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Designed and Practiced a Voltage-mode Sinusoidal Oscillator using Commercially Available ICs

***Abstract**. This paper presents the design of a voltage-mode sinusoidal oscillator using commercially available ICs (AD830). The proposed circuits are a single-phase sinusoidal oscillator and a multiphase sinusoidal oscillator. The first circuit presents a single-phase sinusoidal oscillator with low output impedance. The oscillation frequency and oscillation condition can be easily tuned by the value of the resistors. The proposed single-phase sinusoidal oscillator consists of two AD830, two resistors, and two capacitors. The second circuit presents the multiphase sinusoidal oscillator synthesized on a first-order low-pass filter. The proposed multiphase sinusoidal oscillator consists of three AD830s, nine resistors and three capacitors. The oscillation frequency of the multiphase sinusoidal oscillator can be adjusted without affecting the oscillation condition. The output voltage of the multiphase sinusoidal oscillator is low impedance, allowing for simple external load driving without the use of voltage buffers. The operation of the proposed oscillator circuits is confirmed by experimental testing. The results of experiments achieve a theoretical design that is very appropriate for developing a worksheet for teaching and learning in electrical and electronic engineering laboratories.*

Streszczenie.** W niniejszym artykule przedstawiono projekt oscylatora sinusoidalnego działającego w trybie napięciowym z wykorzystaniem dostępnych na rynku układów scalonych (AD830). Proponowane obwody to jednofazowy oscylator sinusoidalny i wielofazowy oscylator sinusoidalny. Pierwszy obwód przedstawia jednofazowy oscylator sinusoidalny o niskiej impedancji wyjściowej. Częstotliwość oscylacji i stan oscylacji można łatwo dostroić za pomocą wartości rezystorów. Proponowany jednofazowy oscylator sinusoidalny składa się z dwóch AD830, dwóch rezystorów i dwóch kondensatorów. Drugi obwód przedstawia wielofazowy oscylator sinusoidalny zsyntetyzowany na filtrze dolnoprzepustowym pierwszego rzędu. Proponowany wielofazowy oscylator sinusoidalny składa się z trzech AD830, dziewięciu rezystorów i trzech kondensatorów. Częstotliwość drgań wielofazowego oscylatora sinusoidalnego można regulować bez wpływu na stan drgań. Napięcie wyjściowe wielofazowego oscylatora sinusoidalnego ma niską impedancję, co pozwala na proste sterowanie obciążeniem zewnętrznym bez stosowania buforów napięciowych. Działanie proponowanych obwodów oscylatora zostało potwierdzone badaniami eksperymentalnymi. Wyniki eksperymentów pozwalają uzyskać teoretyczny projekt, który jest bardzo odpowiedni do opracowania arkusza roboczego do nauczania i uczenia się w laboratoriach elektrotechnicznych i elektronicznych.* (Projekt i badanie oscylatora sinusoidalnego w trybie napięciowym przy użyciu dostępnych na rynku układów scalonych***)

Keywords: sinusoidal, single-phase, multiphase sinusoidal oscillator, low output impedance.
Słowa kluczowe: sinusoidalny, jednofazowy, wielofazowy oscylator sinusoidalny, niska impedancja wyjściowa.

Introduction

Oscillator circuits are fundamental components that are widely used in control systems, measuring systems, and telecommunication systems [1-3]. Moreover, the sinusoidal signal is important for electrical and electronic engineering instruction in the electronic laboratory [3]. The oscillator circuit consists of a commercially available IC which is very useful for teaching and learning technically. There are three main circuits for the sinusoidal oscillator that are commonly used as learning materials in laboratories: single-phase sinusoidal oscillator [4], quadrature sinusoidal oscillator [3], and multiphase sinusoidal oscillator (MSO) [7-22]. A single-phase oscillator is commonly used to generate sinusoidal clock signals in microcontroller systems and to generate a sinusoidal signal in an inverter system [2]. Commonly, the quadrature oscillator circuit is used as a carrier signal in telecommunication systems and to select the operating range of the voltmeter in a measuring system [3]. Multiphase sinusoidal oscillators find extensive application in the fields of power electronics and communications [1].

Single-phase sinusoidal oscillators are presented and published in both voltage mode [4-5] and current mode [6]. which has the following advantages: It has a low output impedance [5]. The oscillation frequency can be adjusted electronically [4-6]. Use only one active device [4-6]. The above research work is simulated with a computer program but does not carry out an experimental test.

