Enhanced Howland-based constant current source for soil EC_a measurement

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Abstract: In the present work, enhanced Howland current source-based voltage controlled current source (VCCS), used in four probe Wenner array technique to measure apparent electrical conductivity (EC_a) of soil is reported. The distortion in the output signal is negligible and current is maintained constant. To check circuit reliability for constant current characteristics across varying standard load resistance, voltages were measured to calculate value of current, which was then compared with theoretically calculated value. The performance of proposed circuit was studied using TINA-TI software simulations and it was found that proposed source is capable of providing a constant current over the entire range of resistance (0.5 Ω to 20 kΩ) within very low frequency range; with an error less than 5%, and an average error of 0.9466%, which is within acceptable tolerance in present application.

Keywords: enhanced Howland-based current source; voltage controlled current source; VCCS; Wenner array; soil electrical conductivity; EC_a.

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Babankumar S. Bansod completed his doctoral program from the Thapar University, Patiala and post-doctorate from the NMSU, USA. He has vast experience in design and development of sensors and instrumentation in agriculture field, grain moisture determination and field-scale soil sensing using in-situ and mobile platforms in particular. He has successfully completed know-how generation of various technologies and possesses specific interest in developing precision farming technologies. He holds command in designing and developing efficient and compact embedded systems using advanced microcontroller families and digital peripherals. His keen interest is in the areas of spatial and geo-spatial modelling techniques such as clustering analysis, fuzzy c-means, principal component analysis, partial least square and PLS-discriminant analysis, supervised classifications using SIMCA.

1 Introduction

Soil plays a key role in crop production in terms of physical support and as a reservoir of water and nutrients. Electrical conductivity (EC_a), a measurement of how much electrical current soil can conduct, integrates many soil properties affecting crop productivity (Analog Devices, 1995). Many researchers have reported significance and applications of EC_a, e.g., delineation of management zones (MZ), crop yield interpretation, directed soil sampling, prescription maps to govern variable soil input rates, variability analysis, etc., (Chen et al., 2010; Denyer et al., 1993; Fraisse et al., 2001; Hartsock et al., 2000). These applications of EC_a enable precision farming practices and hence help in sustainable agricultural growth. Therefore, EC_a is established as a driving force for site specific farming practices and management recently. Traditionally, EC_a of soil paste analysed in lab has been used to assess soil salinity, but now commercial devices are available to rapidly and economically measure and map bulk soil EC_a across agricultural fields. Hence, an understanding of soil properties representative, such as electrical conductivity, has become important in today's scenario as a means of rapid and inexpensive tool for soil variability assessment. This has led to development of a wide array of chemical, mechanical and electronic sensors to measure this property on fields. Electrical conductivity of soil in fields can be measured using contact type method and non-contact type method. Non-contact type method induces a current into the soil with one coil and determines conductivity by measuring the resulting secondary current with another coil. However, electromagnetic interferences can occur due to presence of any piece of metal in the vicinity and this can lead to ambiguity in results. On the other hand contact type method is used to determine EC_a by Wenner array method (Figure 1).

In this method, current is allowed to flow through a fixed soil volume from the outermost electrodes C_1 and C_2 dug into the ground, and as a result, a voltage difference is generated between the innermost electrodes P_1 and P_2. All the electrodes are placed in line and are equidistant from each other. The current is already known [value of current produced by constant current source (CCS)] and voltage induced between P_1 and P_2 is measured. Consequently, these values of current and voltage are used to measure the resistance, according to Ohm's law:

$$\text{Potential (V)} = \text{Current (I)} * \text{Resistance (R)}$$

Resistivity of soil is then computed from resistance, according to the following formula:

$$\rho = 2\pi AR$$

where

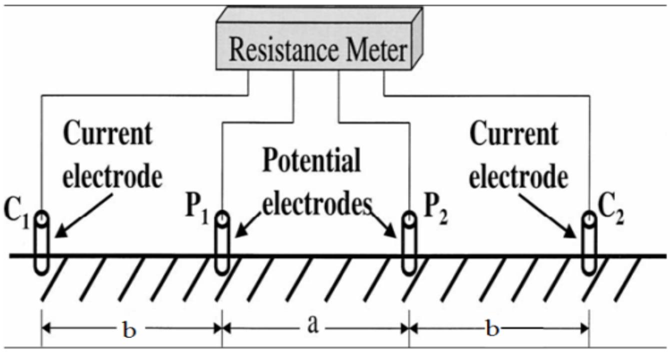
ρ is soil resistivity (Ohm-cm)

A is distance between probes (cm)

R is soil resistance (Ohms), instrument reading

π equals 3.1416.

