

A New Method to Detect and Track the Resonance Frequency of Piezoelectric Transducers in Ultrasonic Power Supplies

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A In this paper, a new method is developed to detect and track the resonance frequency of ultrasonic transducers. In order to
B have an acceptable performance of transducers, power supplies should be able to detect and track the resonance frequency.
S Different methods have been used for this purpose. In this research, the voltage of the transducer and the phase difference
T between the voltage and current are used to find the resonant frequency. The maximum voltage of a transducer is founded in
R a predefined frequency interval. Afterward, the minimum phase difference between the voltage and current is obtained in a
A smaller interval around it. The simultaneous use of the voltage and phase shift increases the accuracy and speed of the
C algorithm. Since the transducer's voltage variations are relatively large near the resonant frequency, it is a versatile
T parameter compared to the current used in other methods to indicate the resonance frequency. The algorithm is implemented
within a microcontroller. An FPGA is used to generate accurate frequency using the Direct Digital Synthesis (DDS) method.
The algorithm can detect the resonant frequency under free conditions. Applying force to transducers or emerging the
transducer's head to the water changes the resonant frequency. The experimental tests showed that the algorithm could find
and track the resonant frequency automatically under loading conditions.

Article Info

Keywords:

Ultrasonic Transducer, Tracking, Resonance Frequency, Power Supply

Article History:

Received 2021-02-16

Accepted 2021-07-30

I. INTRODUCTION

Ultrasonic transducers are widely used in today's industries [1]. In order to have maximum efficiency, power supplies should be able to detect and track the resonance frequency of transducers. Ultrasonic power supplies are used in cleaning, welding, mask sewing machine, and other manufacturing processes. Improvements and innovations in power supplies are still in progress [2] [3]. The resonance frequency would change while an ultrasonic transducer heats up or subjects to loads [4]. In addition, the precise control of the resonant frequency is essential since undesirable natural frequencies might be excited without tracking the frequency [5].

Different methods have been proposed for tracking the resonance frequency of ultrasonic transducers. Agbossou used the class-D power amplifier to excite piezoelectric transducers [6]. This power supply uses an analog integrated circuit to compare a sawtooth signal with a constant voltage to generate a PWM signal. Despite covering a wide range of frequencies, one crucial drawback is the lack of sufficient precision in the frequency generation. Gokcek [7], Lin [8], and Crivii [9] used the analog Phase-Locked Loop (PLL) for tracking and maintaining the resonance frequency. However, this method was not capable of detecting the resonance frequency under sudden and severe mechanical loads. Svilainis used the class-B power amplifier to excite an ultrasonic transducer [10]. The

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signal distortion of the amplifier limits its application in high frequencies. Xiaoyi [11], Huang [12], and Chen [13] used the proportional or proportional-integral controller to find the frequency with the maximum current consumption. Wei-Hua [14] presented a frequency-tracking method using the Direct Digital Synthesizer (DDS) and a fine tracking using the PLL method. Shanli [15] used the maximum power consumption to find the resonance frequency. Longfei [16] implemented the resonance frequency detecting system using the phase difference for an ultrasonic cell destruction system. This system was not able to find the resonance frequency with changing loads. Jing-Shuang [17] designed an ultrasonic power supply and obtained the resonance frequency using a voltage-current phase correlation algorithm. Automatic resonance frequency tracking in this research was influenced by the system noise. Yokozawa [18] proposed the idea of controlling the output terminal impedance to control the resonance frequency. The impedance of the transducer can be changed using FETs which are parallel with piezoelectrics. Therefore, the resonance frequency becomes a function of the duty cycle of the FETs. This method can be used to change the resonance frequency of transducers; however, another method should be used to detect the resonant state. Fu [19] designed an ultrasonic power supply in a wide frequency range. In this power supply, the frequency was swept with a processor to obtain the maximum current amplitude. Using the Fast Fourier Transform (FFT), the new resonance frequency was detected from the phase-frequency characteristics. This power supply was not able to find new resonance frequencies with high and fast variations of loads.