The MSO circuits are designed with a variety of devices and techniques. A number of researchers have designed and developed a multiphase oscillator circuit according to the papers published in references [7-22]. Their details will be noted as follows. The MSO provides voltage-mode [7, 9, 11, 13-15, 17-18, 20-22] and current-mode [8, 10, 12, 16, 19]. In [11, 13, 17-18, 20, 22], the oscillation frequency can be adjusted with the resistor. The voltage-mode MSO in [7, 11, 13, 15, 17-18, 22] only one device is used, so it's easy to experiment. The oscillation frequency and oscillation conditions in [7-9, 11-13, 15-16, 18, 20] can be changed independently. The experiments on sinusoidal oscillators based on commercially available ICs can be found in [9, 13, 17-18, 20, 22].

However, the MSO listed above has a number of disadvantages, as follows:

(i) The proposed circuit uses more than one active device per phase [8-10, 14].

(ii) The output voltage has a high impedance, which requires the use of a voltage buffer [4, 8, 11].

(iii) The devices in use are not commercially available integrated circuits [7-8, 10, 12-13, 15-16, 19, 21].

(iv) The oscillator circuits in [7-8, 10-12, 14-15, 16, 18-19, 21] are merely simulated on a computer, and there is no experimental test. A comparison of the MSO and recent research is shown in Table 1.

From the shortcomings of the research described above, this research presents the design of a voltage-mode sinusoidal oscillator utilizing commercially available integrated circuits (AD830). The first circuit presented a single-phase sinusoidal oscillator designed using a first-order low-pass filter circuit per cascade with a first-order high-pass circuit. It is a sinusoidal oscillator circuit with a single voltage output. The second circuit presented an odd phase MSO synthesized from a first-order low-pass filter circuit. The single-phase and odd-phase MSO circuits use the same sort of commercially available ICs. The operation of the proposed oscillator circuit has been confirmed by experimental testing.

The characteristics of AD830

The AD830 is a product of Analog Devices [23] that is a difference amplifier device. The difference amplifier was designed for use at video frequencies and was helpful in many other applications. This device has an input port and an output port for voltage. The pin position of AD830 is shown in Fig. 1 (a). The voltage input ports Y_1, Y_2, Y_3 and Y_4 (pins 1, 2, 3 and 4) are high impedance ports. The voltage output port X (pin 7) is a low impedance port. The electrical symbol of AD830 is shown in Fig. 1 (b). The following mathematical function can be used to describe the electrical characteristics of the AD830:

Table 1 The proposed multiphase sinusoidal oscillators were compared.

Ref.	Active element	No. of active element per phase	No. of C+R per phase	Designed technique	Non-effect control oscillation frequency and oscillation condition	Low output impedance	Experimental result	Commercial ICs	voltage output
[7]	CDBA	1	1+0	Low-pass filter	Yes	No	No	No	Yes
[8]	OTA	2	1+0	High-pass filter	Yes	No	No	No	No
[9]	OTA	2	1+1	High-pass filter	Yes	No	Yes	Yes	Yes
[10]	CDTA	2	1+0	All pass filter	Yes	No	No	No	No
[11]	OTRA	1	1+2	Low-pass filter	Yes	No	No	Yes	Yes
[12]	CDCTA	1	1+0	Lossy-integrator	Yes	No	No	No	No
[13]	OPAMP	1	1+3	Fractional-order low-pass filter	Yes	Yes	Yes	Yes	Yes
[14]	DCCCII	2	1+0	Low-pass filter	No	No	No	No	Yes
[15]	VDDDA	1	1+2	Low-pass filter	Yes	Yes	No	No	Yes
[16]	CCCDTA	1	1+0	Lossy-integrator	Yes	No	No	No	No
[17]	OPAMP	1	1+2	Low-pass filter	No	Yes	Yes	Yes	Yes
[18]	CDBA	1	1+2	Low-pass filter	Yes	Yes	No	Yes	Yes
[19]	CDTA	1	1+2	All pass filter	No	No	No	No	No
[20]	CCII	1	1+2	Low-pass filter	Yes	Yes	Yes	Yes	Yes
[21]	DO-VDBA	1	1+0	All pass filter	No	Yes	No	No	Yes
[22]	OPAMP	1	1+3	All-pass filter	No	Yes	Yes	Yes	Yes
Propposed circuit	AD830	1	1+3	Low-pass filter	Yes	Yes	Yes	Yes	Yes

(1) $$V_X = A_O\left[\left(V_{Y1}-V_{Y2}\right)+\left(V_{Y3}-V_{Y4}\right)\right].$$

When $A_O \cong \infty$ is the open-loop gain of the AD830. The precise amplifier is accomplished through the closed-loop operation of this topology. Voltage feedback is implemented via the X port where the output is connected to the port Y_4 input for negative feedback, as shown in Fig. 1 (c). The closed-loop property equation of the AD830 is shown as follows:

