A Practical Voltage-Controlled Current Source Design For Electrical Impedance Tomography

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***Abstract*— Electrical Impedance Tomography (EIT), is one of the medical imaging technologies. It can also be used in industrial process monitoring. In this method, the image of the electrical conductivity (or electrical impedance) distribution of the inner part of a conductive subject can be reconstructed. The image reconstruction process is done by injecting an accurate current into the boundary of a conductive subject (e.g. body), measuring the voltages around the boundary, transmitting them to a computer and processing on acquired data with a software (e.g. MATLAB). The images are obtained from the peripheral data by using an algorithm. A precise, high output impedance current source with wide bandwidth plays an important role in the final images quality. In this paper, we have focused first on recent studies on regular current sources (waveform generation and Voltage-to-Current Converter parts), after that with further improvements and doing some physical experiments, a design of practical high output impedance current source (more than 6MΩ output impedance), with a pulse generation part will be proposed.**

Keywords-current source; Howland; VCCS; EIT; electrical impedance tomography

I. INTRODUCTION

A typical current source which is used in electrical impedance tomography systems, consists of waveform generator and Voltage-to-Current Converter (VCC) parts. The VCC part plays a very important and vital role in the quality of final images, hence the quality of VCC designing in an EIT system is specifically important [1]. The VCC part in an EIT system requires stability and high precision, which means that it should have high output impedance.

The main features for a typical waveform generator are as followings; an accurate and stable output waveform (i.e., exact sinusoidal waveform without any jitter), a low output impedance (similar to an ideal voltage source), wide bandwidth, and steady amplitude overall the frequency range. Also the main features to have an excellent Voltage-to-Current Converter (VCC) part are: a high output impedance, linearity in converting voltage to current, precision of the output waveform, supporting a wide range of load, and proper working in a broad range of frequency.

II. VOLTAGE CONTROLLED CURRENT SOURCE

The major part of Voltage Controlled Current Sources (VCCS) is voltage-to-current converter (VCC), since an output current, that produced by them is proportional to an input voltage. An ideal VCC in EIT system requires high precision and stability which means approximately infinite output impedance. In this paper we have a study on VCCS based on DOA, TOA1 and TOA2 structures. They contain a voltage generator and a VCC part. Some experiments have been done on them, to select the best choice for current source designing.

A. VCCS Based on DOA Circuit

The current source circuit based on Double-Operational Amplifier (DOA) is shown in Fig. 1. An active positive feedback (U_2) is added to the non-inverting input pin of U_1, and the R_2 plays the role of negative feedback for U_1. The output current can be calculated by (3); it shows that the value of I_L is related to input voltage V_1 and peripheral resistance Ro but is not related to load resistor R_L [2].

$$U_{P1} = \frac{R_4}{R_3+R_4}V_1 + \frac{R_3}{R_3+R_4}U_{P2} \tag{1}$$

$$U_{O1} = \left(1+\frac{R_2}{R_1}\right)\cdot U_{P1} \tag{2}$$

Let: $R_1 = R_2 = R_3 = R_4$

Then:
$$I_L = \frac{V_1}{R_O} \tag{3}$$

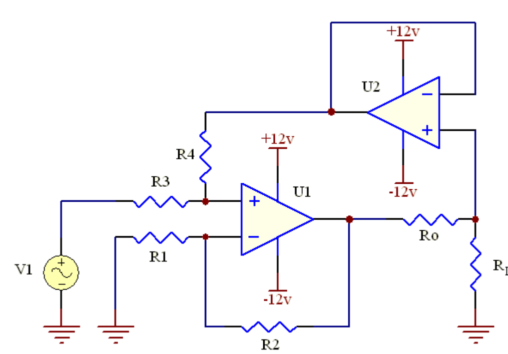

Fig. 1. Double-Operational Amplifier current source circuit.

