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Published in:
International Journal of Electrical and Computer Engineering

DOI:
10.11591/ijece.v13i3.pp3572-3584

Published: 01/06/2023

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Garinto, D., Valerie, T., Yanto, H. A., Sutikno, T., & Simatupang, J. W. (2023). A novel triangular wave quadrature oscillator without passive components for sinusoidal pulse width modulation DC-AC power conversion. *International Journal of Electrical and Computer Engineering*, *13*(3), 3572-3584. https://doi.org/10.11591/ijece.v13i3.pp3572-3584

International Journal of Electrical and Computer Engineering (IJECE)
Vol. 13, No. 3, June 2023, pp. 3572~3584
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i3.pp3572-3584

A novel triangular wave quadrature oscillator without passive components for sinusoidal pulse width modulation DC-AC power conversion

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Article Info

Article history:

Received Oct 4, 2022
Revised Jan 9, 2023
Accepted Jan 14, 2023

Keywords:

DC-AC converter
Op-Amp-based oscillator
Pulse width modulation
Quadrature oscillator
Quadrature triangular oscillator
Sinusoidal PWM
Triangular wave generator

ABSTRACT

In this study, a low-cost quadrature triangle oscillator using a voltage-controlled closed-loop dual operational amplifier (Op-Amp) architecture is proposed. Unlike other typical designs, this oscillator does not require any passive components. The use of an Op-Amp-based circuit is attractive for a triangle oscillator because it is more cost-effective than a microcontroller-based solution. This is especially true for sinusoidal pulse width modulation (SPWM) DC-AC power conversion applications. The slew-rate restriction of an Op-Amp is a useful characteristic for producing a triangle waveform when seen from the perspective of wave shaping techniques. The MC4558 and the JRC4558D are two examples of dual Op-Amps that are evaluated, contrasted, and described in this article. At supply voltages of +7 V and -7 V, the suggested quadrature triangle oscillator that uses Op-Amps MC4558 and JRC4558D has the same oscillation frequency, which is 63 kHz, as demonstrated by simulation and experimental data. The frequency stability is estimated to be around 0.23%. In addition, the findings from the experiment demonstrate that the proposed oscillator is a practical solution for the SPWM DC-AC power conversion application.

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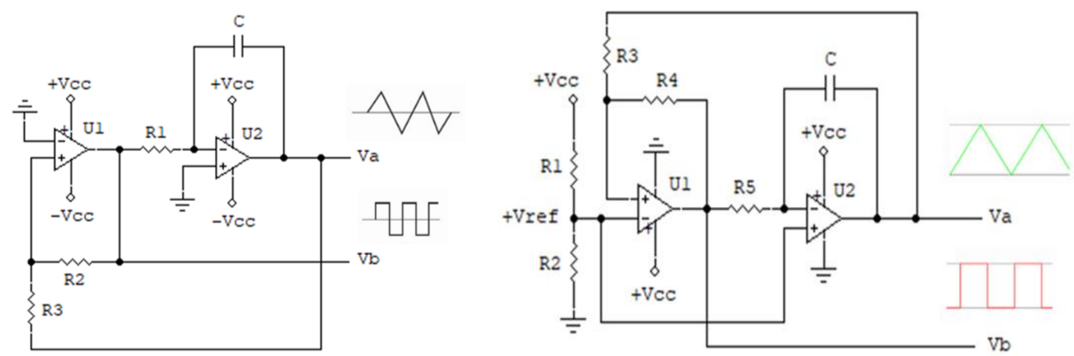
1. INTRODUCTION

A triangular wave generator is a useful circuit for a wide variety of applications. Some application examples include a dual-slope A/D converter, a tone generator, a linearity testing signal for an amplifier, a signal carrier in sinusoidal pulse width modulation (SPWM) DC-AC power conversion, and induction motor controller applications. In recent years, an electronically tunable triangular/square wave generator with IC LT1228 was presented for capacitive sensor interfacing applications. However, the generator circuit requires two LT1228s, a grounded resistor, and a grounded capacitor to produce triangular and square waves [1]. Another square/triangular wave generator circuit was proposed lately using IC AD844 and five passive components. The oscillation frequency of the generator can achieve as low as 19.8 Hz and as high as 19.2 kHz [2]. In addition, an analog triangular wave quadrature oscillator using four Op-Amps with six resistors and two capacitors was suggested a few years ago. The IC TL074 was used to realize this requirement. In this oscillator, the passive components provide abilities to control the amplitude and the oscillation frequency [3]–[5]. Moreover, a triangular/square-wave generator using three operational trans-conductance amplifiers (OTA) and some passive components to provide current-controllable frequency and amplitude was introduced, but it requires excessive components [6]. Additional triangular wave generators based on operational amplifier (Op-Amp) were reported in the literature [7]–[9].

For a long time, sinusoidal waveform generators without resistor and capacitor elements, known as quadrature oscillators, have been previously reported in the literature [10]–[12]. Op-Amp-based oscillator designs, including the quadrature oscillators, are studied and discussed in more detail in the previous papers [13]–[18], [19]–[24]. Also, a relaxation oscillator based on a closed-loop dual comparator with a voltage divider has been investigated in recent times [25]. For a long time, a typical triangular wave generator circuit can be built with a combination of Op-Amp and comparator, as shown in Figure 1 [26]–[28]. While both triangular wave and quadrature triangular wave generators that use Op-Amps have been discussed, the basic configuration of a triangular wave generator circuit with dual Op-Amps and no resistors or capacitors is still being researched to make a single-chip IC device.

A conventional triangular wave generator in Figure 1 is composed of a single comparator and a single Op-Amp with additional passive components to control the amplitude and the frequency. Figure 1(a) is without a voltage divider, and Figure 1(b) uses a voltage divider. Essentially, this design uses an integrator circuit to shape a triangular waveform from a square waveform. In SPWM DC-AC power conversion applications, a triangular waveform is implemented as a carrier signal to be compared with a sinusoidal waveform. Therefore, a triangular waveform generation with natural amplitude and oscillation frequency that is produced using a voltage-controlled dual Op-Amp without passive elements, as will be discussed, is a practical approach and a low-cost solution to accomplish this purpose.