(2) $$V_X = \left(V_{Y1}-V_{Y2}+V_{Y3}\right).$$

(a)

(b)

(c)

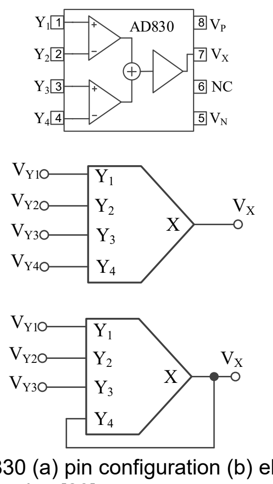


Fig.1. Detail of AD830 (a) pin configuration (b) electrical symbol (c) close-loop connection [23]

Proposed single-phase sinusoidal oscillator

The first circuit presents a single-phase sinusoidal oscillator design using a first-order low-pass filter circuit connected in series with a first-order high-pass circuit. The circuit structure consists of two AD830, two capacitors, and two resistors, as shown in Fig. 2. In addition, the voltage output port is low impedance. The characteristic equation of a circuit can be analysed using the following equation:

(3) $$s^2+s\left(\frac{1}{C_1R_1}-\frac{1}{C_2R_2}\right)+\frac{1}{C_1C_2R_1R_2}=0.$$

Adjusting the oscillation condition of the oscillator circuit in Fig. 2 can be achieved by setting up the following:

(4) $$\frac{1}{C_1R_1}\cong\frac{1}{C_2R_2}.$$

From equation (3), the oscillation frequency can be expressed as follows:

(5) $$\omega_{osc}=\sqrt{\frac{1}{C_1C_2R_1R_2}}.$$

The oscillation frequency can be adjusted by setting $C_1=C_2$ and adjusting R_1 and R_2 concurrently without altering the oscillation condition. Therefore, this oscillator circuit can be utilized for practical application in the laboratory for electronic and electrical engineering. In addition, the sinusoidal oscillator output voltage can simply be utilized for load connection, as this terminal has a low impedance.

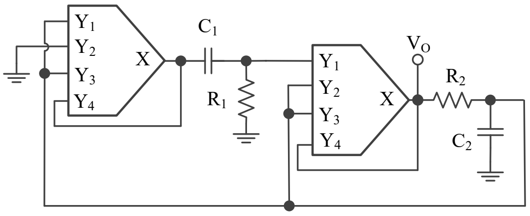


Fig.2. Proposed single-phase sinusoidal oscillator

Single-phase sinusoidal oscillator analysis of non-ideal case

In general, the suggested oscillator performance will be affected by the non-ideal characteristics of AD830. Firstly, the incorrect factor of the voltage transfer errors between input and output ports. Taking into account the incorrect component for the different amplifiers, the non-ideal output voltage of AD830 from equation (2) is modified as

(6) $$V_X = \beta_1 V_{Y1} - \beta_2 V_{Y2} + \beta_3 V_{Y3} .$$

Where β_1, β_2, and β_3 are the inaccurate factors of the different amplifiers from the input voltage to the output voltage of the AD830. Using equation (6), the modified output voltage of the proposed single-phase sinusoidal oscillator in Fig. 2 is given by

(7) $$s^2 + s\frac{1}{C_1R_1} + s\frac{1}{C_2R_2} - \left(s\frac{1}{C_2R_2}\beta_{21}(\beta_{11}+\beta_{13}) + \frac{(\beta_{23}-\beta_{22})(1+sC_1R_1)}{C_1C_2R_1R_2} \right) + \frac{1}{C_1C_2R_1R_2} = 0 .$$

Equations (8) and (9) show the oscillation condition and oscillation frequency derived from equation 7.

(8) $$\left(\frac{1}{C_1R_1} + \frac{1}{C_2R_2} \right) \cong \left(\frac{1}{C_2R_2}\beta_{21}(\beta_{11}+\beta_{13}) + \frac{(\beta_{23}-\beta_{22})(1+sC_1R_1)}{C_1C_2R_1R_2} \right),$$

and

(9) $$\omega_{osc} = \sqrt{\frac{1}{C_1C_2R_1R_2}} .$$

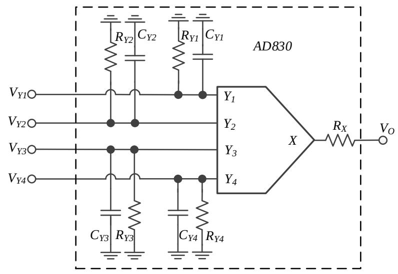


Fig.3. Parasitic elements of AD830

In addition, the AD830 has parasitic elements at all of its ports or pins. Where ports Y_1, Y_2, Y_3, and Y_4 port have resistors and capacitors connected to the ground, as shown in Fig. 3, these parasitic elements are C_{Y1}, R_{Y1}, C_{Y2}, R_{Y2}, C_{Y3}, R_{Y3}, C_{Y4}, R_{Y4}, and R_X. The parasitic capacitor and resistor effect analysis does not consider the effect of the R_W resistor. This is because it affects the circuit very little compared to resistors and capacitors at other ports. These parasitic elements have an impact on the oscillator circuit performance. The equation for the oscillator's characteristics becomes:

