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Analysis of three-phase inverter with switching angle variations

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ABSTRACT

A three-phase inverter is a power conversion device that converts direct current (DC) to three-phase alternating current (AC). Inverter performance is significantly influenced by the switching angle control method used. This study analyzed three-phase inverters with varying switching angles of 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180°. The objective of this study was to determine the effect of varying the switching angle on the output waveform produced by the three-phase inverter. Testing was conducted by observing the gate driver output signal and the phase-to-phase and phase-neutral voltage waveforms using an oscilloscope. The results showed that changes in the switching angle affected the voltage pulse width and the symmetry of the output waveform. The higher the level, the closer it became to a sinusoidal shape. This test used two loads: the resistive load produced a relatively stable waveform, while the incandescent lamp load experienced distortion due to the inductive nature of the filament. The conclusion of this study is that selecting the right switching angle can improve the power quality and efficiency of the inverter performance according to application needs.

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1. INTRODUCTION

Over time, science and technology (IPTEK) continue to experience rapid development, including in Indonesia. Advances in IPTEK have penetrated various fields, one of which is the industrial sector [1]. The development of industrial technology on a large scale has resulted in an increasing demand for electrical energy [2]. Every industrial company generally uses relatively high levels of electrical power, such as three-phase power sources to generate kinetic energy and heat.

A three-phase inverter is a power conversion device that converts a direct current (DC) voltage source to a three-phase alternating current (AC) voltage [3]. This device is widely used in industrial applications, such as induction motor control, renewable energy systems, uninterruptible power supplies (UPS)[4], and power conditioning systems. Inverter performance is greatly influenced by the switching technique used, including the selection of the conduction angle. A three-phase inverter is formed from a combination of three single-phase inverters, each output having a phase angle difference of 120° with respect to each other [4]. The switching angle determines the length of time the upper and lower switches on each phase are in the ON state in one cycle [5]. Variations in this angle directly affect the output voltage waveform, as well as its harmonic content [6]. Switching angles that are too small tend to produce square-shaped waves with high harmonic distortion [7], while larger angles can produce waveforms that are closer to sinusoidal, but impact the resulting voltage magnitude.

Research related to controlling the switching angle in inverters has been extensive, but the application of specific angle variations to different loads, such as resistive loads and incandescent lamps, still requires further study. Resistive loads typically produce stable and symmetrical waveforms, while incandescent loads can introduce additional distortion due to the inductive nature of the filament. Based on this, this study was conducted to analyze the effect of variations in switching angles of 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180° on the output voltage waveform of a three-phase inverter. The focus of the analysis includes changes in the waveforms of phase-phase and phase-neutral voltages, as well as the differences in response between resistive loads and incandescent lamps. The results of this study are expected to be a reference in selecting the optimal switching angle to improve power quality and inverter performance efficiency according to application needs.

2. METHOD

The three-phase inverter as shown in Figure 1 has six power switches, namely S1 to S6. In principle, the switches are controlled by comparing a sinusoidal reference wave with a triangular carrier wave. The resulting output frequency follows the frequency of the reference wave [8]. The three-phase inverter in Figure 1 has two switches forming one phase, namely phases A, B, and C in sequence [9]. The switches are activated alternately and sequentially to produce the desired three-phase AC output waveform [10]. Each switching signal is given a phase angle shift of 120° with respect to the other inverter legs. The output generated from this inverter is then flowed to a balanced three-phase resistor load. The line-to-line voltage is determined from the potential difference between the output terminals of each inverter leg.