(a) (b)

Figure 1. Typical triangular wave generator, (a) without voltage divider and (b) with voltage divider, where U1=comparator, U2=Op-Amp

2. METHOD

Figure 2 shows triangular wave quadrature oscillator. Figure 2(a) depicts a triangular wave quadrature oscillator with two Op-Amp. According to the modeling and experimental data, the slew rate and differential pre-amplifier characteristics of the Op-Amp are critical to producing a triangle waveform output. As a result, extra passive components are not required, particularly in SPWM DC-AC power conversion applications. The numerical analysis may be obtained using the practical model of the Op-Amp depicted in Figure 2(b) as:

$$A_{O2}v_2 - I_1R_o - I_1R_i = 0 \quad (1)$$

$$-A_{O1}v_1 - I_2R_o - I_2R_i = 0 \quad (2)$$

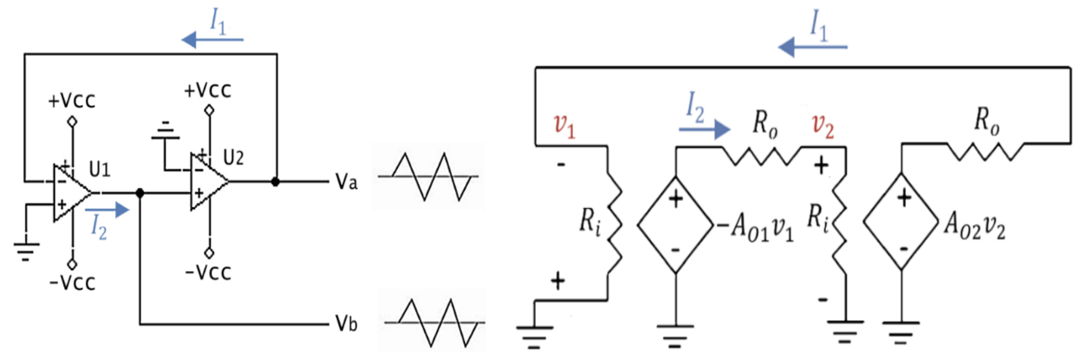
By substituting $I_1 = \frac{v_1}{R_i}$ to (1) and $I_2 = \frac{v_2}{R_i}$ to (2), we can obtain (3) and (4) respectively, as:

$$\frac{v_2}{v_1} = \frac{R_o+R_i}{A_{O2}R_i} \quad (3)$$

$$\frac{v_2}{v_1} = \frac{-A_{O1}R_i}{R_o+R_i} \quad (4)$$

Combining (3) and (4) gives out the following relation:

$$(R_o + R_i)^2 = -A_{O1}A_{O2}{R_i}^2. \quad (5)$$



(a) (b)

Figure 2. Triangular wave quadrature oscillator, (a) proposed circuit and (b) practical model of the proposed oscillator with two Op-Amp

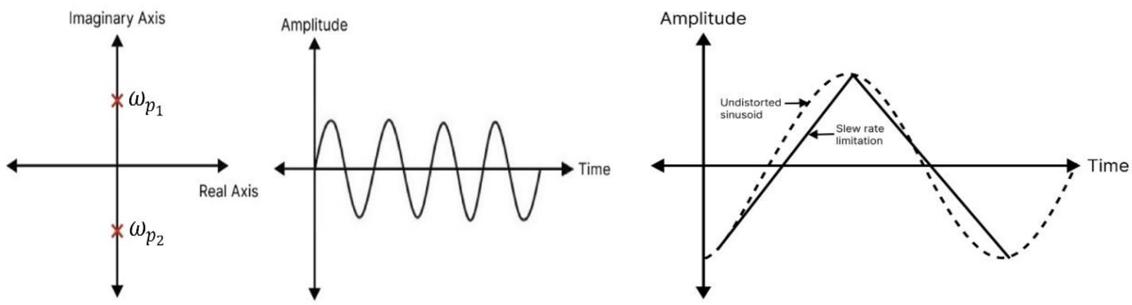
Figure 3 shows the output response of the system. Assuming op-amp U1 and U2 are identical, we know that $A_{O1} = A_{O2} = \frac{B}{\omega_p}$ where B is the gain-bandwidth product of the Op-Amp and ω_p is the angular frequency in the 3 dB point. Rearranging (5) gives out (6) which shows that the system has two complex conjugate roots on the imaginary axis. Thus, the system can be categorized as marginally stable which produces an output response of undamped sinusoidal waveforms as illustrated in Figure 3(a). Using the two-pole model of the Op-Amp, the characteristic equation of the system can be defined as (7).

$$\omega_{p_2} = \pm\frac{BR_i}{R_o+R_i}j \quad (6)$$

$$(s + \frac{BR_i}{(R_i+R_o)}j)(s - \frac{BR_i}{(R_i+R_o)}j) = 0 \quad (7)$$

Despite the output response of the system being sinusoidal, the slew rate limits of the Op-Amp will cause a sine wave that has a high enough amplitude and frequency to be distorted into a triangle or trapezoidal wave, as can be seen in Figure 3(b). The slew rate of an Op-Amp is dependent on the amplitude of the output signal as shown by the relation in (8). The higher the amplitude, the lower the oscillation frequency.

$$SR = \frac{f_{max}}{2\pi V_{pp}} \quad (8)$$



(a) (b)

Figure 3. The output response of the system (a) undamped sinusoidal oscillation as a result of marginally stable system (b) distortion of the sinusoidal oscillation caused by the Op-Amp slew rate limits which form a triangular or trapezoidal wave

3. RESULTS AND DISCUSSION

In this section, the proposed quadrature triangular oscillator is analyzed. The working principle is discussed. Also, PSPICE simulation and experimental results are given.

3.1. Analysis of the proposed quadrature triangular oscillator

Figure 4 shows triangular waveforms with a quadrature characteristic. Based on PSPICE simulations, the transient analysis of the proposed oscillator using Op-Amp MC4558 with supply voltages of +7 V and -7 V is shown in Figure 4(a). Figure 4(b) illustrates the working principle of the proposed quadrature triangular oscillator circuit and describes four operation modes as:

a) Operation mode 1: T0-T1
In this condition, the non-inverting input of Op-Amp U1 has a higher voltage than the inverting input because the voltage at the inverting input becomes negative. As a result, the output voltage Vb of the Op-Amp U1 changes from negative to positive due to the differential nature of the Op-Amp.

b) Operation mode 2: T1-T2
During this period, the output Vb continues to increase linearly due to the slew rate characteristic of the Op-Amp U1. Therefore, the non-inverting input of Op-Amp U2 has a higher voltage compared to the inverting input. Consequently, the output voltage Va of Op-Amp U2 changes from negative to positive due to the differential attribute of the Op-Amp. Between interval T0-T2, the slew rate of the Op-Amp can be calculated as $\Delta V/\Delta t$.