(10) $$s^2 + s\left(\frac{G_2^*}{C_2^*R_2} + \frac{G_1^*}{C_1^*} - \frac{2C_1}{C_1^*C_2^*R_2} \right) + \frac{G_1^*G_2^*}{C_1^*C_2^*R_2} = 0 .$$

The oscillation condition is established in equation (11).

(11) $$\frac{G_2^*}{C_2^*R_2} + \frac{G_1^*}{C_1^*} \cong \frac{2C_1}{C_1^*C_2^*R_2} .$$

The oscillation frequency is changed to

(12) $$\omega_{osc} = \sqrt{\frac{G_1^*G_2^*}{C_1^*C_2^*R_2}} ,$$

where $C_1^* = C_1 + C_{Y21}$, $C_2^* = C_2 + C_{Y11} + C_{Y13} + C_{Y22} + C_{Y23}$, $G_1 = \frac{1}{R_1}$, $G_2 = \frac{1}{R_2}$, $G_{Y11} = \frac{1}{R_{Y11}}$, $G_{Y13} = \frac{1}{R_{Y13}}$, $G_{Y21} = \frac{1}{R_{Y21}}$, $G_{Y22} = \frac{1}{R_{Y22}}$, $G_{Y23} = \frac{1}{R_{Y23}}$, $G_1^* = G_1 + G_{Y21}$, and $G_2^* = R_2\left(G_{Y11} + G_{Y13} + G_{Y22} + G_{Y23} + G_2\right)$.

The performance of the proposed single-phase sinusoidal oscillator is affected by parasitic elements. However, the effect of the oscillation frequency and oscillation condition can be directly solved by slightly adjusting the resistors R_1 and R_2.

The proposed multiphase sinusoidal oscillator circuit

The second circuit presents an MSO designed as shown in Fig. 4. The MSO consists of three AD830s, nine resistors, and three capacitors, which are synthesized from the 3-cascaded first-order low-pass filter circuits. The first-order low-pass filter is constructed from one AD830, three resistors and one capacitor. The low output impedance makes it easy to drive an external load without the need for additional voltage buffers. A circuit's characteristic equation can be expressed as follows:

(13) $$\left[\frac{-K}{sCR+1} \right]^3 = 1 .$$

Where K is the gain of each of the first-order low-pass filters, determined by the resistors R_A and R_B. The proposed circuit can generate a sinusoidal signal by defining the oscillation conditions. This can be expressed as follows:

(14) $$K = \frac{R_A}{R_B} + 1 \geq \sqrt{1 + \tan^2\frac{\pi}{3}} .$$

The oscillation frequency and phase difference of MSO can be expressed as follows:

(15) $$\omega_{osc} = \frac{1}{RC}\tan\frac{\pi}{3} ,$$

and

(16) $$\phi = \frac{2\pi}{n} = \frac{2\pi}{3} = 120^0 .$$

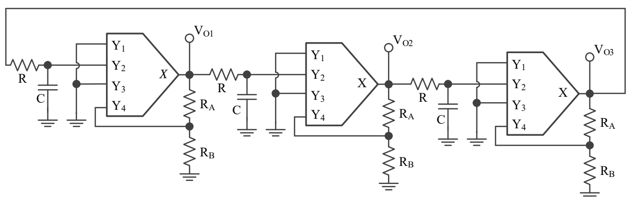


Fig.4. The proposed MSO circuit

The MSO analysis of non-ideal case

In the MSO circuit, it has the same effect as in a single-phase sinusoidal oscillator because it uses the same AD830. When considering the non-ideal case of AD830 in Fig. 4, using equation (6). The equation for the characteristics of the MSO becomes.