B. VCCS Based on TOA Circuit form I

Voltage-Controlled Current Source (VCCS), constructed with Triple-Operational Amplifiers, form I (TOA1) is used to transfer voltage source into current source which is shown in Fig. 2 [3]. In this circuit U_2 is used as the positive feedback line of the main Howland circuit that is added to the positive input pin of U_1 and U_3 is used as the negative feedback line of the main Howland circuit. The output current is calculated by the following equations. (6) shows that the output current is in proportion to the input voltage when R_3, R_4, and R_5 are constant and it's not related to load R_L.

$$I_L = \frac{\frac{R4}{R3+R4}Vi}{\left(\frac{R1}{R1+R2}-\frac{R3}{R3+R4}\right)RL+\frac{R1R5}{R1+R2}} \tag{4}$$

Here if: $$\frac{R1}{R1+R2}-\frac{R3}{R3+R4}=0 \tag{5}$$

Or: $$R_1 . R_4 = R_2 . R_3$$

It can be gotten: $$I_L = \frac{R4}{R3 \,.\, R5} \cdot V_i \tag{6}$$

C. VCCS Based on TOA Circuit form II

Voltage-Controlled Current Source (VCCS) with Triple-Operational Amplifiers, form II (TOA2) as a Voltage-to-Current converter (VCC) is used to transfer the voltage source into the current source which is shown in Fig. 3. In this circuit a non-inverting amplifier U_2 and an inverting amplifier U_3 are used in the feedback path and the forward path consists of an inverting, summing voltage amplifier U_1. As it can be seen in Fig. 3, the output current is calculated by the following equations [1]. (8) shows that the output current is in proportion to the input voltage and R_5, and it's not related to load R_L.

Here if: $$R_1 = R_4 = R_2 = R_3 \quad \& \quad R_6 = R_7 \tag{7}$$

It can be gotten: $$I_L = \frac{-Vi}{R5} \tag{8}$$

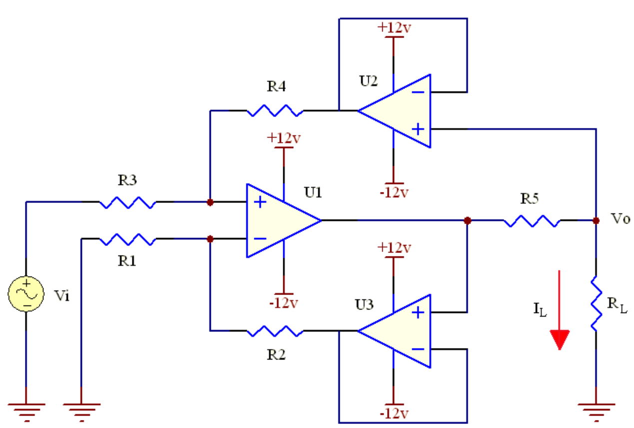

Fig. 2. Triple-Operational Amplifier current source circuit form I.

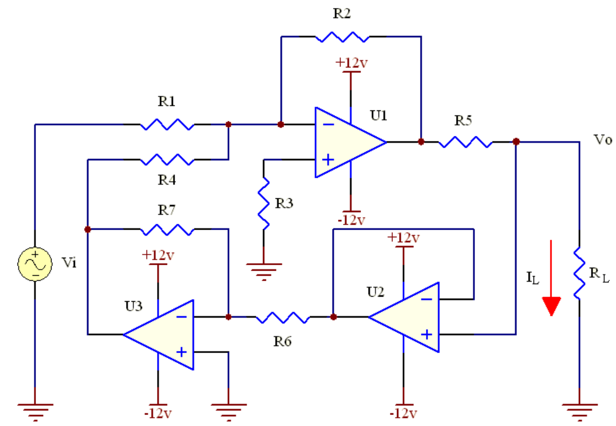

Fig. 3. Triple-Operational Amplifier current source circuit form II.

D. How to Measure Output Impedance of a VCCS

The output impedance Z_{out} of the current source which is shown in Fig.4, can be calculated by (9) where V_1 represents the measured output voltage of R_1, when the switch S is opened and V_2 represents the measured output voltage of R_1, when S is closed [4]. R_P and R_1 are connected at the output of VCCS with optional value but the VCCS should be able to support the amount of (R_1+R_P), means the relationship between output voltage and current of VCCS should be linearly, thus (R_1+R_P) couldn't be more than the allowable maximum load.

$$Z_{out} = \frac{V1}{V2 - V1} \cdot R_P - R_1 \tag{9}$$

In order to measure the output impedance and also the load voltage of a VCCS with an oscilloscope, the input impedance of oscilloscope should be considered. Some oscilloscopes have low input impedance such as 1MΩ (MEGATEK MS-200). Parallel combination of this impedance and the output impedance of VCCS, creates big errors in the measurements. To solve this problem a high input impedance OP-AMP (e.g. LF411 with 10^{12} Ω input impedance [5]) as a buffer, can be put between the test-points and the oscilloscope probes.