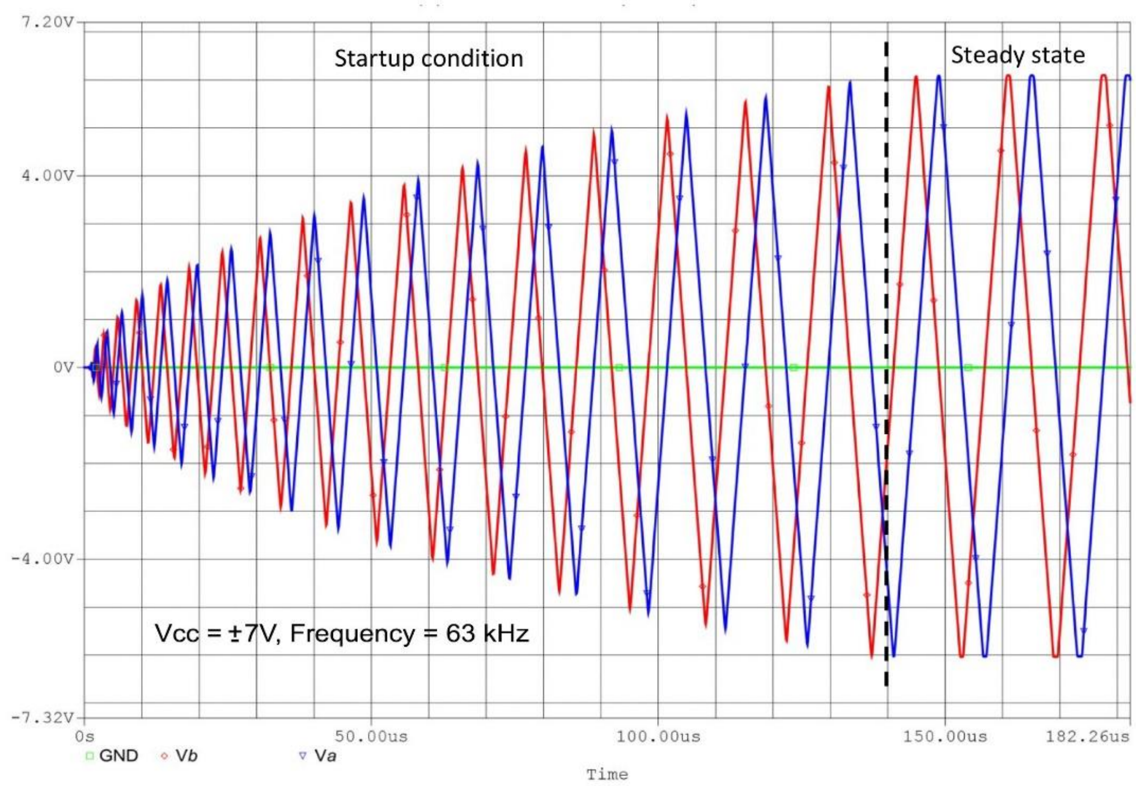
c) Operation mode 3: T2-T3
During this interval, the output voltage Va continues to increase linearly due to the slew rate characteristic of the Op-Amp U2. Because the output Va is routed back to the inverting input of Op-Amp U1, then the inverting input has a higher voltage compared to the non-inverting input of Op-Amp U1. Accordingly, the output voltage Vb of the Op-Amp U1 changes from positive to negative due to the differential characteristic of the Op-Amp.

d) Operation mode 4: T3-T4
In this operation mode, the output voltage Vb continues to decrease linearly due to the slew rate characteristic of the Op-Amp U1. As a consequence, the inverting input of Op-Amp U2 has a higher voltage than the non-inverting input. Hence, the output voltage Va changes from positive to negative due to the differential pre-amplifier of the Op-Amp. At T=T4, the cycle is repeated continuously due to a closed-loop system.

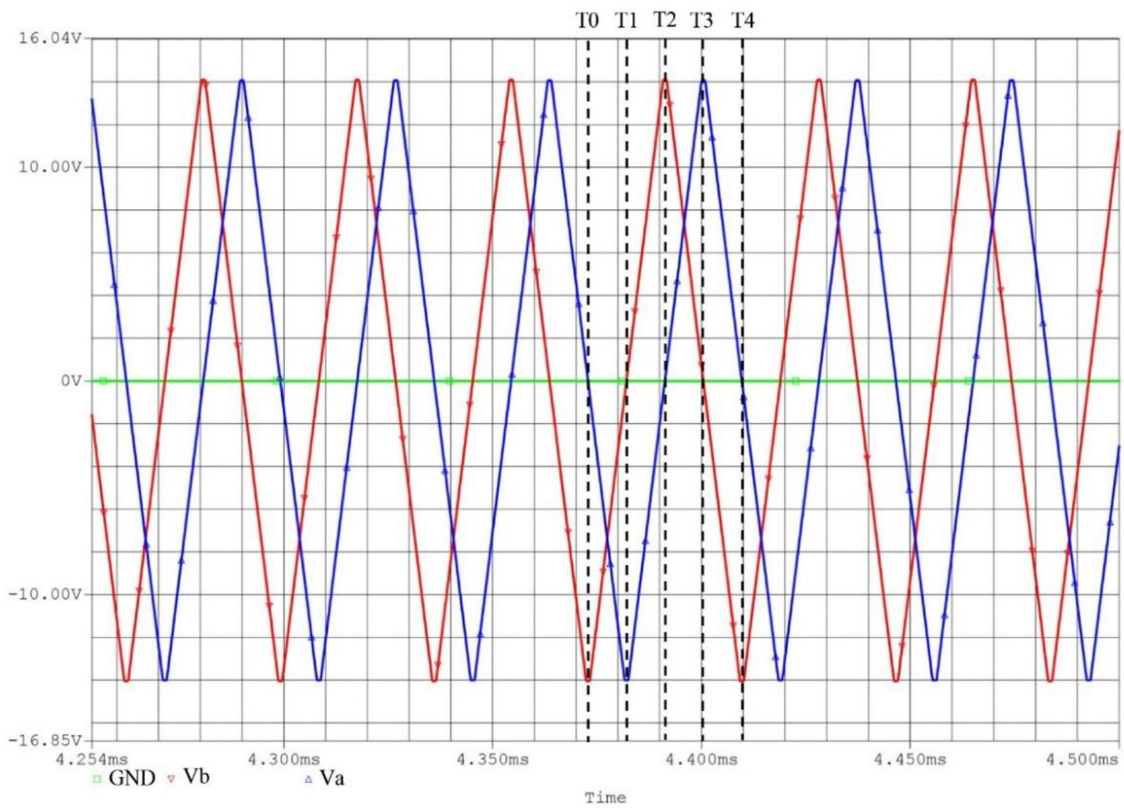
As revealed in Figure 5, the experimental result confirms that the proposed triangular wave oscillator provides a quadrature phenomenon. However, unlike the simulation result, the voltage amplitudes Vb and Va according to the experimental result are about +4.4 V and -4.4 V peak to peak. It is because the experimental result uses supply voltages of +6 V and -6 V. Moreover, the measured natural oscillation frequency of the triangular waveform created by this Op-Amp is 76 kHz. It is higher compared to the simulation result (63 kHz). Table 1 shows how the simulation and experiment results relate to the parameters and values of the proposed triangular wave quadrature oscillator.