(17) $$\left(\frac{1}{sCR+1}\left(\frac{\beta_{12}R_A}{R_B\beta_{14}} + \frac{\beta_{12}}{\beta_{14}} \right) \right)^3 = 1 .$$

Where K is the gain of each of the first-order low-pass filters in the case of non-ideal. From equation (17), the oscillation condition and oscillation frequency are as follows:

(18) $$K = \left(\frac{\beta_{12} R_A}{R_B \beta_{14}} + \frac{\beta_{12}}{\beta_{14}} \right) \geq \sqrt{1 + \tan^2 \frac{\pi}{3}} \ ,$$

and

(19) $$\omega_{osc} = \frac{1}{RC} \tan \frac{\pi}{3} \ .$$

In Fig. 4, when evaluating the influence of parasitic resistance and parasitic capacity. The characteristic equation of the oscillation condition and the oscillation frequency is as follows:

(20) $$\left(C_{Y14} R_A + \frac{R_A}{R_{Y14}} + \frac{R_A}{R_B} + 1 \right) \geq \sqrt{1 + \tan^2 \frac{\pi}{3}} \ ,$$

and

(21) $$\omega_{osc} = \left(\frac{R}{(CR + C_{Y14} R) R_{Y14}} + \frac{1}{CR + C_{Y14} R} \right) \tan \frac{\pi}{3} \ .$$

The non-ideal elements affect the performance of the proposed MSO. The effects of oscillation frequency and oscillation conditions can be directly corrected by slightly adjusting resistor R.

Experimental results

Experiment with the sinusoidal oscillator circuit presented in Fig. 2 to test its operation. By assigning the external passive elements $R_1=R_2=1\text{k}\Omega$ and $C_1=C_2=1\text{nF}$ in accordance with equation (4), the circuit can generate a sinusoidal signal. The Siglent SPD330C power supply was utilized to power the voltage bias of the circuit by setting it at ±6V. An oscilloscope, the Keysight DSOX3024T, was used to measure the output sinusoidal waveform. Fig. 5 shows the experimental output waveform of the single-phase sinusoidal oscillator. When the theoretical oscillation frequency in equation (5) is 159.15kHz, while the experimental oscillation frequency is about 155.81kHz. The variation in oscillation frequency between the theory and the experiment is 2.09%. This may be due to the resistor error value and capacitor used in the circuit. The frequency spectrum is shown in Fig. 6. In the output signal, there is a total harmonic distortion (THD) of 0.134%.

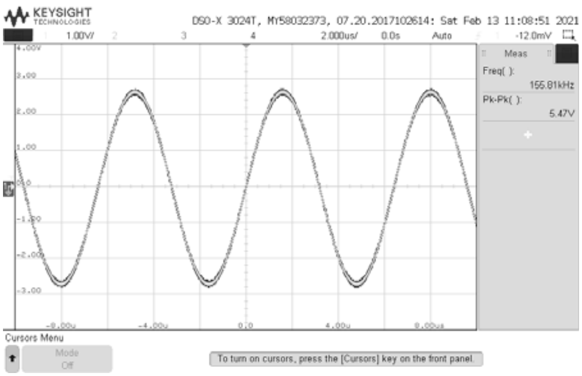


Fig.5. Sinusoidal waveform of a single-phase sinusoidal oscillator

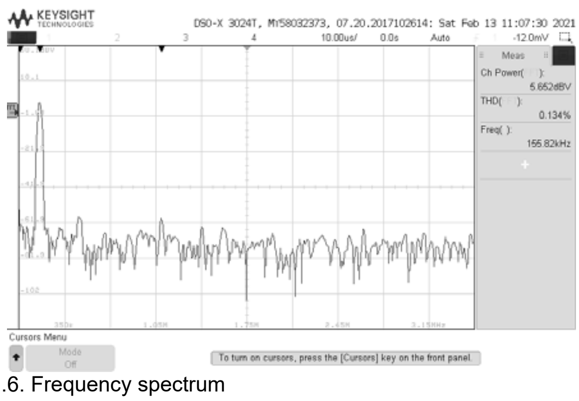


Fig.6. Frequency spectrum

According to Fig. 7, the oscillation frequency is adjustable by changing the values of resistors R_1 and R_2 concurrently. While adjusting from 250Ω to 3kΩ, the resistor values R = R1 = R2 are set. The resistor adjustment experiments result in a change in oscillation frequency from 55.56kHz to 615.2kHz. Fig. 8 shows the theoretical and experimental oscillation frequency error, with an absolute mean error lower than 3.86%. This error may be caused by the error value of the resistors and capacitors used in the circuit. The effect of the oscillation frequency can be directly solved by slightly adjusting the resistors R_1 and R_2. Fig. 9 shows the percent total harmonic distortion of the sinusoidal signals for each frequency. Total harmonic distortion (THD) is found to be less than 4.5%.