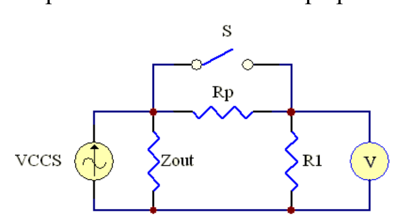

Fig. 4. A method for measuring VCCS output impedance.

III. VCCS Primary Physical Tests

Some structures of the VCCSs have been tested on the breadboard with various OP-AMPs (AD844, AD811, and LF411), several resistance values, and several load ranges (10Ω to 15KΩ). As it can be seen in Table 1, the results of several physical experiments are shown briefly. These tests were done on the breadboard with different resistance values in 20KHz frequency and 1mA load current. As it was mentioned before, an LF411 IC has been put between the test-points and the oscilloscope probes, to prevent error occurrence in the measurements. An XR2206 was applied as the VCO, before the VCC part. The output impedance of the oscillator without and with output amplifier was ≈ 690Ω and ≈ 14Ω respectively.

The first column of Table 1, shows the types of VCCS, the second column shows that, the VCCS, has been tested with amplifier between oscillator and VCC parts or not. The columns R_1 up to R_5 illustrate the main resistor values which a typical VCCS has been tested with them. The "Max Load" column shows the maximum allowable value of load, which can be supported by a typical VCCS, without any wave distortion. The last column (output impedance) shows the value of output impedance, which have been calculated for a typical VCCS with (9). The allowable load range and also the output impedance are the most important and significant features of the VCCSs.

From the primary tests, It can be gotten as a conclusion that the VCCS based on TOA1 in the sixth row (yellow row) is the best choice to have an excellent Voltage-controlled Current Source. Because it can support the load value in range of 10Ω to 10KΩ linearly, means the behavior of its output current would be nonlinear for the load more than 10KΩ, and also it has ≈ 5MΩ output impedance which calculated with (9).

IV. Final Proposed Precise Design of the VCCS

The current source in EIT system, should be able to deliver current over a frequency range between 10KHz to 1MHz and be able to support the load less than 1KΩ [6], and in other reference between 100Ω to 10KΩ [1]. The output impedance should be more than 100KΩ [7]. Therefore an excellent current source design should satisfy above conditions. The flowchart shown in Fig. 5, is our proposed plan for designing the practical current source. It contains a VCO part, a band-pass filter (low-pass and high-pass filters in a serial connection), and a VCC part. XR-2206, has been applied in mentioned part as the VCO [8]. In fact the price of this IC is very lower than MAX038. Also an AD844 has been put at the output of VCO, to amplify the sinusoidal waveform and create low impedance value at the output of waveform generation part.

TABLE I

The Results of VCCS Primary Physical Tests.

VCCS Type	Amp ?	R_1	R_2	R_3	R_4	R_5	Max Load	Z_{out} MΩ
DOA	No	1K	1K	1K	1K	5K	4.5K	0.5
DOA	Yes	1K	1K	1K	1K	5K	5K	3
DOA	No	10K	10K	10K	10K	10K	4.5K	0.15
DOA	Yes	10K	10K	10K	10K	10K	10K	0.75
TOA1	Yes	1K	1K	1K	1K	5K	10K	5
TOA1	Yes	1K	1K	1K	1K	10K	10K	1
TOA1	Yes	2K	2K	2K	2K	5K	10K	1
TOA1	Yes	2K	2K	2K	2K	10K	10K	1.5
TOA1	Yes	5K	5K	5K	5K	5K	10K	0.5
TOA1	Yes	10K	10K	10K	10K	5K	7K	0.5
TOA1	Yes	22K	22K	22K	22K	5K	3K	0.15
TOA1	Yes	27K	27K	27K	27K	5K	2.5K	0.1
TOA1	Yes	33K	33K	33K	33K	5K	2K	0.1
TOA2	No	1K	1K	1K	1K	5K	10K	0.6
TOA2	Yes	1K	1K	1K	1K	5K	10K	0.6

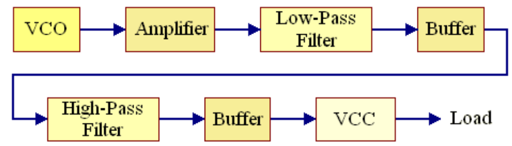

Fig. 5. Flowchart of the proposed VCCS.