Based on the experimental results, as shown in Figures 5, 6, and 7, the higher the supply voltages, the lower the oscillation frequency obtained at the output of the Op-Amp. In fact, the supply voltages also influence the oscillation frequency and wave shaping. Therefore, the proposed oscillator circuit can be viewed as a voltage-controlled oscillator. The supply voltage can transform the output signal from a triangular into a trapezoidal waveform or from a trapezoidal into a triangular waveform. The phenomena depend on the supply voltages, the slew rate, and other characteristics of the Op-Amp. In the case of the supply voltages +7 V and –7 V, as shown by simulation and measurement results in Figure 6, the Op-Amps MC4558 and JRC4558D have a similar oscillation frequency. It is necessary to select the right Op-Amp characteristics using the proposed oscillator circuit to shape the determined waveform. For example, if the high slew rate Op-Amp is selected, then the generated waveform could be a square wave quadrature or a sinusoidal wave quadrature. Figure 8 depicts the frequency spectrum of the quadrature triangular oscillator based on Figure 2(a).

The JRC4558D operational amplifier can produce a triangular wave quadrature oscillator and has a slew rate of around 1.2 V/us, as shown in Figure 5. In terms of integrated circuit layout design, more specifically in complementary metal-oxide semiconductor (CMOS) technology, the suggested triangular wave quadrature oscillator does not require any external resistors or capacitors; as a result, it only needs a very little amount of space on the chip itself. In ultra-low-power applications, such as body sensor networks in biomedicine or temperature sensors for internet of things (IoT) applications, this distinction is also quite important. A high-impedance input is one of the benefits offered by the proposed oscillator. This feature makes it possible to use a resistive component with a range of Mega-ohms when the oscillator is put to use in specialized resistive sensing applications.



(a)



(b)

Figure 4. Triangular waveforms with a quadrature characteristic, (a) simulation results show the transient response analysis of the proposed oscillator and (b) the working principle in four operation modes

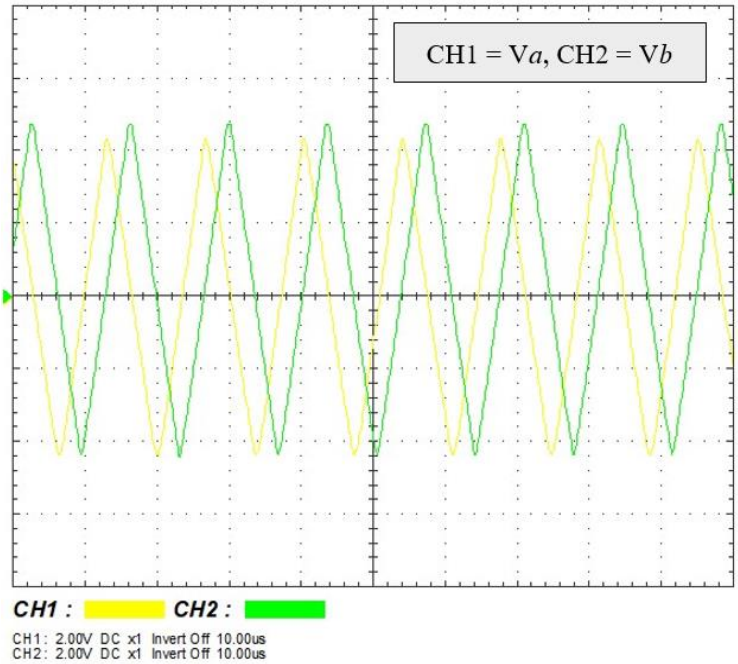


Figure 5. Experimental result of the proposed triangular wave quadrature oscillator circuit using dual Op-Amp JRC4558D

Table 1. The parameter and value of Figure 3 based on Figure 2(a)

Parameter	Value of Figure 3(a)	Value of Figure 3(b)	Value of Figure 3(c)
U1, U2	MC4558	MC4558	JRC4558D
+Vcc	+7 V	+15 V	+6 V
-Vcc	-7 V	-15 V	-6 V

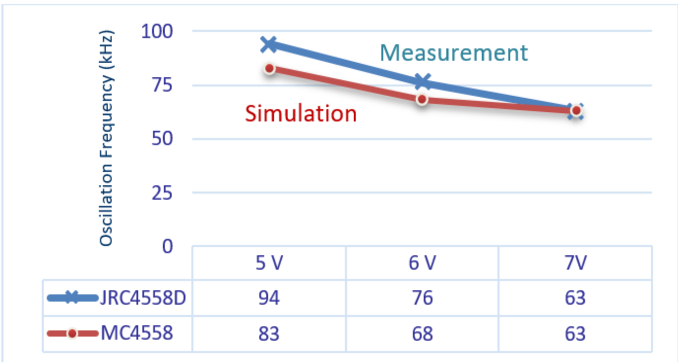


Figure 6. Simulation and measurement results of the oscillation frequency in relation to the supply voltages using Op-Amps MC4558 and JRC4558D

3.2. Implementation of the proposed triangular oscillator for SPWM DC-AC converters

SPWM is the technique that is utilized most frequently in power electronics technology to accomplish the transformation of direct current (DC) voltage into alternating current (AC) voltage [29]–[31]. Figure 9 provides a simulation result of the SPWM approach, which makes use of a comparator to generate the SPWM signal and a proposed triangular wave quadrature oscillator as a reference signal for the technique. Generally, the SPWM signal is coupled to a gate driver in the case of single-phase DC-AC power conversion applications. This allows the signal to turn on and off semiconductor devices like metal oxide silicon field effect transistors (MOSFETs) and insulated gate bipolar transistor (IGBTs). Table 2 describes the parameters and the value of Figure 8.