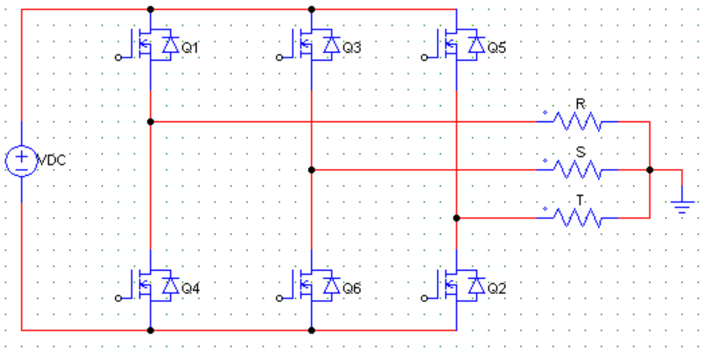


Figure 1. Three Phase Inverter Circuit

In a three-phase inverter, the switching conduction mode refers to the length of time the upper two switches of the three phases are in the ON state in one cycle. Conduction angles vary from 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180°. The following is an explanation of several conduction mode variations. In conduction mode, no switch is in the ON state simultaneously for two phases at a time. In other words, there is no overlap in conduction time between the two upper switches in a waveform cycle. In 30° Conduction Mode, the upper two switches of the three-phase inverter are in the ON state simultaneously for 30° of a full waveform cycle (360°). The switching configuration at each conduction angle interval is presented in Table 1.

Table 1. Switching Configuration of 3-phase inverter with 30° conduction mode.

θ	Device	Device
0°-60°	S1	S5
60°-120°	S1	S2
120°-180°	S2	S3
180°-240°	S3	S4
240°-300°	S4	S5
300°-360°	S5	S6

In 45° conduction mode, each switch conducts for 45° of a full 360° cycle, resulting in 8 switching steps per cycle as shown in Table 2. The 45° conduction mode provides an output voltage waveform that is closer to sinusoidal due to the increased number of switching transitions occurring in a single period, but has a short pulse width.

Table 2. 3-Phase Inverter Switching Configuration: 45° Conduction Mode

θ	**Device**	**Device**	**θ**	**Device**	**Device**
0°-45°	S1	S5	180°- 225°	S2	S5
45°-90°	S1	S3	225°- 270°	S2	S5
90°-135°	S3	S4	270°- 315°	S4	S6
135°-180°	S3	S5	315°- 360°	S1	S4

One switching technique used in inverters is the 60° conduction mode, where each switch is active for 60° in a 360° cycle. In this mode, the inverter operates with six switching steps, and at each step, two switches are activated simultaneously, as shown in Table 3: one on the top side and one on the bottom side, creating two current conduction paths from the DC source to the load. A three-phase inverter with 90° conduction mode is a variation of the switching control technique in a full-bridge inverter, which consists of six switches. In this mode, each switch is activated for 90° of a 360° cycle, with overlapping firing patterns between switches. 120° conduction mode is a three-phase inverter operating method where each power switch conducts for 120°. In this mode, two switches are always active simultaneously, and the conduction between the switches occurs every 60°. The 135° conduction mode allows each switch to conduct for 135° in one complete cycle. The operation of the switches in 135° conduction mode is shown in Table 6, which shows the three-phase inverter switching configuration in twelve 30° switching steps. In this mode, each inverter switch works for 180° of a full cycle, meaning that three switches are active simultaneously at any one time. The operation of the switches in 180° conduction mode is shown in Table 7. Switch switching occurs every 60°, with one switch turning off and being replaced by another switch.

Table 3. Switching Configuration of a 3-Phase Inverter with 60° Conduction Mode

Device	S1	S1	S3	S3	S5	S5
Device	S6	S2	S2	S4	S4	S6
θ	0°-60°	60°-120°	120°-180°	180°-240°	240°- 300°	300°-360°

Table 4. Switching Configurations for a 3-Phase Inverter in 90° Conduction Mode

Device	S1	S1	S3	S3	S5	S5
Device	S6	S2	S2	S4	S4	S6
Θ	0°-60°	60°-120°	120°-180°	180°-240°	240°- 300°	300°-360°

Table 5. 3-Phase Inverter Switching Configurations in 120° Conduction Mode

Device	S1	S2	S3	S4	S5	S6
Device	S6	S1	S2	S3	S4	S5
Θ	0°-60°	60°-120°	120°-180°	180°-240°	240°- 300°	300°-360°

Table 6. 3-pass inverter switching configuration with 135° conduction mode

θ	**Device**	**Device**	**θ**	**Device**	**Device**
0°-30°	S1	S6	180°-210°	S1	S5
30°-60°	S1	S2	210°-240°	S1	S2
60°-90°	S2	S3	240°-270°	S2	S3
90°-120°	S3	S4	270°-300°	S3	S4
120°-150°	S4	S5	300°-330°	S4	S5
150°-180°	S5	S6	330°-360°	S5	S6