Figure 1 Four probe Wenner array



Contact type method has been reported by numerous researchers in the past as follows: time domain reflectometry (TDR) was reported for estimating the pore-water electrical conductivity of saturated sandy soils using a single TDR test (Jaynes et al., 1993). The capacitance (CAP) method using modified four-electrode Wenner array sensor to enhance the capacitive effect has been reported (Jaynes et al., 1995). The Veris® 3100 (Veris Technologies, Salina, Kansas) is a commercially available contact type sensor which measures EC_a with a system of coulters that are in direct contact with the soil (Johnson et al., 2001). Despite of few commercial manufacturers available for field usable sensors, there is an increased demand for the development of low cost, field scale geo-sensors from the farming community of developing economies. In order to develop low cost, on-the-go vehicle mounted EC_a measurement devices to generate high resolution spatial information maps, reliable current source is one of the key elements of the system. Many of the earlier reported works have discussed d.c. current sources for measuring soil EC_a. However, d.c. would lead to polarisation which is not desirable, hence it is important to use a.c. current source. The frequency of source should be low so as to eradicate the capacitance effect. The requirement of a low cost a.c. current source which will provide precise and accurate current can be fulfilled by Howland current source. The 'basic Howland current pump' was invented in 1962 (Pouliquen et al., 2008). The basic Howland current pump is advantageous because the feedback from the output to both the + and – inputs of the op-amp is at equal strength (Pease, 2008). The advantage of this circuit over other current sources is that it does not employ additional transistors or switches (William, 2003). Due to the use of an operational amplifier, very good performance is offered and true symmetric bi-directional currents are supplied. However, output current range of Howland current source is limited and precision resistors or trim pots are required. Zhang et al. (1980) have discussed about getting increased output from an improved Howland current pump. If the load is single ended, one end must be connected to ground, and where bipolar current flow is required, an improved Howland current pump may be used. The improved version of Howland current source strives for a higher stability and greater efficiency. Keeping in mind all these factors, the authors have proposed an application specific, field deployable and digitally programmable voltage controlled current source (VCCS) based on enhanced Howland current source. The proposed scheme makes use of a mixed-signal advanced microcontroller for supplying programmed a.c. voltage to the Wenner array. The microcontroller is also used to measure the output voltage from the potential electrodes of the array. Hence, the designed current source provides high accuracy and flexibility to the user while developing field-usable sensors and systems. Also, the improved Howland source is cost effective and thus makes field usable soil property measurement sensors to be easily affordable for farmers.

2 Proposed scheme

The proposed improved howland circuit based current source uses a closed loop feedback structure that enhances its output current precision (Figure 2).

Capacitor C1 prevents oscillations when load = 0. The source was designed to supply constant current of 0.26 mA to the varying load (soil resistance).

Let I_1 be the current flowing through R1 and I_2 be the current flowing through R2, V_a be the voltage at non-inverting input of op-amp, V_b be the voltage at inverting input of op-amp.

The circuit values were selected as R1 = R5 and R2 = R4.

$$I_1 = \frac{V_{G2}}{R1 + R2}$$

$$V_a = I_1 * R2$$

The voltage V_b is same as that of V_a, therefore V_{out} must equal to $2V_a$.