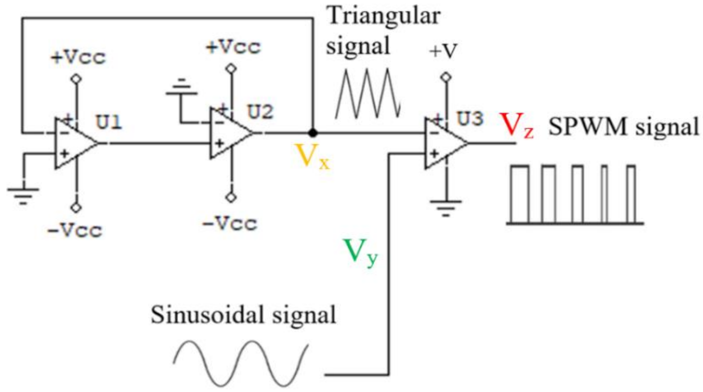


Figure 7. Implementation of the proposed triangular wave quadrature oscillator for SPWM DC-AC power conversion application

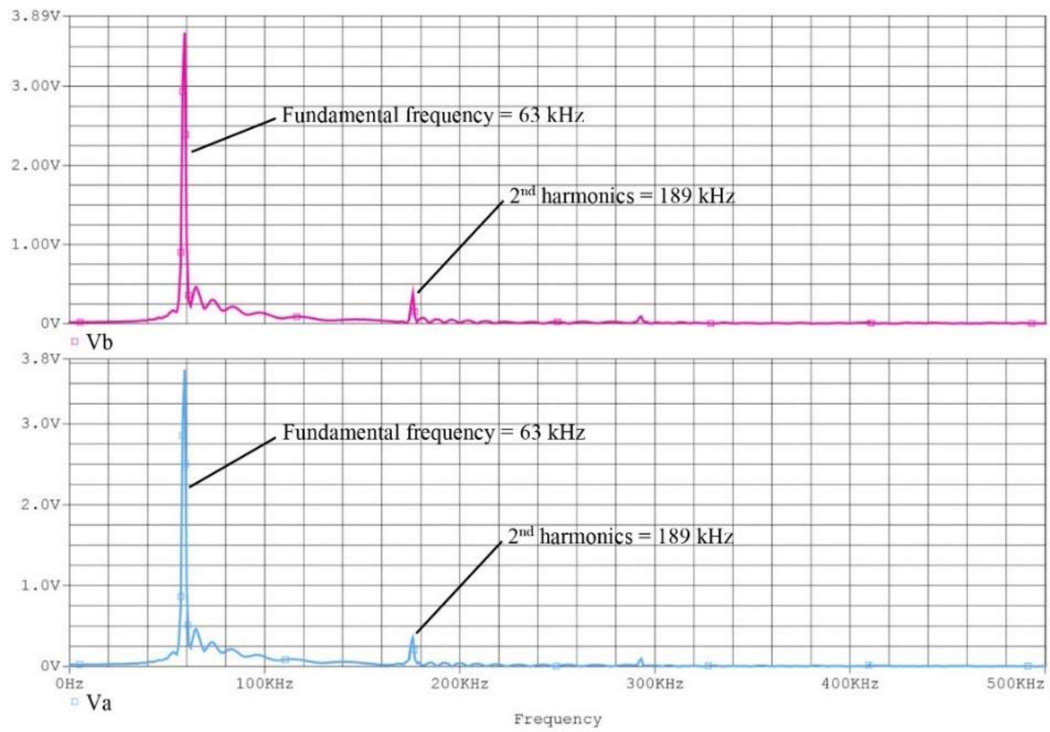
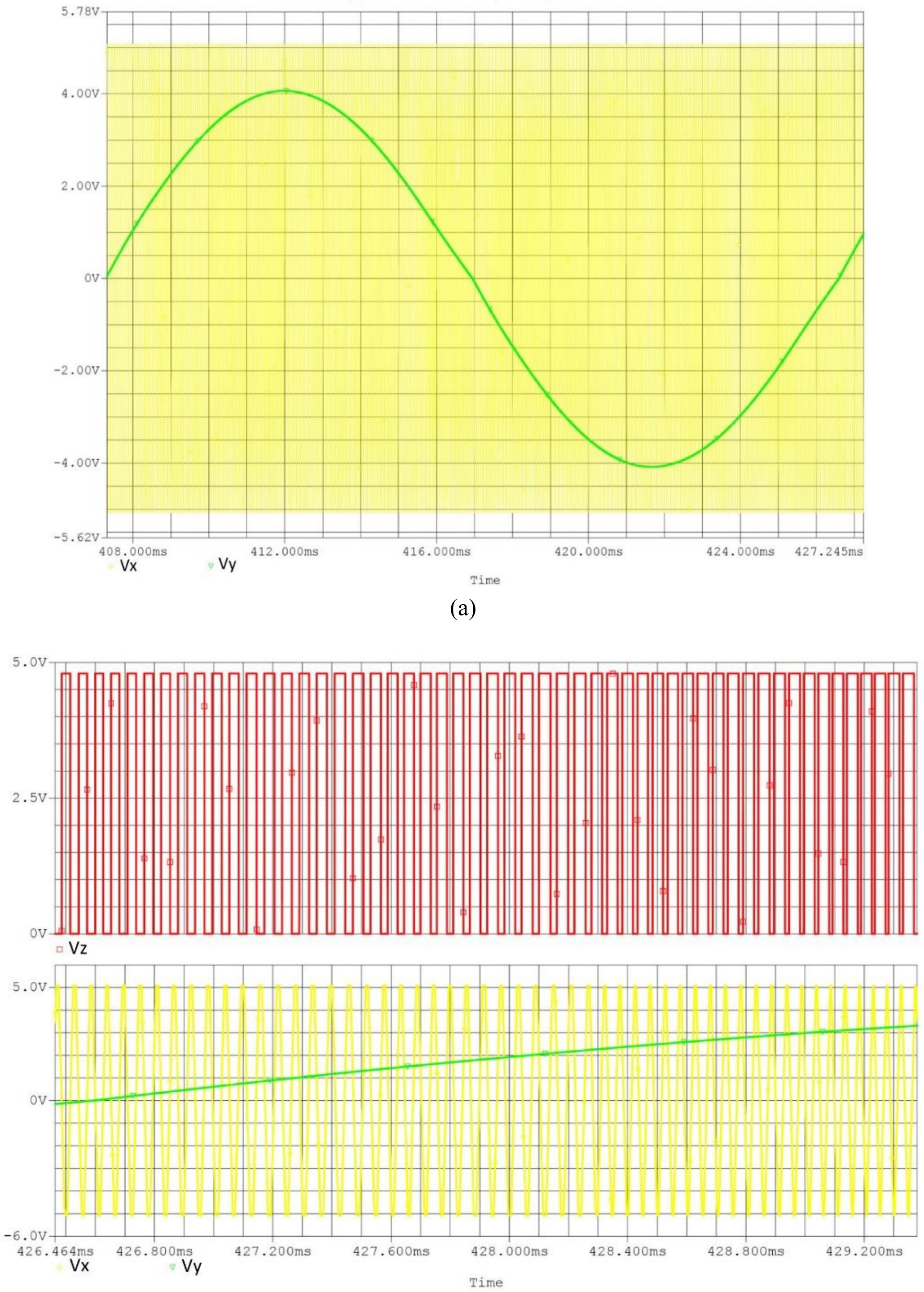


Figure 8. Fourier spectrum of quadrature triangular waveform based on Figure 2(a). The harmonics of Va and Vb triangular waves are odd multiples of the fundamental frequency

Figure 10 demonstrates the experimental results carried out with the operational amplifiers JRC4558D and NE5532P. It is possible to generate the SPWM signal 63 kHz using Op-Amp JRC4558D with supply voltages +7 V and -7 V. The slew rate for the Op-Amp JRC4558D is 1 V/us, as stated in the datasheet for this component. On the other hand, the slew rate of this Op-Amp is 8.4 V/7 us, which equals 1.2 V/us, according to the results of several experiments. In addition, the slew rate is stated to be 9 V/us in the datasheet that comes packaged with the NE5532P. On the other hand, the slew rate is measured and calculated to be 8.5 V/4us, which equals 2.2 V/us, according to the findings of the experiments.