Table 7. 3-Phase Inverter Switching Configurations: 180° Conduction Mode

Device	S1	S2	S3	S4	S5	S6
Device	S5	S6	S1	S2	S3	S4
Device	S6	S1	S2	S3	S4	S5
θ	0°-60°	60°-120°	120°-180°	180°-240°	240°- 300°	300°-360°

In 150° conduction mode, each power switch conducts current for 150° of a complete cycle. This duration is shorter than 180° mode but longer than 120° mode, so its operating characteristics fall between the two modes [11]-[15]. To produce a full cycle of the inverter output voltage, 12 switching patterns are required, as shown in Table 8, with each pattern lasting 30°.

Table 8. 3-phase inverter switching configurations with 150° conduction mode

θ	Device	Device	Device
0°-30°	S1	S5	S6
30°-60°	S1	S6	-
60°-90°	S1	S2	S6
90°-120°	S1	S2	-
120°-150°	S1	S2	S3
150°-180°	S2	S3	-
180°-210°	S2	S3	S4
210°-240°	S3	S4	-
240°-270°	S3	S4	S5
270°-300°	S4	S5	-
300°-330°	S4	S5	S6
330°-360°	S5	S6	-

3. RESULTS AND DISCUSSION

In this experiment, an inverter designed to convert a direct current (DC) voltage source to alternating current (AC) voltage was used. The test objective was to evaluate the inverter's performance. The output voltage was observed at various conduction angles, with the trigger signal (gating signal) generated by a microcontroller. To measure this performance, a high-voltage differential probe was used as one of the primary instruments. With the support of a four-channel digital oscilloscope, the trigger pulse and voltage waveforms of the three-phase inverter were displayed at conduction angles of 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180°. The test circuit is shown in Figure 2, with the primary voltage source coming from a DC power supply. The load used was a resistor connected in a star configuration. The switching trigger signal for the three-phase inverter was generated by an Arduino Uno board based on an ATmega328 microcontroller.