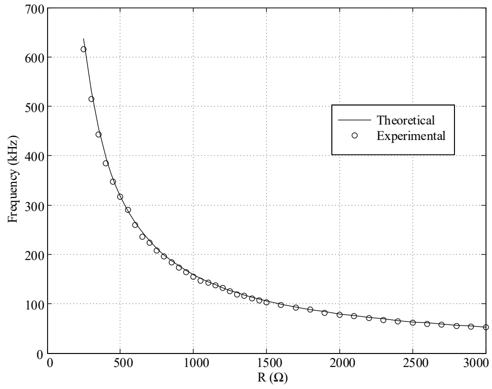


Fig.7. Frequency tuning of proposed single-phase oscillator

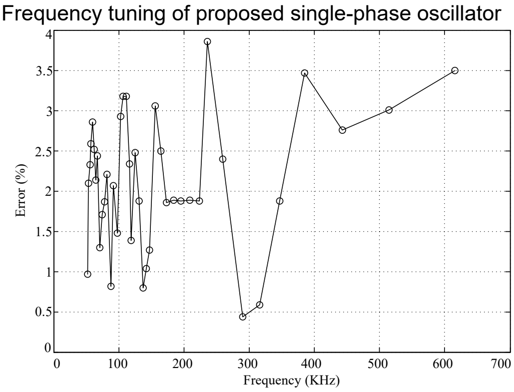


Fig.8. Absolute error of frequency

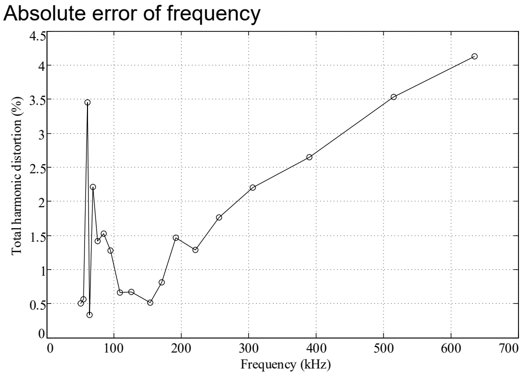


Fig.9. Total harmonic distortion of sinusoidal signals

To test the proposed MSO in Fig. 4. The proposed circuit supply voltage was set at ±6V. The passive components of the oscillator are C=1nF, R=1kΩ, and $R_A=R_B=500\Omega$. The theoretical oscillation frequency calculated from equation (15) is 278.31kHz, while the experimental oscillation frequency is 279.11kHz. The experimentation showed that the oscillation frequency differed from the theory by 0.28%. Fig. 10 shows the output waveforms of the V_{O1}, V_{O2} and V_{O3}. The experimental spectrum analysis results of MSO are shown in Fig. 11. The phase relation of V_{O1}, V_{O2}, and V_{O3} is 119.25°, 122.12°, and

118.58°, which deviates from 120° by around 0.4%, 1.76%, and 1.18% respectively. Fig. 12 illustrates the relationship between the phase of the sinusoidal signals and the XY plot.

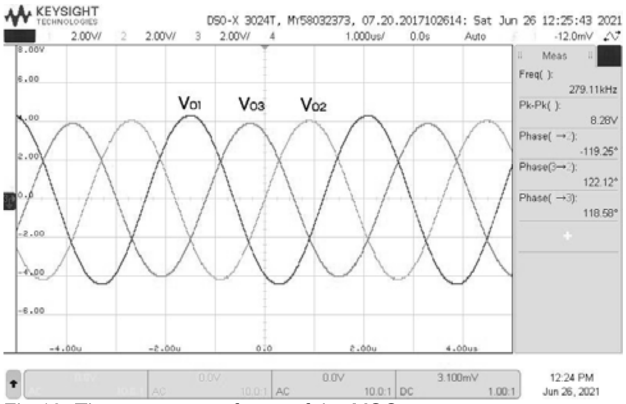
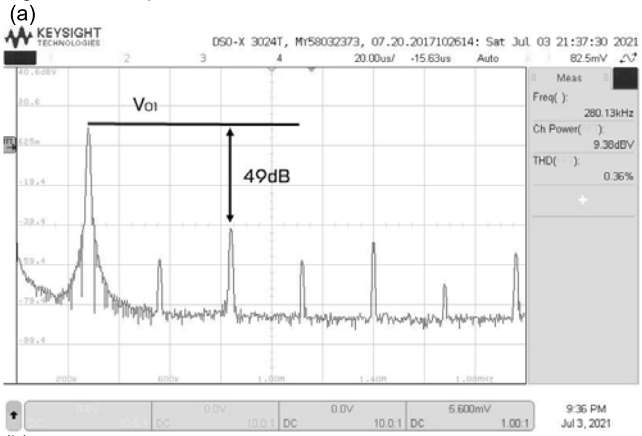
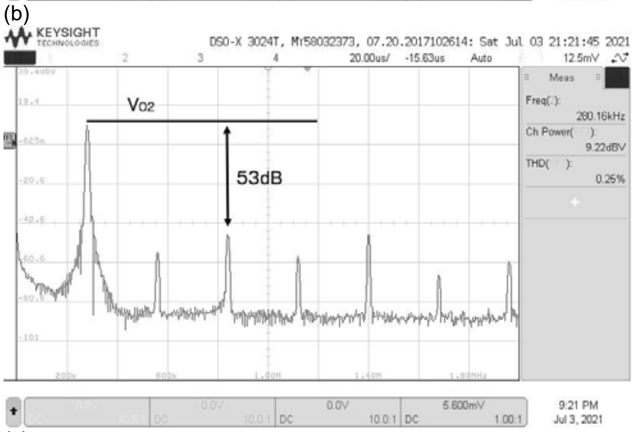