$$I_2 = \frac{V_{out}}{R3}$$

$$I_{out} = I_1 + I_2$$

$$I_{out} = \frac{V_{G2}}{R1 + R2} + \frac{V_{out}}{R3}$$

$$V_{out} = 2V_a = 2I_1 * R2$$

$$V_{out} = 2V_{G2} * \frac{R2}{R1 + R2}$$

Therefore

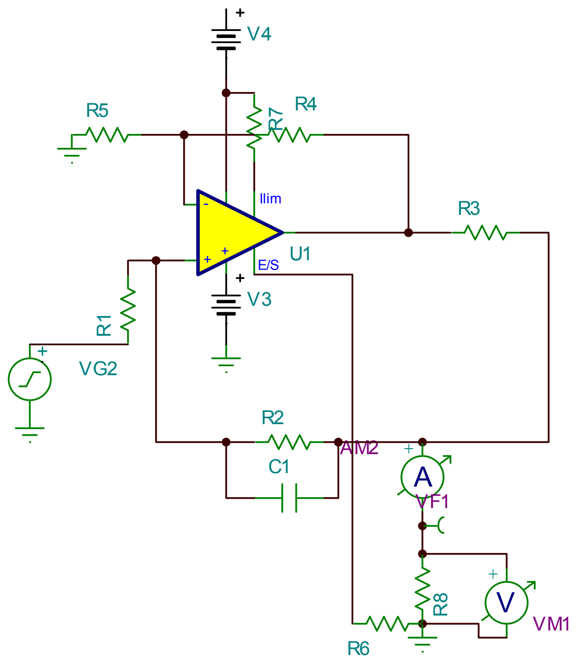
$$I_{out} = \frac{V_{G2}}{R1+R2} + 2V_{G2} * \frac{R2}{R3(R1+R2)}$$

$$I_{out} = \frac{V_{G2}}{R1+R2}\left(1+\frac{2R2}{R3}\right)$$

$$VM1 = \frac{V_{G2} * R8}{R1+R2}\left(1+\frac{2R2}{R3}\right)$$

As it can be seen from the expression of I_{out}, the output current is directly proportional to the input voltage (V_{G2}), irrespective of the load; thus the circuit provides constant current for variable loads.

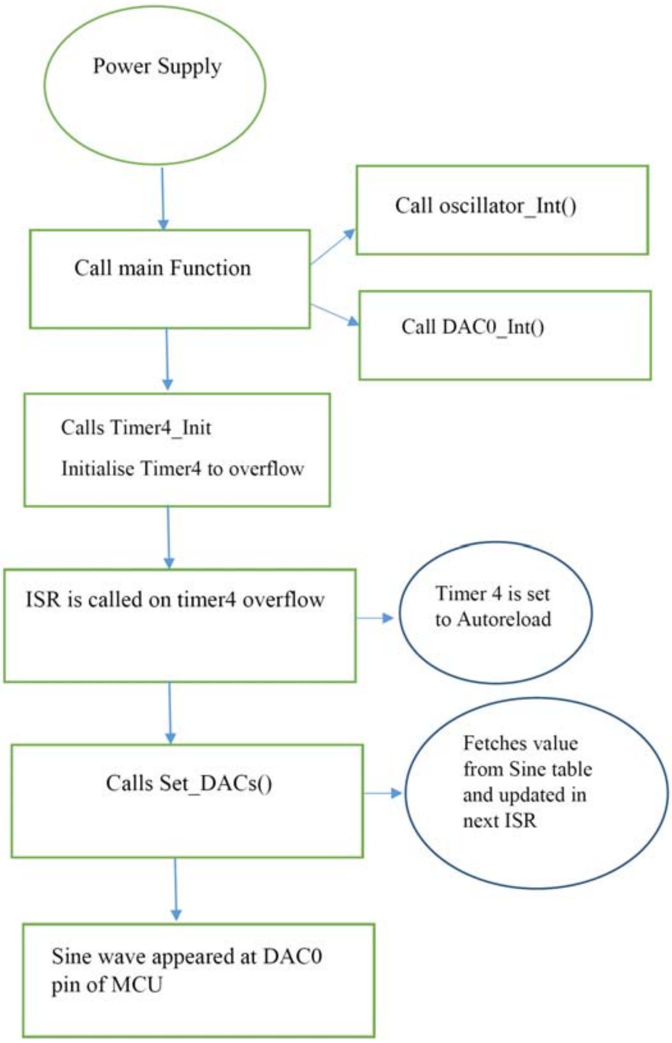
Figure 2 Improved Howland circuit (see online version for colours)



3 Software development

The proposed source is digitally programmable; it uses number of inbuilt MCU configuration registers to invoke desired mode and operation of digital to analogue conversion (DAC) and programmable gain amplifier (PGA) in order to achieve the required frequency and amplitude of the input voltage signal. The associated programming flow chart of MCU firmware for generating desired sine wave is shown in Figure 3.