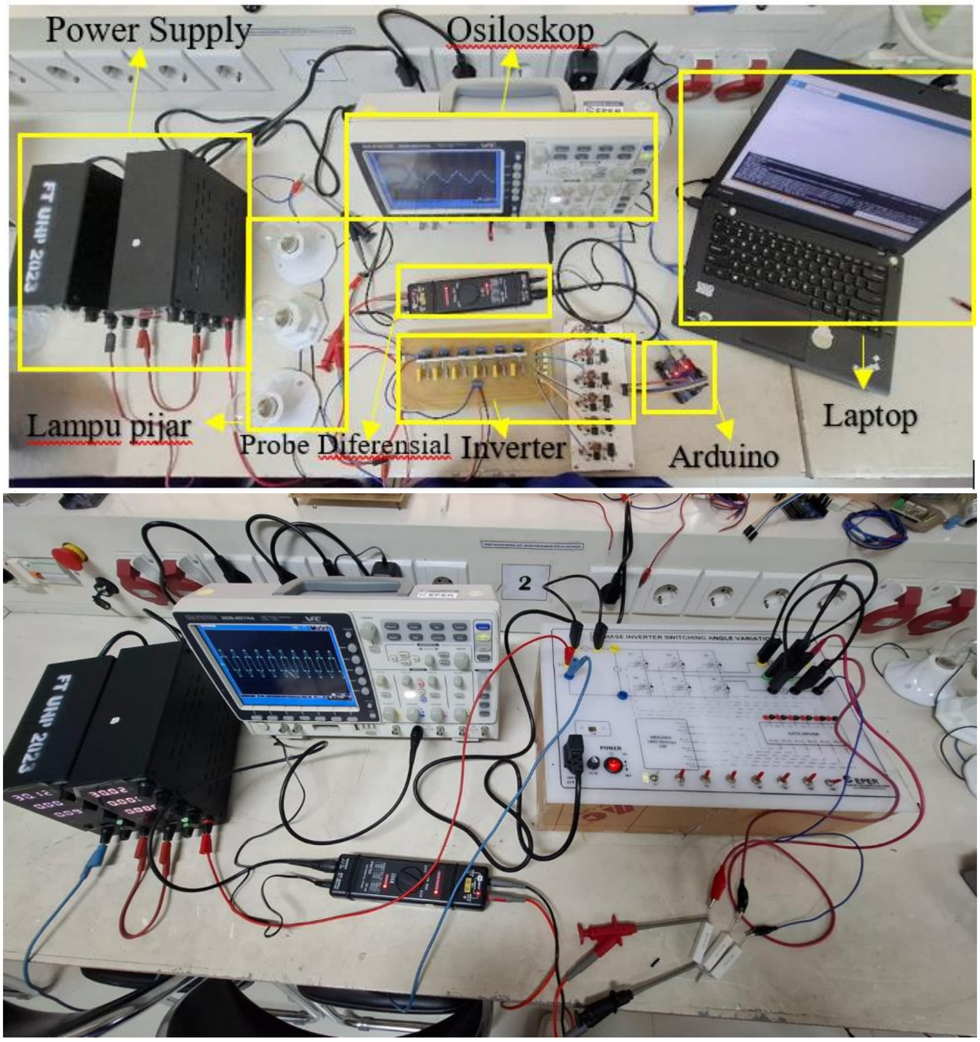
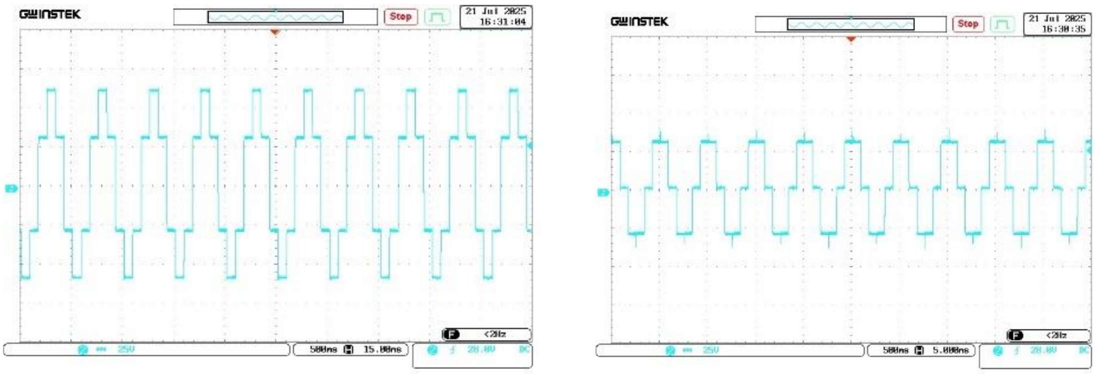


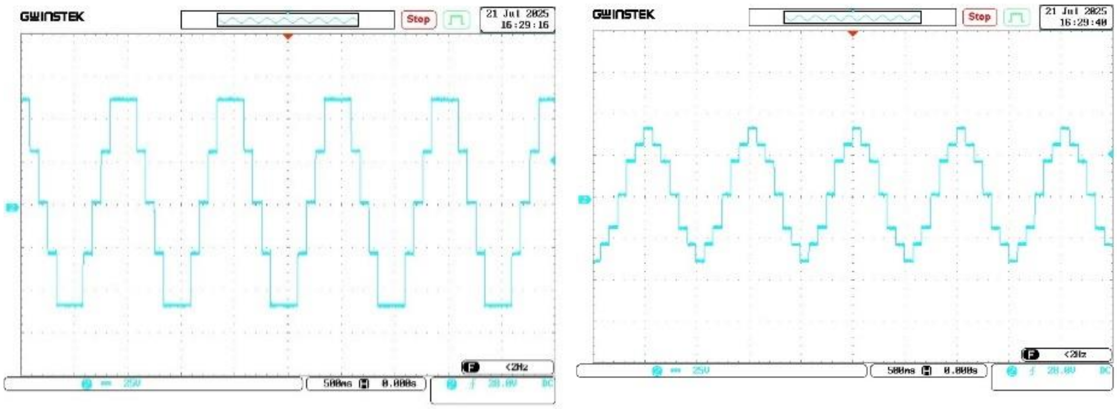
Figure 2. Three-phase inverter testing equipment