The proposed algorithm of this paper uses the voltage and phase difference to find the resonant frequency. The simultaneous use of the maximum voltage and the minimum phase difference of voltage and current increases the accuracy and speed of the algorithm in comparison to other methods. Since the variations of the transducer's voltage are relatively large near the resonant frequency, it is versatile compared to the current to indicate the resonance frequency. If the transducer leaves its resonance state, the system sweeps the frequency and obtains a new frequency with the maximum piezoelectric voltage. Afterward, in a smaller interval around it, the frequency is swept again, and the minimum phase difference is achieved. Three types of tests, including applying loads to the transducer, immersing the head of the transducer into the water, and increasing the transducer's temperature, are conducted to evaluate the performance of the systems.

In this paper, the frequency response of a transducer is explained first. Then the hardware configuration of the system is described. After that, a flowchart of the algorithm used in the software is stated. Finally, experimental results are expressed.

II. FREQUENCY RESPONSE OF A PIEZOELECTRIC ULTRASONIC TRANSDUCER

The most well-known transducers equivalent circuit is the Butterworth-Van Dyke model [20]. Fig. 1 shows the model.

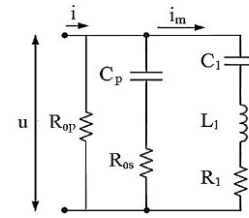


Fig. 1. Butterworth-Van Dyke Model for a Piezoelectric Ultrasonic Transducer.

In this model, i , i_m , and u are the input current, mechanical branch current, and the input voltage, respectively. C_p is the piezoelectric static capacitor, R_{0p} is the piezoceramic dielectric resistance, R_{0s} is the series resistance. The mechanical part of the transducer is modeled with a series RLC circuit in which the elements R_1 , C_1 , and L_1 are damping, stiffness, and the mass of the transducer, respectively. Thus, Eq. (1) expresses the total admittance of the equivalent circuit. In this equation R_{0s} is ignored.

$$Y = G + jB$$

$$= \frac{1}{R_{0p}} + \frac{R_1}{\left(L_1\omega - \frac{1}{C_1\omega}\right)^2 + R_1^2}$$

$$+ j \left(\frac{-\left(L_1\omega - \frac{1}{C_1\omega}\right)}{\left(L_1\omega - \frac{1}{C_1\omega}\right)^2 + R_1^2} C_p\omega \right) \quad (1)$$

where G represents the conductance, and B is the susceptance. Using Eq. (2), the transducer's resonance frequency can be calculated according to Eq. (3).

$$\text{Im}(Y) = B = 0 \quad (2)$$

$$f_r = \frac{\sqrt{2C_1L_1C_p + C_1^2L_1 - C_1^2R_1^2C_p - \sqrt{M}}}{2\pi\sqrt{2C_1^2L_1^2C_p}} \quad (3)$$

The variable M in Eq. (3) is defined as follows.

$$M = C_1^3(R_1^4C_p^2C_1 + L_1^2C_1 - 4C_p^2R_1^2L_1 - 2C_1L_1C_pR_1^2) \quad (4)$$

The resonance frequency of the mechanical branch is also expressed as follows.

$$f_{rs} = \frac{1}{2\pi\sqrt{L_1C_1}} \quad (5)$$

The difference between the resonance frequency in Eq. (3) and (5) is shown in Fig. 2. According to this figure, the overall resonance frequency of the transducer is approximately equal to the resonance frequency of the mechanical part, and the maximum transducer's current consumption occurs at this frequency.

$$|i| = u|Y| \quad (6)$$

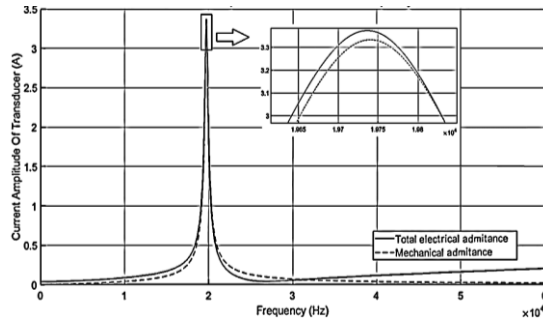


Fig. 2. Comparison of the resonance frequency of the whole transducer with the resonance frequency of the mechanical branch. Equivalent circuit parameters are $u=100$ V, $R_{Op}=2.6$ k Ω , $C_p=6$ nF, $R_1=30$ Ω , $C_1=5$ nF and $L_1=13$ mH.