Fig.10. The output waveforms of the MSO

(a)



(b)



(c)

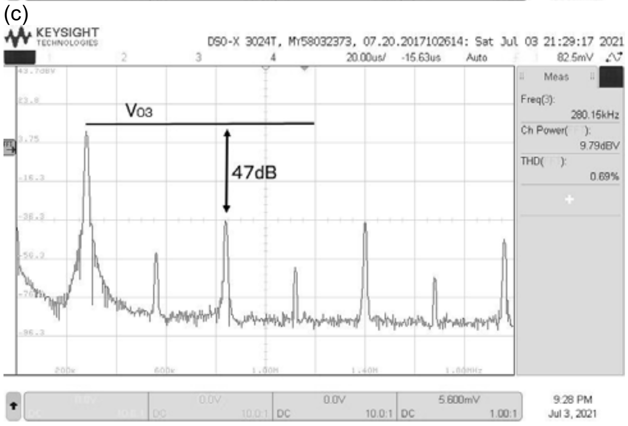
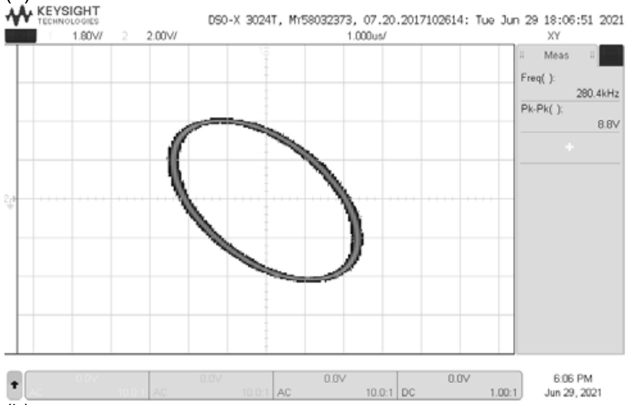
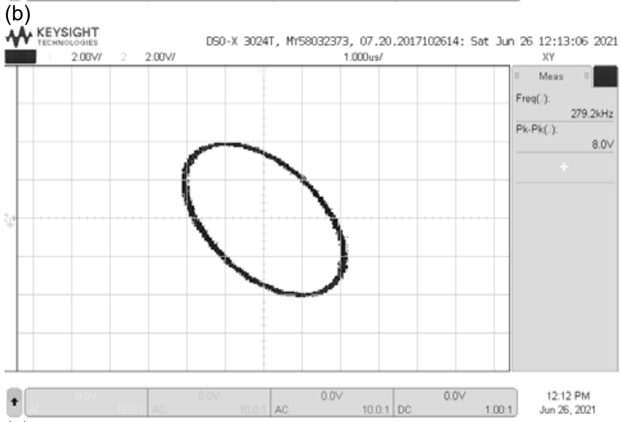


Fig.11. The experimental spectrum analysis results of the MSO (a) V_{O1} (b) V_{O2} (c) V_{O3}

(a)



(b)



(c)

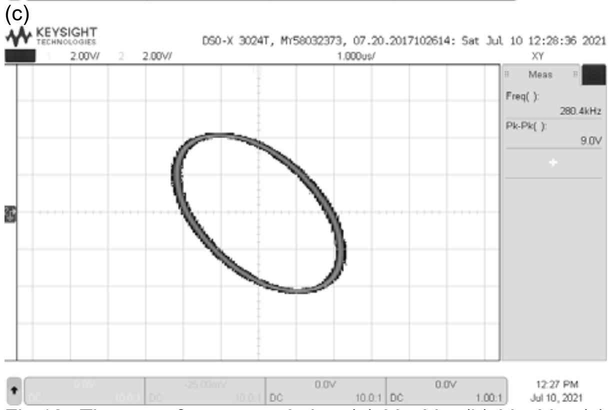


Fig.12. The waveforms correlation (a) V_{O1}-V_{O2} (b) V_{O2}-V_{O3} (c) V_{O1}-V_{O3}