Test results for each conduction angle variation. Analysis was performed sequentially at 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180° conduction modes to facilitate reading and comparison between modes. Figure 3 shows the test results performed in 30° mode. In this mode, each switch is turned on every 30° of a full cycle, resulting in the phase-to-phase voltage output containing four DC voltage levels, while the phase-to-neutral voltage contains three DC voltage levels, as shown in Figures 3a and 3b. Figure 4 shows the results of tests conducted in 45° mode. In this mode, each switch is turned on every 45° of a full cycle, resulting in the output phase-phase voltage containing five DC voltage levels, while the phase-neutral voltage contains seven DC voltage levels, as shown in Figures 4a and 4b. Figure 5 shows the results of tests conducted in 60° mode. In this mode, each switch will turn on every 60° of a full cycle, resulting in the phase-phase voltage output containing four DC voltage levels, while the phase-neutral voltage contains three DC voltage levels, as shown in Figures 5a and 5b.



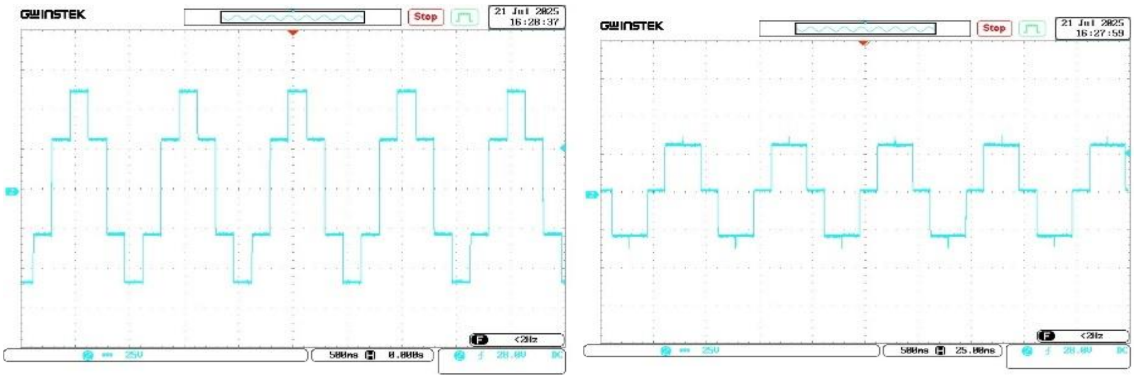
(a) (b)

Figure 2. Voltage Waveforms for 30° Conduction. a). Phase-Phase Voltage. b). Phase-Neutral Voltage.



(a) (b)

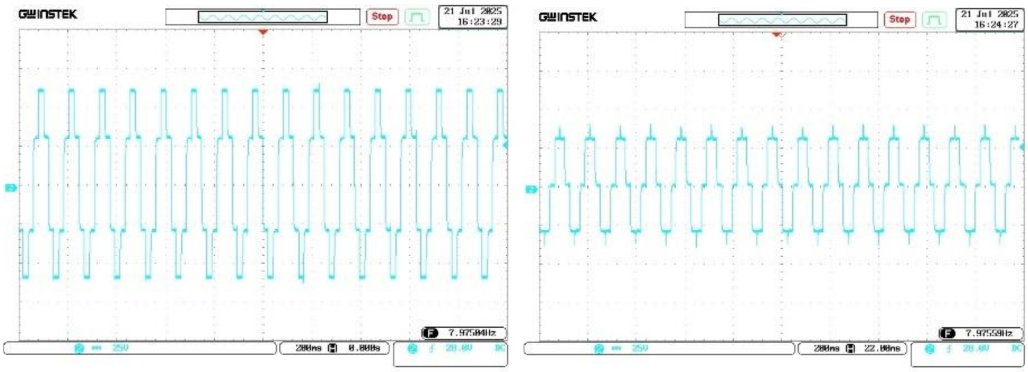
Figure 3. Voltage Waveforms for 45° Conduction, a). Phase-Phase Voltage. b). Phase-Neutral Voltage.