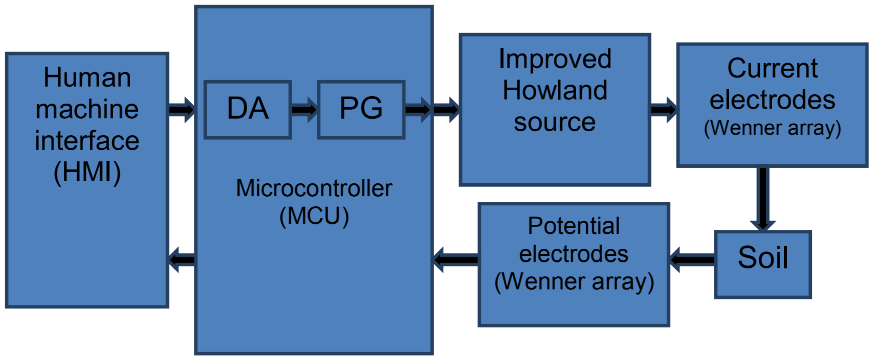
Figure 3 Flow chart for programming MCU firmware (see online version for colours)



PGA provides the necessary gain to boost the signal level within the dynamic range of the DAC. The frequency and voltage level of the V_{G2} signal which governs output load current (I_{out}) characteristics is reconfigurable and can be controlled by the user without changing hardware and hence the source proves versatile.

The in-built DAC of microcontroller generated an input voltage signal of suitable frequency for the current source. The source will measure the voltage across the 2 probes of Wenner array with the help of microcontroller and display the result on LCD, as shown in Figure 4.

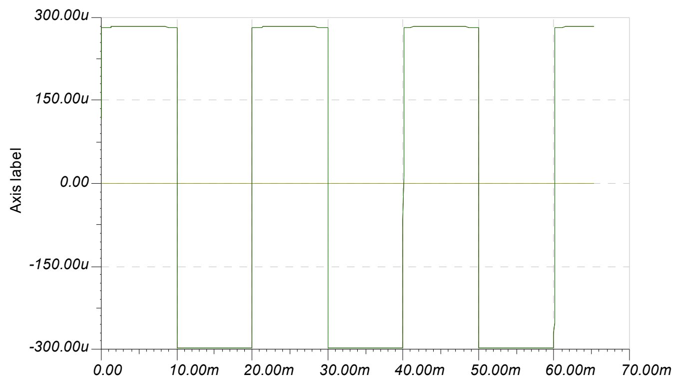
Figure 4 Block diagram of enhanced Howland current source based soil EC_a sensor (see online version for colours)



4 Results and discussions

TINA 7-TI software was used to simulate the proposed circuit and it was observed that the source is able to measure resistance and hence electrical conductivity precisely over a wide range. A few plots of simulation using different values of load resistance showing the output voltage observed across the load are shown in Figures 5–8.

Figure 5 Output voltage across 1 Ω load (see online version for colours)



On plotting the graph between voltage and resistance, linear curve with regression coefficient $R^2 = 0.997$ was obtained over the entire range (Figure 9).

Figure 6 Output voltage across 100 Ω load (see online version for colours)

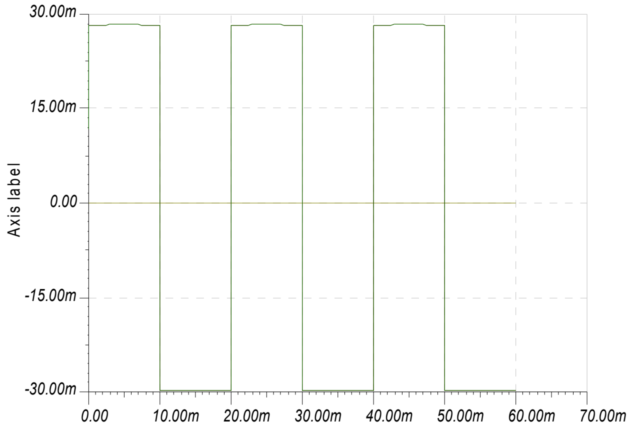


Figure 7 Output voltage across 10 kΩ load (see online version for colours)

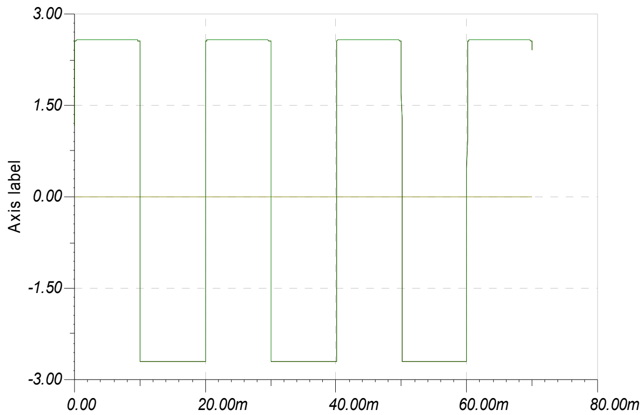


Figure 8 Output voltage across 20 kΩ load (see online version for colours)