Figure 11 depicts the experimental performance of the triangle oscillation frequency in response to the supply voltages. It is important to note that the proposed voltage-controlled triangular wave quadrature oscillator with a closed-loop dual Op-Amp design can be utilized to quickly verify the real performance of the Op-Amp, in particular the slew rate and the waveform generating properties. It is reasonable to suppose that the IC manufacturer has some influence over the performance of the Op-Amp.



(a)

(b)

Figure 9. Simulation result of the proposed SPWM controller based on Figure 8, (a) using Op-Amp MC4558 and (b) the output at Vz

Table 2. The parameter and value of Figure 8

Parameter	Value
U1, U2	JRC4558
U3	MAX942
+Vcc	+5 V
-Vcc	-5 V
+V	+5 V

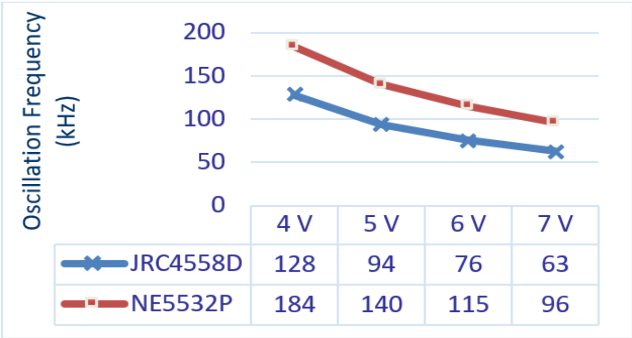
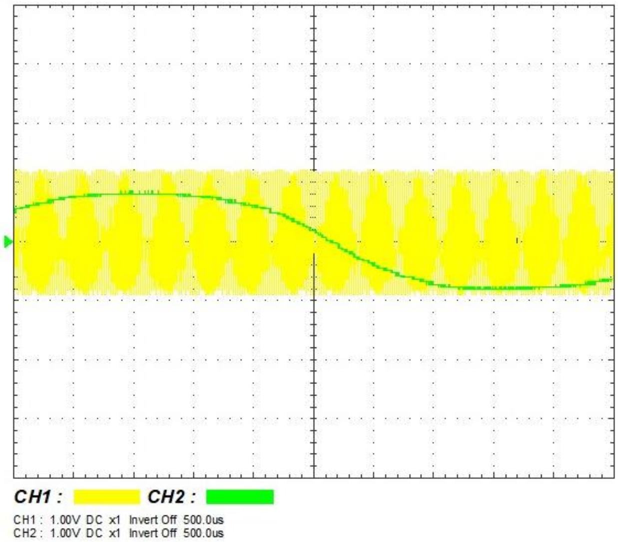
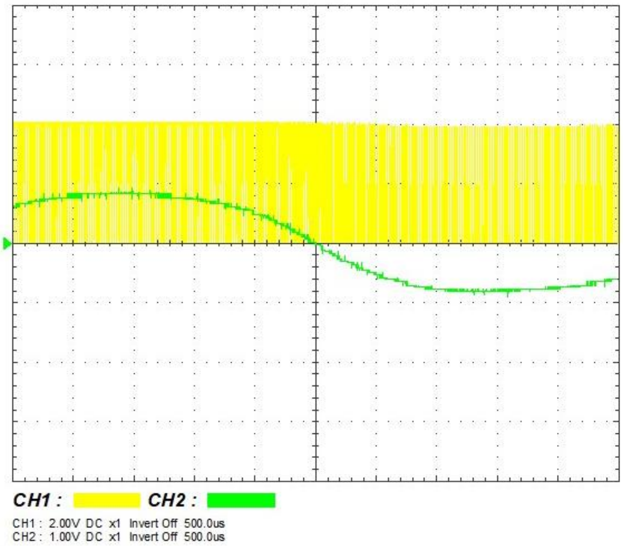


Figure 10. Triangular oscillation frequency performance in relation to the supply voltages based on the experimental results using Op-Amps JRC4558D and NE5532P



(a)

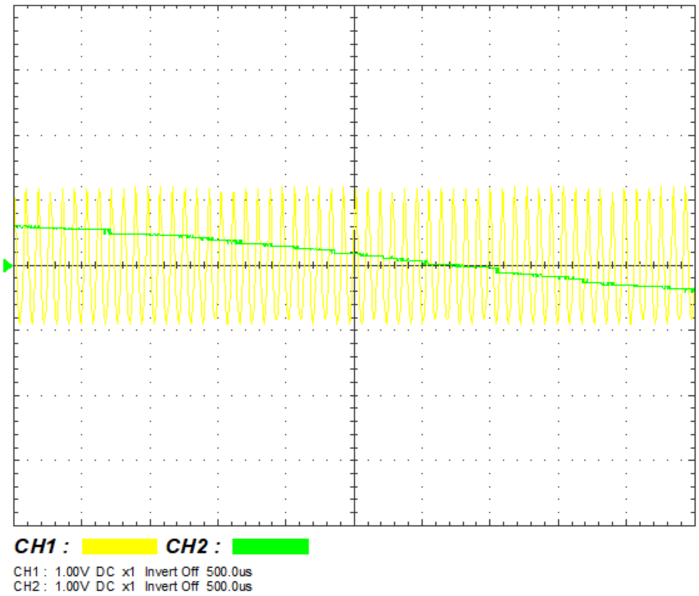


(b)