III. HARDWARE CONFIGURATIONS OF THE SYSTEM

The system consists of a control unit, power unit, and signal sampling circuits. The control unit generates drive signals for the power unit based on feedback from the transducer. The connection between different parts of the system is shown in Fig. 3.

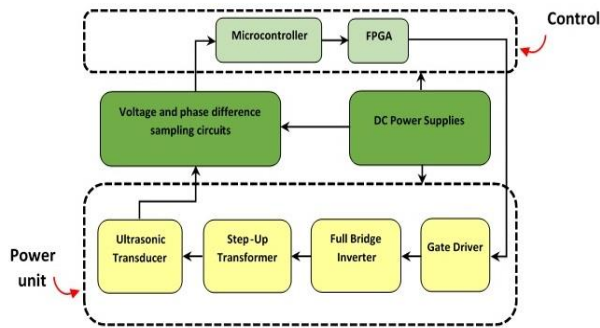


Fig.3. Block diagram of the system

Drive signals of the inverter are generated using a Field Programmable Gate Array (FPGA). Control commands are sent to the FPGA from a microcontroller. First, the piezoelectric voltage and the voltage-current phase difference are measured using sampling circuits. Afterward, they are sent to the microcontroller as feedbacks. Finally, the microcontroller sends a desired frequency command to the FPGA after processing and executing a control algorithm. The Direct Digital Synthesizer (DDS) method was used to generate the frequency. More information about the implementation of the system is provided in Appendix 1. Fig. 4 shows the driver circuits of the inverter.

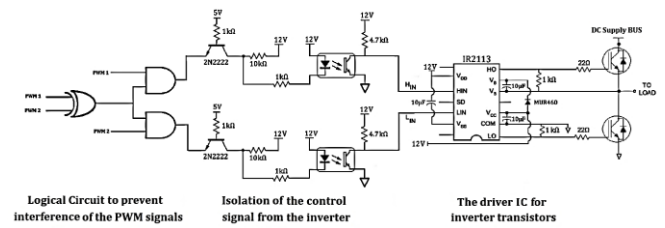


Fig. 4. The circuit for driving the inverter

The schematics of the inverter circuit, step-up transformer, and transducer are shown in Fig.5. The alternating signal generated by the inverter, transmitted to the transducer via a transformer. Connecting the transducer to the secondary of the transformer allows the output voltage to increase at the resonance frequency. If the load is directly connected to the output of the inverter, its voltage follows the inverter voltage.

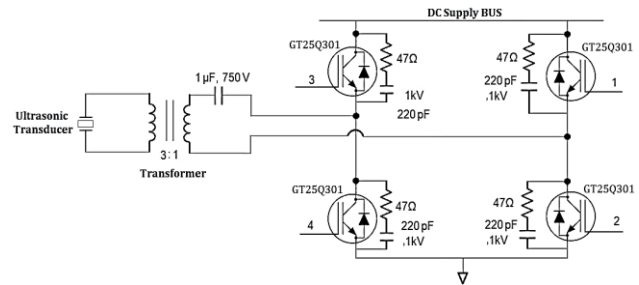


Fig. 5. Inverter circuit

Fig. 6 shows the sampling circuits to measure the voltage and phase difference.

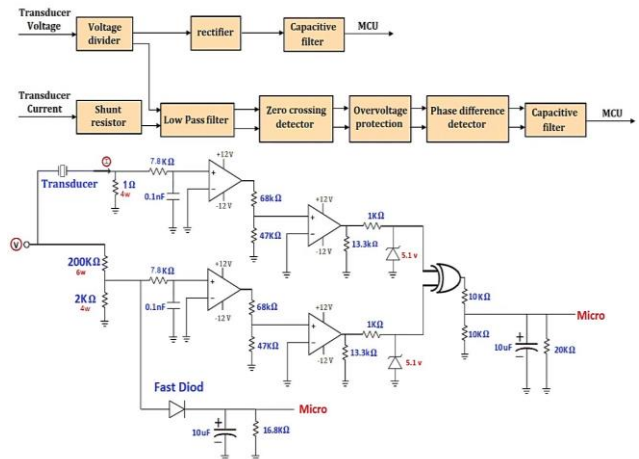


Fig. 6. Schematic of the sampling circuits

The first Analogue to Digital Converter (ADC1) of the microcontroller was used to acquire the voltage, and the second one (ADC2) was used for the phase difference.

