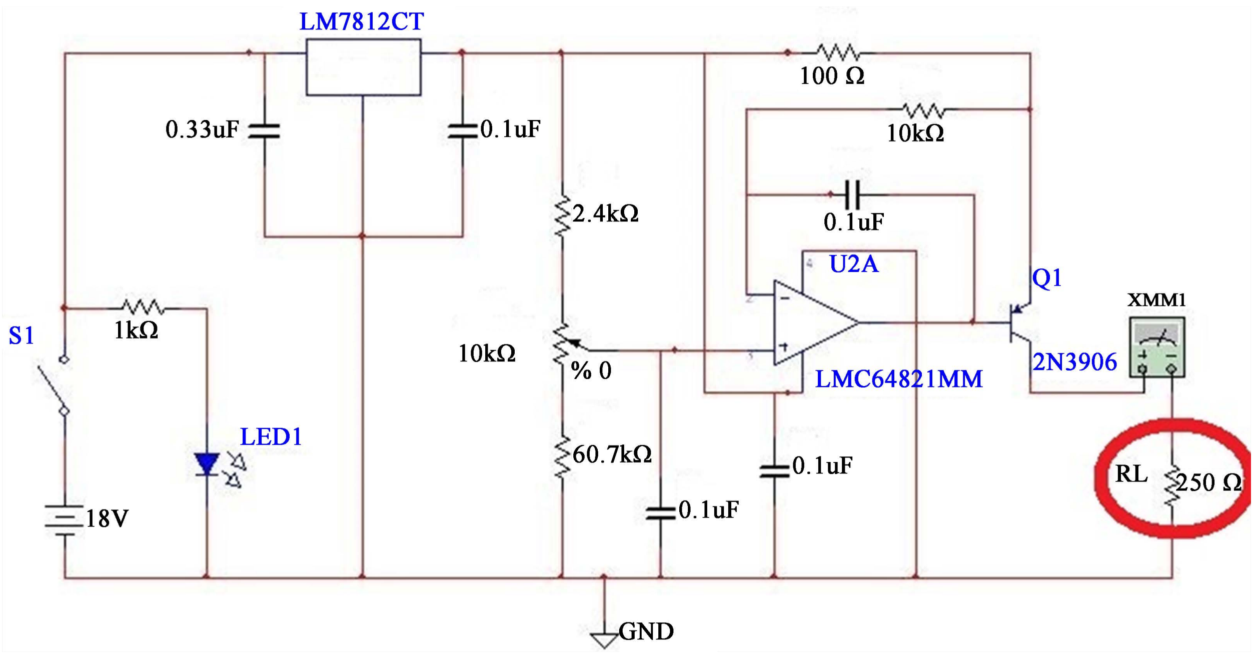

Figure 6. Design simulation with circuit multisim.

calibrator before the prototype was constructed.

5. Results and Discussion

A prototype of the loop calibrator was constructed and tested against the underlying theory. Beginning with a simplified equivalent circuit of the current generator, adjustable voltage is set by the voltage divider, and the current through the load is given by:

$$I_{out} = \frac{V - V_{in}}{R_s} \quad \text{From (3)}$$

V_{in} which is predetermined, sets the required voltage drop across the shunt R_s and to generate the required current. See Table 2 below for measured and calculated values of V_{in} and V_s.

5.1. Measured and Designed Current and Voltages

From Figure 7, it can be seen that the measured values of V_{in} were almost the same as theoretical values. The little difference can be attributed to the limitations of physical components.

As the potentiometer increased from 0 to 10 kΩ, V_{in} reduced from its maximum

Table 2. Values obtained from the experiment and those calculated.

S/N	Measured V_{in}	Measured V_s	Designed V_{in}	Designed V_s
10 K Pot (KΩ)	V_{in} (V)	V_s (V)	V_{in} (V)	V_s (V)
0.0	11.60	0.41	11.61	0.40
2.5	11.24	0.77	11.20	0.81
5.0	10.85	1.16	10.79	1.22
7.5	10.42	1.59	10.38	1.63
10.0	10.01	2.00	9.96	2.05