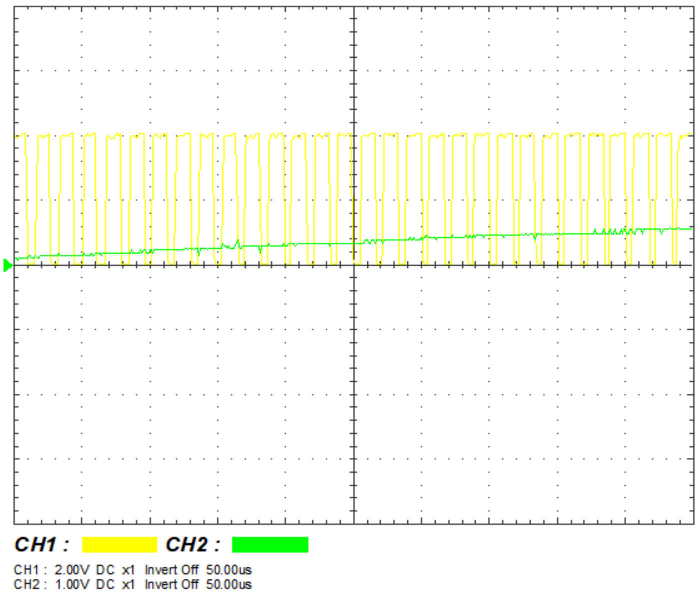
Figure 11. Experimental result of the proposed oscillator circuit for SPWM DC-AC converter applications (a) triangular wave as a carrier signal and sinusoidal wave as a reference signal at the input MAX942 and (b) the SPWM signal at the output Vz for DC-AC converter applications

The experimental result of a triangular wave as a carrier signal produced by using JRC4558D based on the proposed oscillator circuit is displayed in Figure 12(a). Also, a part of a sinusoidal wave as a reference signal is displayed in green color, both of which are connected to the inverting and non-inverting inputs of the comparator MAX942. Figure 12(b) is a demonstration of the practical SPWM signal that is based on the proposed oscillator circuit for applications involving DC-AC power conversion.

The frequency stability measured with Allan deviation is 190 Hz in an oscillation frequency of 82.44 kHz while utilizing the MC4558 with supply voltages of +5 V and -5 V. These results are based on the outcomes of the PSPICE simulation, with observing the frequency variation throughout a period of 20 milliseconds as depicted in Figure 13. Overall, the suggested triangular wave quadrature oscillator can sustain a frequency deviation of around 0.23%. Furthermore, the proposed circuit has the capability of adjusting the oscillation frequency in response to changes in supply voltages, hence it is a voltage-controlled oscillator (VCO) [32].



(a)



(b)

Figure 12. Experimental results (a) actual triangular and sinusoidal inputs at comparator MAX942 and (b) the sinusoidal reference is in green color and the SPWM signal is in yellow at the output of MAX942

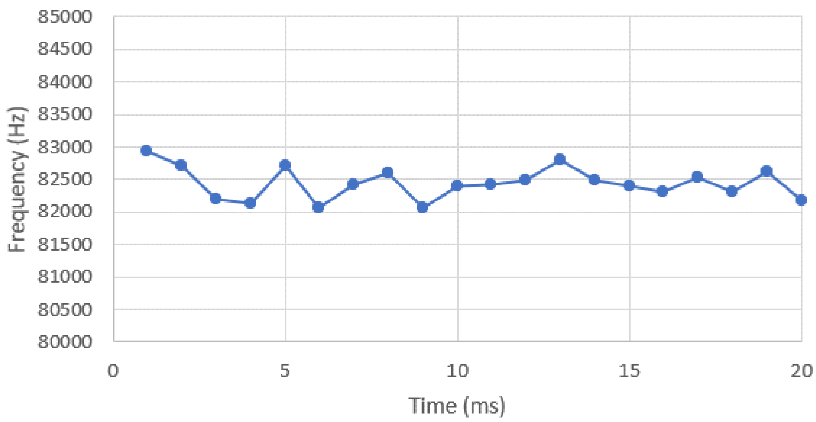


Figure 13. Frequency stability measurement of the proposed triangular wave quadrature oscillator based on simulation result with Op-Amp MC4558 PSPICE model

4. CONCLUSION

A triangular wave quadrature oscillator with no passive components for DC-AC power conversion applications was proposed. The proposed oscillator is beneficial for testing and comparing the linearity characteristics of Op-Amps. The simulation and practical results show that the suggested quadrature triangle oscillator using Op-Amps MC4558 and JRC4558D has a similar oscillation frequency at supply voltages of +7 V and -7 V. The frequency stability of the proposed oscillator circuit with Op-Amp MC4558 was demonstrated by PSPICE simulation results of approximately 0.23% in 20 ms of observation time. Experiment findings confirmed the implementation of the suggested triangular wave quadrature oscillator circuit for SPWM DC-AC converter applications, particularly for the multi-function CNC machine power supply in relation to the project. It is evident that the suggested oscillator has fewer components than today's triangle waveform generators. As a result, higher efficiency, smaller area, and lower cost can be accomplished, and production capability is improved. The proposed quadrature triangular oscillator has the potential for monolithic IC device and low-power applications because it does not contain any passive components. Other waveform creations, such as square-wave, trapezoidal, sinusoidal, and sawtooth waveforms, should be researched further in future studies in relation to the suggested voltage-controlled closed-loop dual Op-Amp arrangement and its applications for DC-AC power conversion.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Indonesia Endowment Fund for Education (*Lembaga Pengelola Dana Pendidikan*) for their financial support of this study regarding the Multi-Function CNC Machine project. The authors would also like to thank Astra Polytechnic, Aalto University, Universitas Ahmad Dahlan, and President University for their support of this collaboration.

REFERENCES

[1] P. Silapan, P. Choykhuntod, R. Kaewon, and W. Jaikla, "Duty-cycle electronically tunable triangular/square wave generator using LT1228 commercially available ICs for capacitive sensor interfacing," *Sensors*, vol. 22, no. 13, Jun. 2022, doi: 10.3390/s22134922.

[2] A. Kumar and B. Chaturvedi, "Experimental realization of square/triangular wave generator using commercially available ICs," *Journal of Circuits, Systems and Computers*, vol. 29, no. 14, Nov. 2020, doi: 10.1142/S0218126620502242.

[3] M. Stork, "Analog and digital triangular wave generators," in *2017 6th Mediterranean Conference on Embedded Computing (MECO)*, Jun. 2017, pp. 1–4, doi: 10.1109/MECO.2017.7977214.

[4] M. Stork, "Some quadrature waveform generators," in *2017 10th International Conference on Electrical and Electronics Engineering (ELECO)*, 2017, pp. 1192–1196.

[5] M. Stork, "Control of triangular wave quadrature oscillator," in *2017 27th International Conference Radioelektronika (RADIOELEKTRONIKA)*, Apr. 2017, pp. 1–4, doi: 10.1109/RADIOELEK.2017.7936639.

[6] W.-S. Chung, H.-J. Kim, H.-W. Cha, and H.-J. Kim, "Triangular/square-wave generator with independently controllable frequency and amplitude," *IEEE Transactions on Instrumentation and Measurement*, vol. 54, no. 1, pp. 105–109, Feb. 2005, doi: 10.1109/TIM.2004.840238.