3.1. The algorithm of the system

Fig. 7 shows a flowchart of the algorithm of the system.

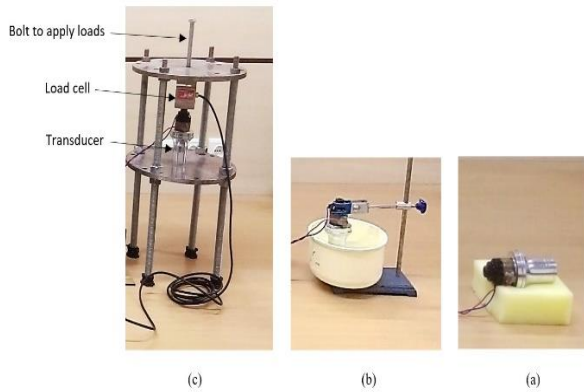


Fig. 9. The transducer under different test conditions, (a) free conditions, (b) head immersion in the water, (c) mechanical loading

The diagram of the current envelope of the transducer and the excitation frequency versus time are shown in Fig.10. After switching on the power supply, the excitation frequency is swept, and the maximum voltage is founded. The maximum current of the transducer is shown in Fig.10. The frequency is set on the maximum current consumption of the transducer. The resonant frequency under free conditions is 18860 Hz, and its maximum current is about 1.6 A.

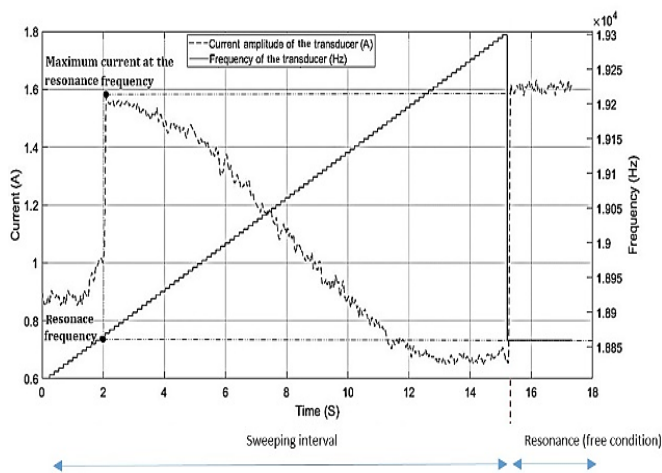


Fig. 10. Frequency sweeping to detect the resonance frequency of the transducer

By applying loads, the resonant frequency changes, and the algorithm conducts a new sweep. A DBBP-100 load cell manufactured by Bongshin Company, South Korea, is used to measure forces. Fig. 11 illustrates the operation of the algorithm under loading conditions.

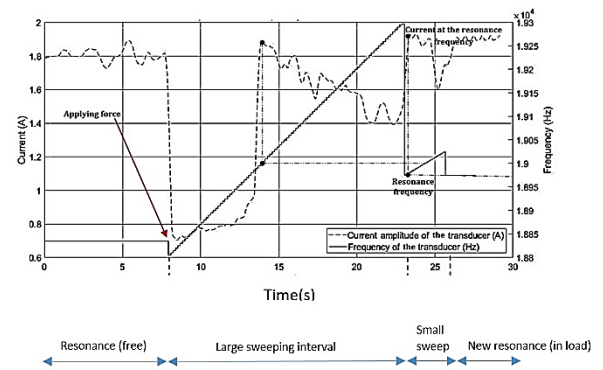


Fig. 11. Frequency sweeping of the system to detect the resonance frequency under a 35 kg load

According to Fig.11, the transducer is in the resonant state from zero to 8 seconds. Its current is about 1.8A in this situation. At the eighth second, a 35 kg force is applied to the transducer. Therefore the voltage of the transducer reduces, and the algorithm starts a large sweep. The large sweep ends at the 23rd second. Then the small sweep is conducted through the next 3 seconds. The maximum current of the transducer in this interval is about 1.9 A, and its new resonant frequency is 18975 Hz. However, its resonant frequency under free conditions was 18840 Hz. Increasing the resonant frequency is due to the increase of mechanical stiffness.