(a) (b)

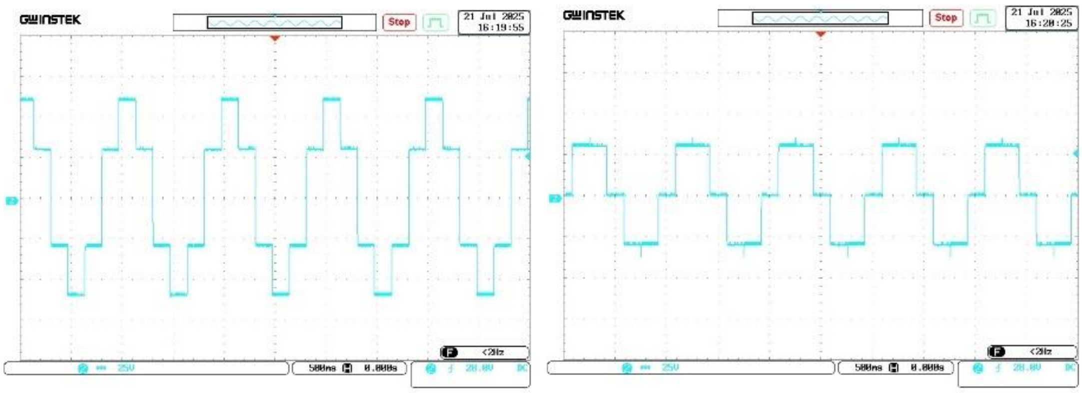
Figure 4. Output Voltage Waveforms for 60° Conduction Mode (a). Phase-Phase Voltage. (b). Phase-Neutral Voltage.

Figure 6 shows the results of tests conducted in 90° mode. In this mode, each switch will turn on every 90° of a full cycle, resulting in the phase-phase voltage output containing four DC voltage levels, while the phase-neutral voltage contains three DC voltage levels, as shown in Figures 6a and 6b. Figure 7 shows the results of tests conducted in 120° mode. In this mode, each switch turns on every 120° of a full cycle, resulting in the phase-phase voltage output containing four DC voltage levels, while the phase-neutral voltage contains three DC voltage levels, as shown in Figures 7a and 7b. Figure 8 shows the results of tests conducted in 135° mode. In this mode, each switch turns on every 135° of a full cycle, resulting in the phase-phase voltage output containing four DC voltage levels, while the phase-neutral voltage contains three DC voltage levels, as shown in Figures 8a and 8b.



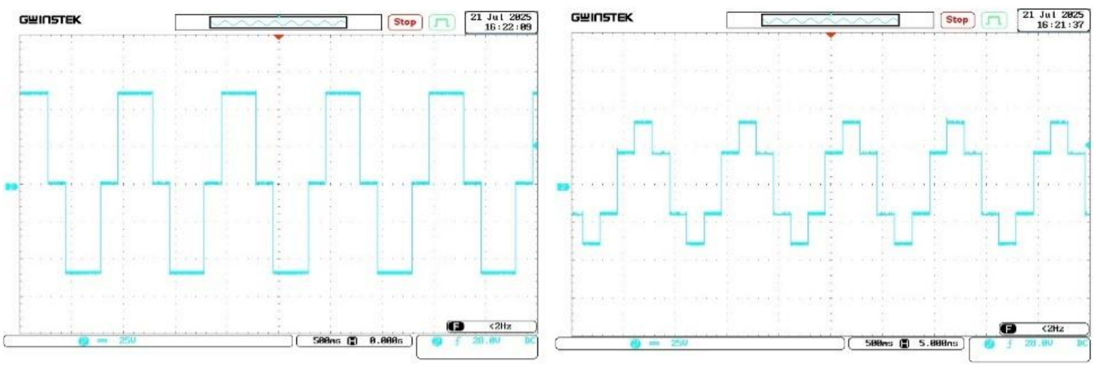
(a) (b)

Figure 5. Output Voltage Waveforms for 90° Conduction Mode (a). Phase-Phase Voltage. (b). Phase-Neutral Voltage.