[7] E. Vidal, A. Poveda, and E. Alarcon, "Amplitude stabilization in a triangular wave quadrature oscillator," in *Proceedings of the 39th Midwest Symposium on Circuits and Systems*, 1996, vol. 3, pp. 1083–1086, doi: 10.1109/MWSCAS.1996.593008.

[8] B. Z. Kaplan, D. Har-Zahav, and A. Blau, "A simple quadrature oscillator for generating triangular waves and square waves," *Proceedings of the IEEE*, vol. 67, no. 11, pp. 1566–1567, 1979, doi: 10.1109/PROC.1979.11520.

[9] E. Vidal, A. Poveda, and E. Alarcon, "Amplitude control in a triangular wave quadrature oscillator," in *1998 Midwest Symposium on Circuits and Systems (Cat. No. 98CB36268)*, 1998, pp. 348–351, doi: 10.1109/MWSCAS.1998.759503.
[10] M. T. Abuelma'atti and H. A. Alzaher, "Active-only sinusoidal oscillator," *Microelectronics Journal*, vol. 29, no. 7, pp. 461–464, Jul. 1998, doi: 10.1016/S0026-2692(97)00104-3.
[11] N. Herencsar, A. Lahiri, J. Koton, and K. Vrba, "VM and CM quadrature sinusoidal oscillators using commercially available active devices," in *2010 International Conference on Applied Electronics*, 2010, pp. 1–4.
[12] S. Minaei and O. Cicekoglu, "New current-mode integrator, all-pass section and quadrature oscillator using only active elements," in *ICCSC'02. 1st IEEE International Conference on Circuits and Systems for Communications. Proceedings (IEEE Cat. No.02EX605)*, 2002, pp. 70–73, doi: 10.1109/OCCSC.2002.1029047.
[13] E. Lindberg, "Is the quadrature oscillator a multivibrator?," *IEEE Circuits and Devices Magazine*, vol. 20, no. 6, pp. 23–28, Nov. 2004, doi: 10.1109/MCD.2004.1364772.
[14] E. Lindberg, "Oscillators-an approach for a better understanding," *Proceedings of the 2003 European Conference on Circuit Theory and Design, Krakow, Poland*, 2003.
[15] R. Senani, D. R. Bhaskar, V. K. Singh, and R. K. Sharma, *Sinusoidal oscillators and waveform generators using modern electronic circuit building blocks*. Cham: Springer International Publishing, 2016.
[16] B. Knobnob and M. Kumngern, "Electronically tunable quadrature oscillator with voltage and current outputs," in *ECTI-CON2010: The 2010 ECTI International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, 2010, pp. 28–31.
[17] S. S. Borah, A. Singh, and M. Ghosh, "A novel low-power electronically tunable higher-order quadrature oscillator using CDBA," in *2021 34th International Conference on VLSI Design and 2021 20th International Conference on Embedded Systems (VLSID)*, Feb. 2021, pp. 1–6, doi: 10.1109/VLSID51830.2021.00012.
[18] A. Raj, P. Kumar, and D. R. Bhaskar, "Four OTA-based mixed-mode filter configuration and quadrature voltage mode sinusoidal oscillator," in *2021 3rd International Conference on Advances in Computing, Communication Control and Networking (ICAC3N)*, Dec. 2021, pp. 1154–1158, doi: 10.1109/ICAC3N53548.2021.9725521.
[19] A. Rodriguez-Vazquez, B. Linares-Barranco, J. L. Huertas, and E. Sanchez-Sinencio, "On the design of voltage-controlled sinusoidal oscillators using OTAs," *IEEE Transactions on Circuits and Systems*, vol. 37, no. 2, pp. 198–211, 1990, doi: 10.1109/31.45712.
[20] M. Joshi, Kirti, and P. Thakur, "Design and implementation of third order oscillator using CFOA and OTA," in *2021 International Conference on Electrical, Computer and Energy Technologies (ICECET)*, Dec. 2021, pp. 1–5, doi: 10.1109/ICECET52533.2021.9698785.
[21] C. S. Pittala and A. Srinivasulu, "Quadrature oscillator using operational transresistance amplifier," in *2014 International Conference on Applied Electronics*, Sep. 2014, pp. 117–120, doi: 10.1109/AE.2014.7011681.
[22] P. Mongkolwai, T. Pukkalanun, T. Dumawipata, and W. Tangsrirat, "CFOA-based single resistance controlled quadrature oscillator," in *2008 SICE Annual Conference*, Aug. 2008, pp. 1147–1150, doi: 10.1109/SICE.2008.4654832.
[23] S. Maneewan, B. Sreewirote, and W. Jaikla, "A current-mode quadrature oscillator using a minimum number of active and passive components," in *Proceedings of 2011 IEEE International Conference on Vehicular Electronics and Safety*, Jul. 2011, pp. 312–315, doi: 10.1109/ICVES.2011.5983835.
[24] R. Mancini and R. Palmer, "Sine wave oscillators," in *Op Amps for Everyone*, Elsevier, 2003, pp. 239–260.
[25] T. Valerie, D. Garinto, S. Budiyanto, A. Syahriar, and F. D. Wijaya, "Closed-loop dual comparator and its applications," in *2021 3rd International Conference on Electrical, Control and Instrumentation Engineering (ICECIE)*, Nov. 2021, pp. 1–6, doi: 10.1109/ICECIE52348.2021.9664733.
[26] A. Bhat, "Precision triangular-wave generator uses a single IC," *MAXIM application notes*, 2010.
[27] B. Moore and J. Donaghy, *Operational amplifier circuits*. Elsevier, 1986.
[28] D. Terrell, *Opamps: design, application and trouble-shooting*. Newnes, 1996.
[29] A. A. Qazalbash, A. Amin, A. Manan, and M. Khalid, "Design and implementation of microcontroller based PWM technique for sine wave inverter," in *2009 International Conference on Power Engineering, Energy and Electrical Drives*, Mar. 2009, pp. 163–167, doi: 10.1109/POWERENG.2009.4915171.
[30] M. Lakka, E. Koutroulis, and A. Dollas, "Design of a high switching frequency FPGA-based SPWM generator for DC/AC inverters," in *2011 21st International Conference on Field Programmable Logic and Applications*, Sep. 2011, pp. 15–19, doi: 10.1109/FPL.2011.14.
[31] N. Ahmed and Z. R. Khan, "Microcontroller based pure sine wave inverter," in *2021 IEEE International Conference in Power Engineering Application (ICPEA)*, Mar. 2021, pp. 173–177, doi: 10.1109/ICPEA51500.2021.9417841.
[32] M. Stork, "Voltage controlled oscillators: Sinusoidal and square wave ring and relaxation oscillators," in *2014 3rd Mediterranean Conference on Embedded Computing (MECO)*, Jun. 2014, pp. 180–183, doi: 10.1109/MECO.2014.6862689.

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