In the immersion tests, the transducer is first in its resonance frequency under a free condition. The resonant frequency in this condition is about 18830 Hz, and the consumption current is about 1.5A. The resonance frequency of the transducer changes as its head is immersed in the water. At around 7.5s, the head of the transducer is immersed 14mm into 25 °C water. Fig. 12 shows the performance of the system in this test.

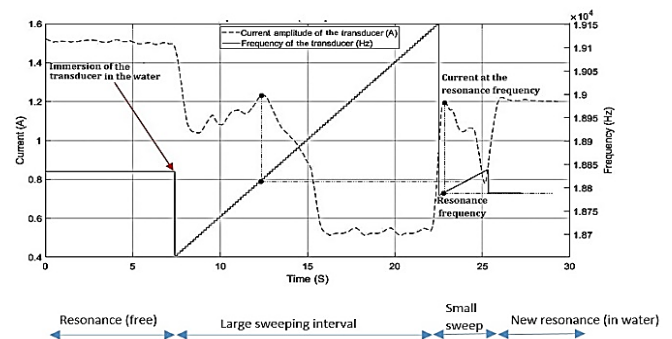


Fig. 12. Operation of the system in the immersion test

According to Fig.12, after the immersion of the transducer, the algorithm conducts the two sweeps and finds a new resonant frequency of 18770 Hz. The consumption current in this

condition is about 1.2 A.

Similar tests are conducted in different heights of the immersion and forces applied to the transducer. Table 1 summarizes the results of the tests.

TABLE I
RESULTS OF THE EXPERIMENTAL TESTS OF THE SYSTEM

Type of tests	Test conditions	Resonance frequency (Hz)	Changing the current amplitude after tuning (mA)
Free	unloaded	18860	<50
Mechanical loading	35kgf	18975	<50
	45kgf	19081	<50
	55kg	19181	<50
Head immersion	14mm	18881	<50
in the water at 25 °C	34mm	18902	<50
	60mm	18939	<50
Head immersion in boiling water	14mm	18789	<50

The resonant frequency of the transducer is 18860 Hz under free conditions. Applying mechanical loads or immersing the transducer in the water increases the resonant frequency because of increasing the mechanical stiffness. However, the resonant frequency decreases as the temperature rises. This is due to the mechanical expansion and the material properties changes of piezoelectrics. After finding the new resonance frequency, the current amplitude of the transducer had a deviation lower than 50mA.

V. CONCLUSION

In this paper, a new method was developed to detect and track the resonance frequency of transducers. Piezoelectric voltage and the phase difference between the voltage and current were used to find the resonance frequency. Simultaneous use of the maximum voltage and the minimum phase difference increased the accuracy and speed of the algorithm in comparison to other methods. The developed algorithm conducted two sweeps with different intervals and steps. The first one was a larger sweep with a course step, and the second one was a smaller one with a fine step. In the first sweep, the maximum voltage was founded, and in the second one, the minimum phase difference was set. The performance of this system was tested experimentally. The system could detect and track the resonance frequency automatically under free and different loading conditions. After finding the new resonance frequency, the current amplitude had a deviation lower than 50mA. The algorithm was sensitive to changing the transducer's voltage. The resonant frequency of transducers increased with applying mechanical loads or immersion in 25 °C water. The more mechanical was the loads or immersion

heights, the more resonant frequency would be. However, increasing the transducer's temperature decreased the resonant frequency. These were the typical variations of the resonant frequency of ultrasonic transducers under loading conditions. The speed of the algorithm could be faster to compensate for rapid changes in mechanical loads.

APPENDIX

A.1. Frequency Generator Unit

The Direct Digital Synthesizer (DDS) method is used to generate the frequency. A 32-bit binary number is generated by the microcontroller as an input. The procedure of loading the binary number on the FPGA is shown in Fig. A.1. The 32-bit data is separated into two 16 bits (high and low bits) and loaded on a multiplexer through a data bus of Data_0 through Data_15. The control bit of l_h_d specifies which group of data are stored on flip-flops (registers). After storing the data on the flip-flops, a clock is triggered, and the data is transferred to the final flip-flop (register). The 32-bit binary number is used as the input of an adder.