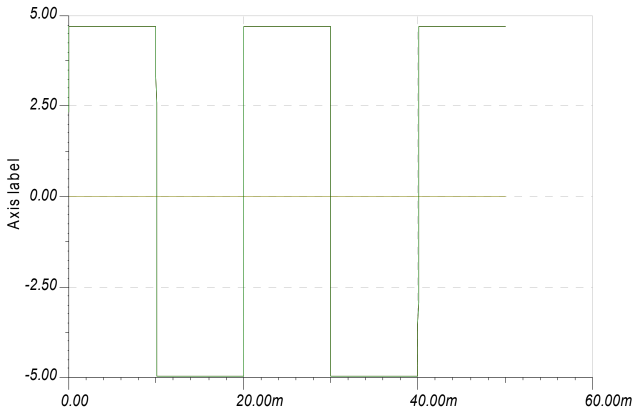
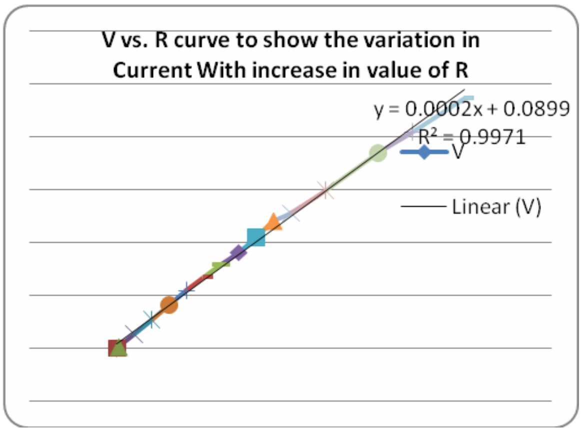
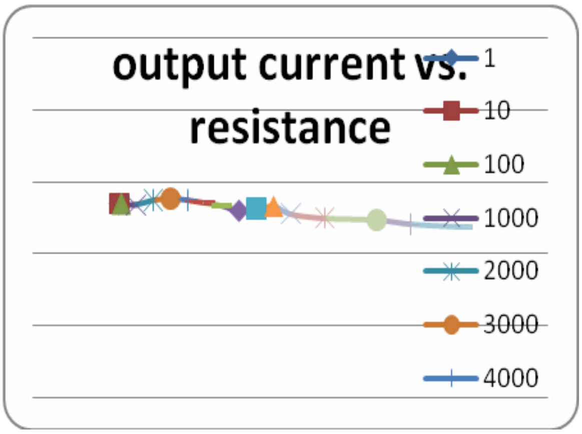


Figure 9 V vs. R plot (see online version for colours)



It demonstrates VCCS characteristics of the reported circuit whose output changes proportional to load resistance variations as expected keeping current unchanged. This shows that the proposed scheme is capable of providing a constant current over the entire range of resistance, i.e., 0.5 Ω to 20 kΩ.

Figure 10 I vs. R plot (see online version for colours)



The current is almost constant over a wide resistance range (Figure 10).

Ideally, ΔI, i.e., change in current from the pre-set value (0.26 mA) should be equal to zero, although it is not exactly zero, in present case (Figure 11) it approaches ideal behaviour.

It was observed (Figure 12) that the output voltage remained constant over a wide frequency range of 1 Hz–10 kHz.

The source designed offers a maximum compliance voltage of 5.2 V which is quite tolerable.

Table 1 and Table 2 show the value of current measured through simulations across various values of load resistance and actual measured values respectively. A comparison of the two shows the accuracy of the developed current source.