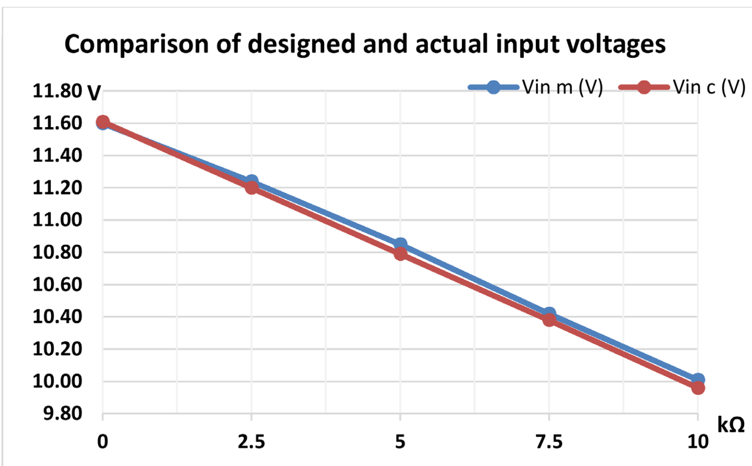

Figure 7. Graph comparing the designed voltage with actual voltage against the corresponding resistance.

value to its minimum value thus, $R_{pot} \propto \frac{1}{V_{in}}$.

This is a required objective as we choose to use a ramp current input. Figure 8 shows that the measurements taken at 0%, 25%, 50%, 75% and 100% of the span of the loop calibrator established the fact that the required V_{in} of 0.4 V to 2.0 V for the instrument span was accurately set.

5.2. Linearity Verification

Linearity is the property of a system characterized by a linear relationship of independent variables with one or more dependent variable. The linearity check carried out was sufficient to control the end-points and the middle of the calibration interval to be sure that the instrument did not drift out of calibration.

- This experiment is deemed necessary to check the quality of the instrument's output.
- This characteristic is good as it argues well for system predictability.
- Check standards require at least three points; the lower-end, mid-range and upper-end of the regime of the instrument. Five points are used here. (See Table 3)

The relationship is so linear as it can be seen in Figure 9 over the established range. It is difficult to differentiate between the plot and the trend line which is a good indication for linearity.

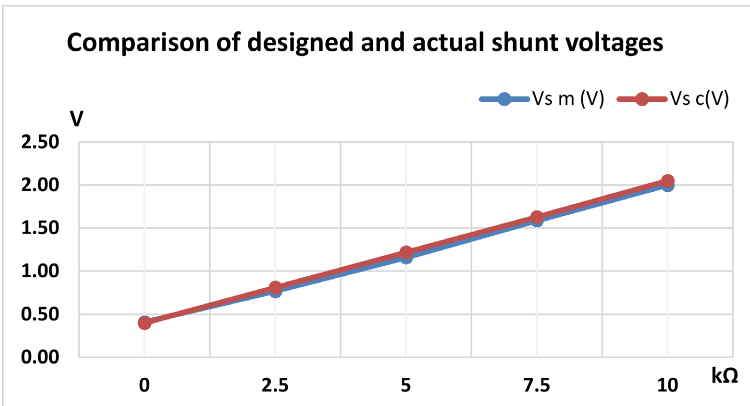

Figure 8. Graph comparing the designed shunt voltage with actual shunt voltage against the corresponding resistance.

Table 3. Verification of the 4-20 mA calibrator linearity.

%	R (KΩ)	I_{out} (mA)
0	0	3.96
25	2.5	8.01
50	5	12.03
75	7.5	16.07
100	10	20.11

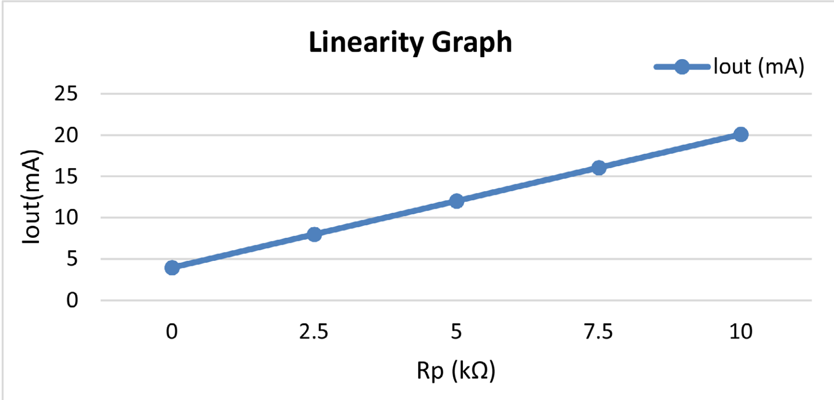

Figure 9. Graph showing the linearity of the 4-20 mA calibrator output current.