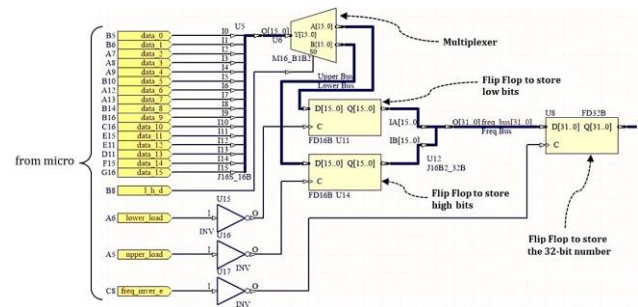


Fig. A.1. Loading of the 32-bit binary number from the microcontroller to the FPGA

An adder adds the 32-bit binary number with each clock pulse while an overflow occurs. The period of the elapsed time to overflow is represented by the parameter T . The inverse of this period is the adder's overflow frequency. If in each clock pulse, the adder output adds with the number N , the overflow period of the adder is expressed by Eq. (A.1), and the overflow frequency is expressed by Eq. (A.2).

$$T = \frac{2^{32}}{N} \frac{1}{f_s} \quad (A.1)$$

$$f_{out} = \frac{1}{T} = \frac{f_s}{2^{32}} N \quad (A.2)$$

The frequency resolution in this method is equal to $\frac{f_s}{2^{32}}$. The left 8 bits (higher bits) of the output of the adder are chosen to generate the desired frequency. These 8 bits change from 0 to 255 during each overflow period. Fig. A.2 illustrates how to use the higher 8 bits of the adder's output. This 8-bit number is used to compare with predefined numbers.

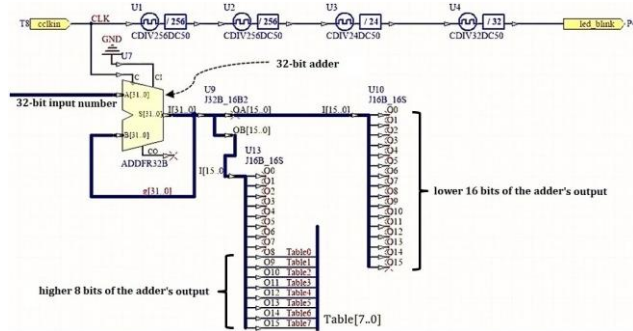


Fig. A.2. the higher 8 bits of the adder's output

To drive the inverter, two complementary PWM signals are required with a dead time. The two signals with the described features are generated using the circuit in Fig. A.3.

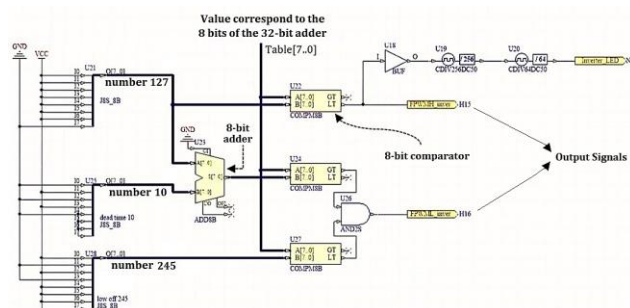


Fig. A.3. Conversion of the 8-bit data to the two complementary PWM signals

Three comparators and one adder are employed to generate the two PWM signals. The 8-bit number is inserted into the three comparators and compares with predefined binary numbers that determine the duty cycle, phase difference, and dead time. Table A.1 illustrates the logic used to generate signals.

TABLE A.1
THE LOGIC TO GENERATE THE TWO PWM SIGNALS WITH COMPARATORS

8-bit number	First signal	Second signal
≥ 0 < 117	1	0
≥ 117 ≤ 127	0	0
> 127 < 245	0	1
≥ 245 ≤ 255	0	0

Fig. A.4 shows the two PWM signals in one period.

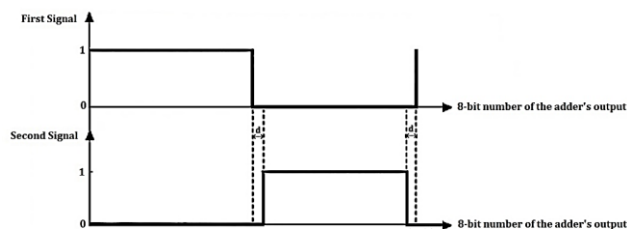


Fig. A.4. PWM signals used to drive the inverter

In this way, the frequency of the inverter can be controlled by changing the number N.

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