(a) (b)

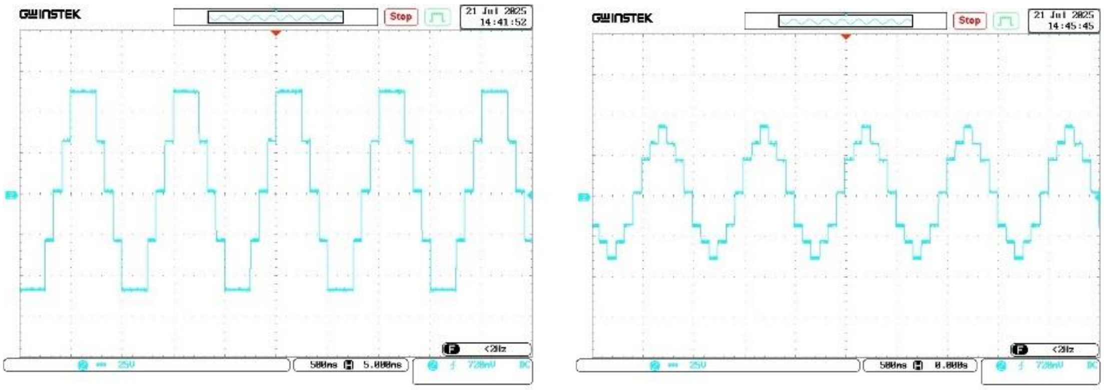
Figure 6. Output Voltage Waveforms for 120° Conduction Mode (a). Phase-Phase Voltage. (b). Phase-Neutral Voltage.



(a) (b)

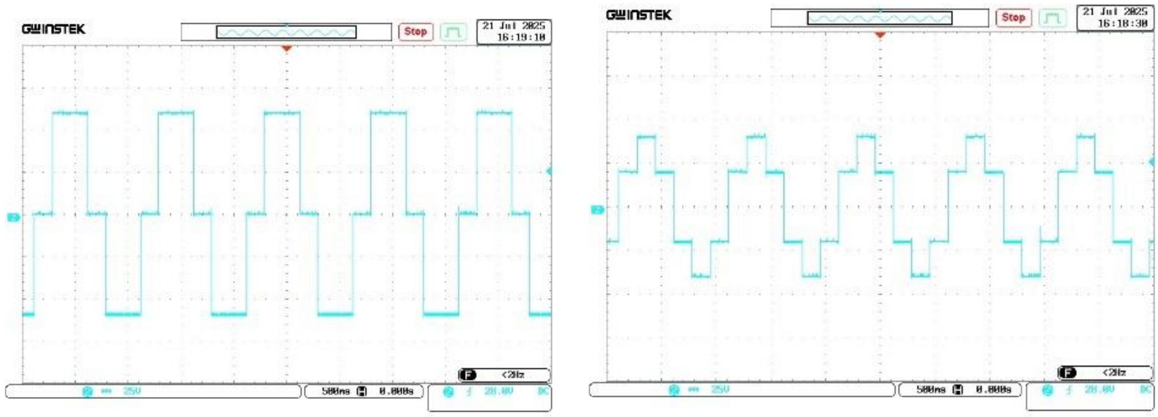
Figure 7. Output Voltage Waveforms for 135° Conduction Mode (a). Phase-Phase Voltage. (b). Phase-Neutral Voltage.

Figure 9 shows the results of tests conducted in 150° mode. In this mode, each switch is turned on every 150° of a full cycle, resulting in the phase-phase voltage output containing four DC voltage levels, while the phase-neutral voltage contains three DC voltage levels, as shown in Figures 9a and 9b. Figure 10 shows the results of tests conducted in 180° mode. In this mode, each switch will turn on every 180° of a full cycle, resulting in the phase-phase output voltage containing four DC voltage levels, while the phase-neutral voltage contains three DC voltage levels, as shown in Figures 10a and 10b.



(a) (b)

Figure 8. Output Voltage Waveforms for 150° Conduction Mode (a). Phase-Phase Voltage. (b). Phase-Neutral Voltage.



(a) (b)

Figure 9. 180° Conduction Mode Output Voltage Waveforms (a). Phase-Phase Voltage. (b). Phase-Neutral Voltage

4. CONCLUSION

This study shows that the variation of the switching angle of the three-phase inverter conduction mode is 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180°. Arduino uno is used to generate pulses for the three-phase voltage source inverter with six switches in various conductions. This test shows that in mode 150 it is close to sinusoidal because the more levels there are, the closer it is to the sinusoidal shape.

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