Table 1 Simulated values of current and error using different values of load resistances

R (Ω)	*V (volts)*	*I (mA) simulated*	*ΔI (mA)*	*% error*
1	0.00027	0.27	–0.01	–3.84615
10	0.0027	0.27	–0.01	–3.84615
100	0.027	0.27	–0.01	–3.84615
1,000	0.268	0.268	–0.008	–3.07692
2,000	0.55	0.275	–0.015	–5.76923
3,000	0.83	0.276667	–0.01667	–6.41026
4,000	1.1	0.275	–0.015	–5.76923
5,000	1.35	0.27	–0.01	–3.84615
6,000	1.6	0.266667	–0.00667	–2.5641
7,000	1.82	0.26	0	0
8,000	2.1	0.2625	–0.0025	–0.96154
9,000	2.4	0.266667	–0.00667	–2.5641
10,000	2.56	0.256	0.004	1.538462
12,000	3	0.25	0.01	3.846154
15,000	3.7	0.246667	0.013333	5.128205
17,000	4.1	0.241176	0.018824	7.239819
20,000	4.75	0.2375	0.0225	8.653846
Average error = –0.9466				

Figure 11 ΔI vs. R plot (see online version for colours)

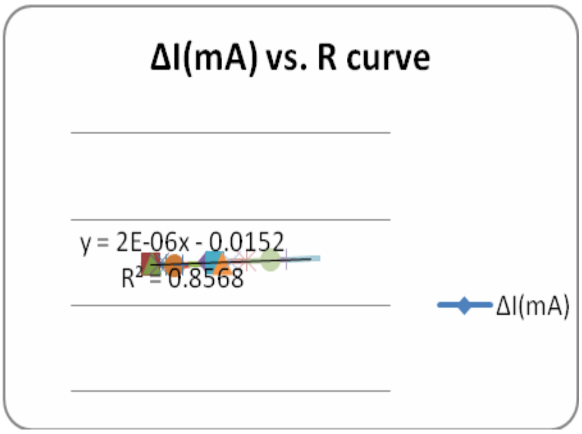


Figure 12 V vs. frequency plot for 5 kΩ load (see online version for colours)

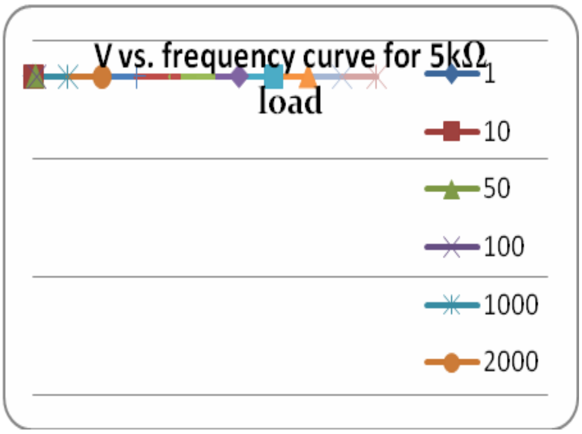


Table 2 Practical values of current and error using different values of load resistances

R (Ω)	*V (volts)*	*I (mA)*	*ΔI*	*% error*
1	0.000265	0.265	–0.005	–1.92307
10	0.00263	0.263	–0.003	–1.15384
120	0.0315	0.2625	–0.0025	–0.96154
400	0.1047	0.26175	–0.00175	–0.67308
1,000	0.261	0.261	–0.001	–0.38462
2,000	0.518	0.259	0.001	0.384615
3,000	0.771	0.257	0.003	1.153846
4,000	1.021	0.25525	0.00475	1.826923
5,000	1.286	0.2572	0.0028	1.076923
6,000	1.542	0.257	0.003	1.153846
7,000	1.782	0.254571	0.005429	2.087912
8,000	2.028	0.2535	0.0065	2.5
9,000	2.264	0.251556	0.008444	3.247863
10,000	2.516	0.2516	0.0084	3.230769
12,000	2.971	0.247583	0.012417	4.775641
15,000	3.618	0.2412	0.0188	7.230769
17,000	4.093	0.240765	0.019235	7.39819
20,000	4.7	0.235	0.025	9.615385
Average error = 2.3456%				

5 Conclusions

The paper demonstrates performance of an improved Howland current source circuit proposed for measuring soil EC_a. This scheme can be easily used for measuring the conductivity of different soil types, compositions and textures. The results obtained indicate that the proposed low cost, viable and reliable source can be used in many applications. Components used in the design of the CCS are low cost, readily available and can be easily replaced, if need be. The proposed scheme makes use of a microcontroller for supplying programmed a.c. voltage to the Wenner array and can support a wide range of applications. The microcontroller is also used to measure the output voltage from the potential electrodes of the array. Hence, the system provides high accuracy as it can be programmed depending upon application need and also is less complex. The improved Howland source is cost effective and can make sensor and system development easily affordable for farmers of developing countries.

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