Table 4. Output current I_{out} for varying loads, R_L at various potentiometer R_{pot} positions.

R_L (Ω)	R_{pot} @ 0% I_{out} (mA)	R_{pot} @ 25% I_{out} (mA)	R_{pot} @ 50% I_{out} (mA)	R_{pot} @ 75% I_{out} (mA)	R_{pot} @ 100% I_{out} (mA)
0	4.00	8.00	12.00	16.00	20.10
100	4.00	8.00	12.00	16.00	20.11
200	4.00	8.00	12.00	16.00	20.10
400	4.00	8.00	12.00	16.00	19.92
600	4.00	8.00	11.99	12.29	11.77
800	4.00	7.99	10.04	9.61	9.19
1000	4.00	7.99	8.24	7.87	7.52
1200	4.00	7.27	6.99	6.67	6.37
1400	3.99	6.33	6.06	5.80	5.52

Therefore, it is convincingly established that precisely 4-20 mA is generated over the design range, and the calibrator output is linear.

5.3. Functionality Verification

To demonstrate that the loop calibrator meets the technical requirements. Data was collated from measuring the output current against varying loads as seen in **Table 4**.

The graph of current output I_{out} against load resistance R_L in **Figure 10** shows that the calibrator produces a constant current of 4-20 mA output over a range of 0 - 400 Ω at the maximum current output. This agrees entirely with the design specification.

5.4. Calibrator Validation

The current output from the loop calibrator is compared with three standard laboratory ammeters. (See **Figure 11**)

Here below is the comparison between the calibrator and the three standard laboratory ammeters. See Table 5 which graphically shown in Figure 12.

Comparing the loop calibrator with standard meters in the laboratory, the difference between the first, second and third standard ammeters and the loop calibrator was observed to be 0.01 mA, 0.02 mA and 0.01 mA respectively. The average accuracy therefore is =0.013.

In summary, the 4-20 mA loop calibrator depicted in Figure 13, holds true for the purpose to which it was created. The accuracy is about 0.01 mA, which is the instrument's absolute error and not percentage accuracy. It is also shown that this accuracy is consistent throughout the 4-20 mA span of the calibrator.

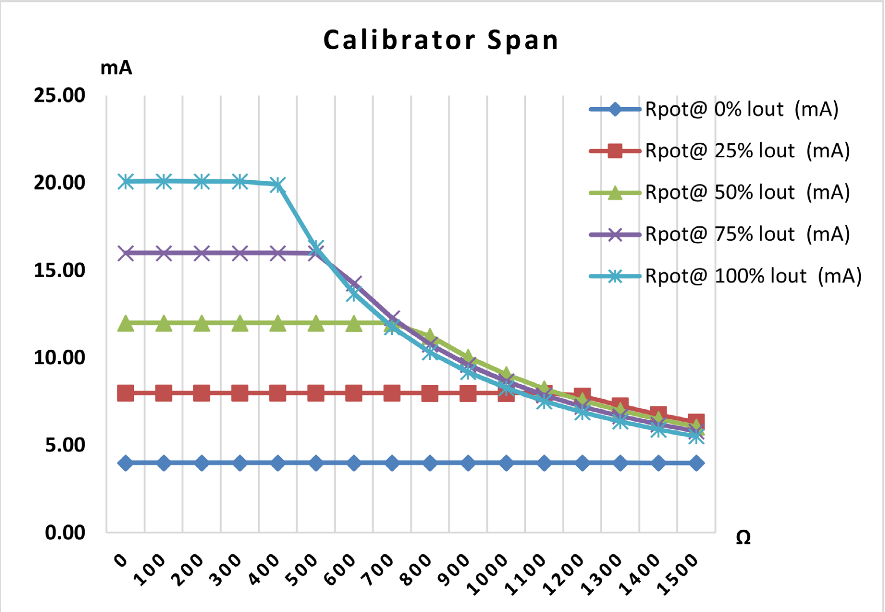

Figure 10. Graph of output current over load resistance to verify the calibrator span.