To have an exact waveform without jitter and distortion, and to create low output impedance for the next stage (VCC), a Butterworth band-pass filter with corner frequencies: F_L = 10KHz and F_H = 250KHz, has been designed and put between the VCO and VCC parts. In order to design a filter for other frequencies, the Butterworth coefficients are cited in [9]. The circuit of filter is shown in Fig. 6. LF412 ICs, have been applied in the filter structure as the OP-AMPs, but if desired frequency and therefore F_H of filter would be more than mentioned range (e.g., 1MHz), it's necessary to apply AD844 or AD811 instead of LF412. But putting resistors instead of the short connections (connection between pins 2 and 6), should be considered. The filter consists of a fourth-order Butterworth low-pass filter (U_1 and U_2) and a fourth-order Butterworth high-pass filter (U_4 and U_5), that are connected serially.

The end part of the VCCS is the Voltage-to-Current converter (VCC), which many experiments were done to improve and modify its operation. According to the primary physical tests on the mentioned structures of Voltage-Controlled Current Source (VCCS), with different resistance values for their resistors, different OP-AMPs and loads, the best structure is shown in Fig. 7.

V. Final Tests For Proposed VCCS

In the primary results, the output impedance of VCCS based on TOA1 was about 5MΩ, but after using the proposed structure, and exact tuning of potentiometer R_3, only in one point of its resistance value (a few ohms more than 1KΩ), the output impedance more than 6MΩ, was achieved, that it wasn't possible to measure it by oscilloscope (reason of saying "more than 6MΩ"). When the value of R_3 is less than that specific value, the term ($V_2 - V_1$) in (9) would be positive, and when the value of R_3 is more than that specific value, the term ($V_2 - V_1$) in (9), is negative, hence only on the mentioned specific value, ($V_2 - V_1$), is limited to zero and results high output impedance.

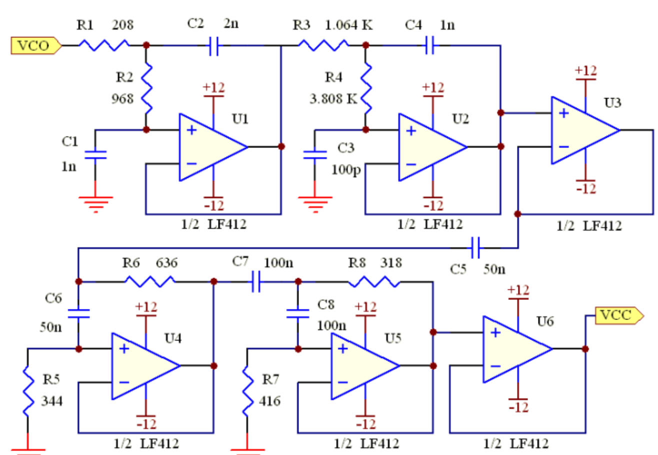

Fig. 6. Butterworth band-pass filter that is put between VCO & VCC.

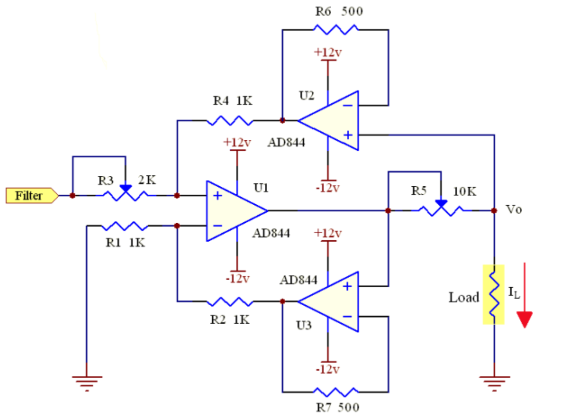

Fig. 7. Triple-Operational Amplifier VCC with proposed values.

Fig. 8 shows the results of the final test for the maximum load, which the proposed VCCS can support that, exactly and without distortion. According to the curve (Fig. 8) the best value for R_1 to R_4 is 1KΩ. In fact the circuit was also tested with resistors less than 1KΩ (0.5KΩ), but the waveform was distorted and the OP-AMPs were getting warm.

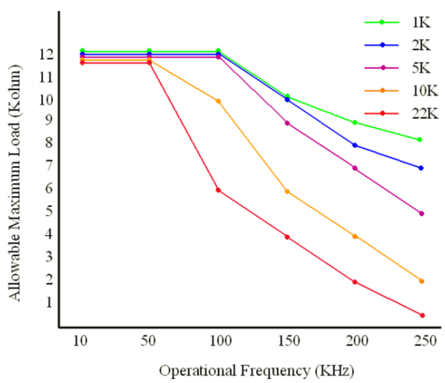

Fig. 8. Showing maximum allowable load in output impedance more than 6MΩ, different frequencies and different values for R_1 to R_4 according to circuit Fig. 7.