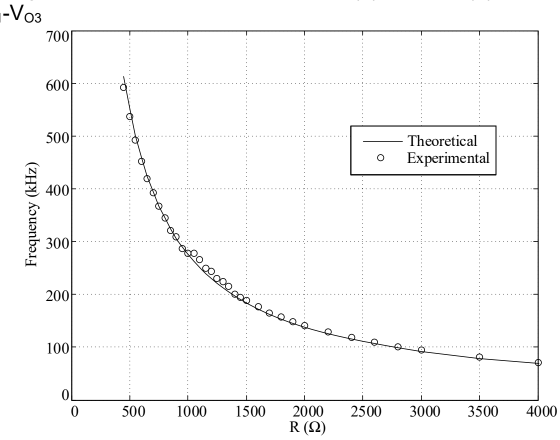


Fig.13. The frequency tuning of the MSO

As demonstrated in equation (15), the frequency can be tuned by altering the resistor R. Experiment to adjust the oscillation frequency of the MSO circuit as shown in Fig. 13. In this experiment, resistance R was adjusted from 450Ω to 4kΩ**.** The experimental frequency varies from 75kHz to 590kHz. Fig. 14 shows a visualization of the error vs frequency. Frequency errors ranged from 0.04% to 3.44%. The frequency error stems from the resistance error value and capacitor used in the circuit. The total harmonic distortion percentage of the MSO is shown in Fig. 15. The total harmonic distortion (THD) is found to be less than 5%.

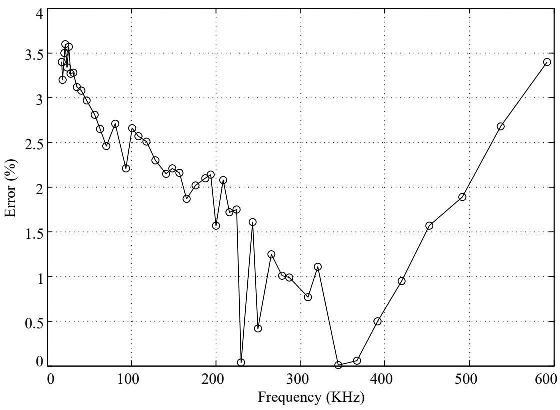


Fig.14. The frequency error of the MSO

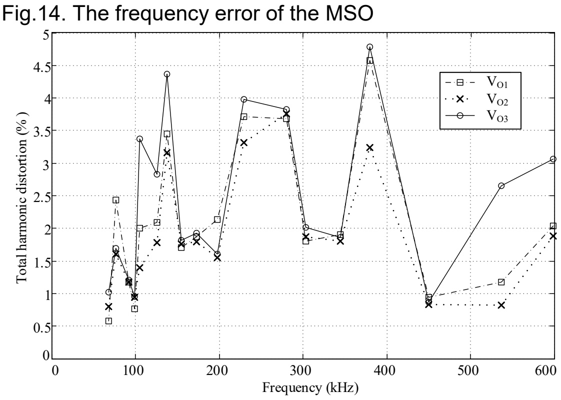


Fig.15. The total harmonic distortion percentage of the MSO

As demonstrated in equation (15), the frequency can be tuned by altering the resistor R. Experiment to adjust the oscillation frequency of the MSO circuit as shown in Fig. 13. In this experiment, resistance R was adjusted from 450Ω to 4kΩ. The experimental frequency varies from 75kHz to 590kHz. Fig. 14 shows a visualization of the error vs frequency. Frequency errors ranged from 0.04% to 3.44%. The frequency error stems from the resistance error value and capacitor used in the circuit. The total harmonic distortion percentage of the MSO is shown in Fig. 15. The total harmonic distortion (THD) is found to be less than 5%.

Conclusion

This paper presents the design of the single-phase sinusoidal oscillator and the MSO using commercially available ICs (AD830). The single-phase sinusoidal oscillator is created from two AD830, two capacitors, and two resistors. The single-phase output sinusoidal has a low impedance. The oscillation frequency can be varied between 55.56kHz and 615.2kHz by adjusting the resistance values R_1 and R_2. The proposed MSO circuit is synthesized from the first-order low-pass filter. The proposed oscillator consists of three AD830s, nine resistors, and three capacitors. This MSO output is sinusoidal and has low output impedance terminals. The MSO can be connected to load without a voltage buffer or matching impedance. The oscillation frequency of MSO can be varied between 75kHz and 590kHz. The experimental results of the sinusoidal oscillator in both circuits confirm the analytical theory and are very appropriate for developing a worksheet for teaching and learning in electrical and electronic engineering laboratories.

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