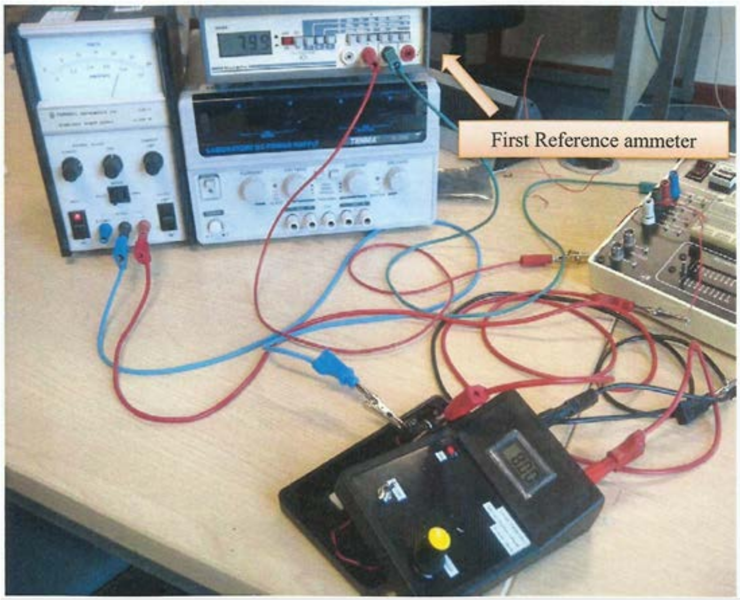

Figure 11. Designed loop calibrator with first standard ammeter.

Table 5. Loop calibrator readings compared to the three reference ammeters.

(mA)	Loop Calibrator	Reference Ammeter 1	Reference Ammeter 2	Reference Ammeter 3
1	4.00	4.00	3.98	4.00
2	8.00	7.99	7.98	7.99
3	12.00	11.99	11.98	11.99
4	16.00	15.99	15.98	15.99
5	19.99	19.98	19.97	19.98
6	Overcurrent	20.00	20.00	20.00

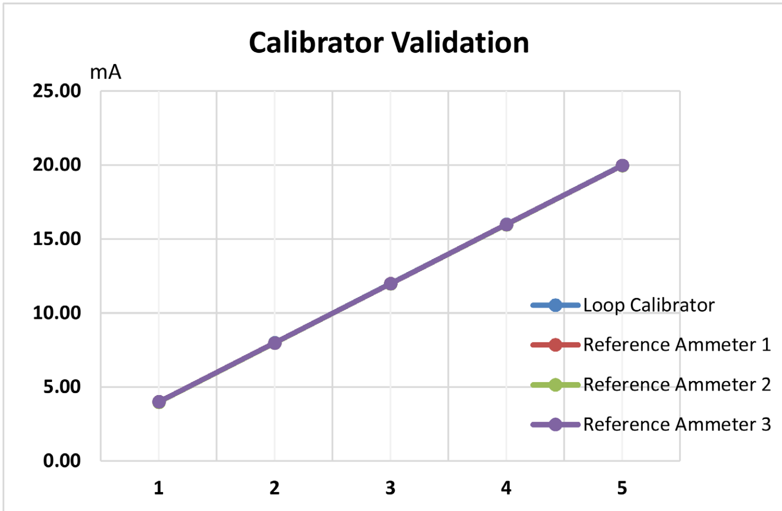

Figure 12. Graph of calibrator output compared to three standard ammeters.

Figure 13. The 4-20 mA loop calibrator prototype.

6. Conclusions

The loop calibrator designed and constructed in this paper is a piece of equipment used in testing, simulating and calibrating instruments on the 4-20 mA platform. It is established that a cheaper and reliable 4-20 mA loop calibrator is feasible.

Several steps in the form of controlled experiments were taken to verify and validate the finished product; a standard loop calibrator with a range of 0 - 400 Ω, an absolute error of ±0.01 mA, its functionality level is basic and the components are greatly reduced which cost only about $50.70.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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List of Symbols

V_{in}	Input Voltage
V_{cc}	Circuit Voltage
R1,2,3…	Resistors
R_L	Load Resistance
R_s	Shunt Resistance
V_s	Shunt Voltage
V_e	Transistor Emitter Voltage
V_c	Transistor Collector Voltage
V_b	Transistor Base Voltage
I_{out}	Output Current
I_c	Transistor Collector Current
I_e	Transistor Emitter Current
I_b	Transistor Base Current
$V_c max$	Maximum Collector Voltage
$R_L max$	Maximum Load Resistance
$I_{out} max$	Maximum Output Current
R_{pot}	Resistance of Potentiometer
Designed xx	Calculated Value from Design of xx
Measured xx	Actual Value from Experiment of xx
GND	Ground