To complete the current source, a pulse generation part (shown in Fig. 9) can be added to main VCCS design, to generate a pulse train for detecting maximum or zeros of the output current waveform (peak and zero detection).

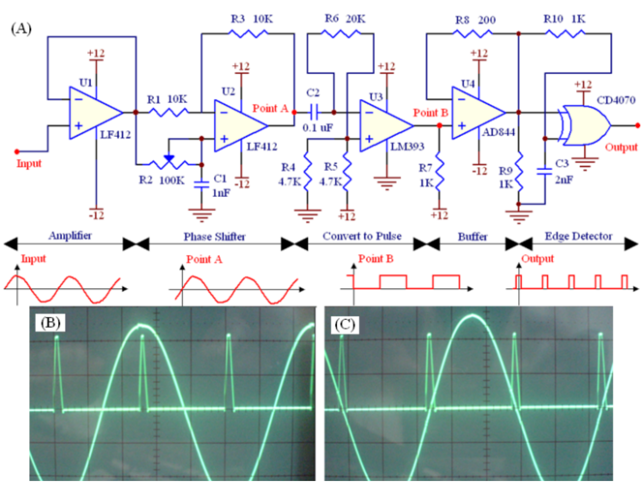

Fig. 9. A) Pulse generation part. B) Peak detection. C) Zero detection.

These pulses can be used for demodulating the measured voltage of the phantom or getting sample from specific points of electrode voltages. The input of pulse generation part, should be connected to the output of filter. The position of the pulses and the pulse width can be changed with R_2 and C_1 respectively. In Fig. 9, part B and C show the useful usage of this part (oscilloscope is on DUAL mode).

VI. Conclusions

In this paper, a high output impedance precise design of a VCCS with a wide range of operational frequencies was proposed. The VCCS with more than 6MΩ output impedance and 1mA constant precision current, can supply a load in resistance range of 10Ω to 12KΩ, in operational frequency less than 100KHz, and 10Ω to 8KΩ in < 250KHz, (according to curve in Fig. 8). The current can also be tuned in values more than 1mA. By applying MAX038 as the VCO and designing a filter for required frequency [9], the performance of this design can be improved and the operational frequency can be increased to higher frequencies. The pulse generation part is also added to current source to complete it for some required operations in EIT. The best result to approve the quality of design is the final image that is shown in Fig. 10, which was obtained by using the mentioned made current source.

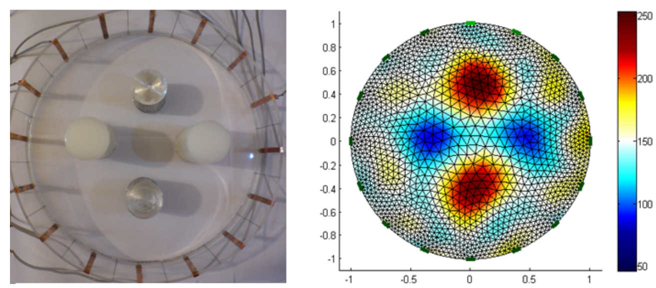

Fig. 10. Final image reconstruction by using the instrumentation which contains mentioned current source.

References

[1] David S. Holder, "*Electrical impedance tomography methods, history and applications*", published by IOP.

[2] L. Zhangyong, X. Zhui, R. Chaoshi, W. Wei, Z. Dechun and Z. Huiquan, "Study of voltage control current cource in electrical impedance tomography system", IEEE, 2010.

[3] Z. Shuai, X. Guizhi, W. Huanli and G. Duyan, "Multi-frequency EIT hardware system based on DSP", China.

[4] C. William, "Electronics for real-time and three-dimensional electrical impedance tomography", A thesis of Oxford Brookes University for the degree of Doctor of Philosophy.

[5] Data-sheet, *LF411, Low Offset, Low Drift JFET Input Operational Amplifier*, National Semiconductor Inc.

[6] B. Pilho, " Comparison of current generators", Physiol.Meas., 2000.

[7] Denyer, F. Lidgey, and Q. Zhu, " A high output impedance current source" , Physiol. Meas., 1994, vol. 15, pp. A79-A82.

[8] Data-sheet, *XR-2206, Monolithic Function Generator*, EXAR Inc.

[9] T. Kugelstadt, "OP-AMPs for everyone" published by Texas Instruments.