A new single DC source five-level buck-boost inverter for single phase application

Leonardus Heru Pratomo, Slamet Riyadi, Neru Hatta Tantyono
Department of Electrical Engineering, Faculty of Engineering, Soegijapranata Catholic University, Semarang, Indonesia

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ABSTRACT

Recent decades have seen an amazingly fast development of inverter topology, including multilevel inverters. This kind of inverter typically functions as a buck converter; a boost converter is the reverse of this kind of inverter. The two inverters limitation to operating in either buck mode or boost mode is a negative. In this study, a five-level inverter that can operate in both buck and boost modes and only requires a single DC source input voltage is proposed. The suggested inverter will therefore have a large operational area. This new inverter's possible conduction modes are examined in order to determine the control system that will be used. A test based on computational modeling and hardware implementation is then conducted in the lab after the new control structure based on sinusoidal pulse width modulation is established. This new inverter can operate in five-level in a buck and/or boost converter in terms of the output voltage to the input voltage, according to the results of simulation and testing. The proposed new inverter outperforms traditional inverters that solely run on buck or boost.

Corresponding Author:

Leonardus Heru Pratomo
Department of Electrical Engineering, Faculty of Engineering, Soegijapranata Catholic University
Pawiyatan Luhur Street IV/1 Bendan Duwur, Semarang 50234, Indonesia
Email: leonardus@unika.ac.id

1. INTRODUCTION

In recent decades, inverters have advanced relatively quickly as a method of converting energy from DC to AC. The transmission and distribution of electrical energy employ this energy conversion technique extensively [1]. Voltage source inverters (VSI) and current source inverters (CSI) are two broad categories for inverters [2]–[4]. The most often used inverters are voltage source inverters, which have a few advantages including low cost and easy control [5]. Due to the fluctuating input DC voltage, voltage source inverters are typically only able to function in step down voltage (buck mode) [6], making them unsuitable for use in photovoltaic (PV) systems [7]. In order to this system to provide a greater output voltage, an inverter is typically needed [8]. The buck-boost inverter was created as a solution to this problem since the inverter needs to be able to operate in both step-down and step-up voltage modes (buck-boost mode) [9], [10].

Although the output voltage range of a buck-boost inverter can vary widely, it is useful for applications with a fixed DC source because it can be used as either a buck or a boost [10]. A boost type DC-DC converter followed by a conventional VSI inverter is another method for achieving a buck-boost mode of operation [5], [11]. For the buck-boost mode of operation to be enabled by the combination of the two converters, the DC-DC converter will play the function of boosting voltage while the VSI inverter will play the duty of reducing voltage [12]. Vazquez *et al.* [13] and Chang *et al.* [14] presented this application of the topology concept, but it has constraints on the construction because it calls for many inductors and capacitors. The intended topology is more appealing to build since it has fewer, more passive components.

Tang *et al.* [15] introduced a buck-boost inverter in his research that combines a full bridge inverter and an AC-AC converter to reduce the number of passive components. Due to the application of a two-stage inverter in the buck-boost inverter test, the output has poor power quality [16]–[18] and requires a large filter size. A multilevel inverter can be used as a solution because this form of inverter also has significant switching losses and frequency. Multilevel inverters have waveforms that are more close to sinusoidal waves and reduced harmonic distortion, which improve output [19]–[21], necessitating smaller, more affordable filters [22]. Danyali *et al.* [23] and Matiushkin *et al.* [24] investigated a single-phase inverter combined with a boost DC-DC converter, which was composed structurally of two converters, two separate controls for the boost DC-DC converter, and an H-type inverter. Moreover, multilevel inverters are more efficient because they operate at lower switching frequencies, which lowers switching losses and puts less strain on switching components [25], [26]. The five-stage inverter in use is a result of research in [27] and work done in the research section on boost [15]. Pujianto and Pratomo [27] employs many switches, resulting in a complex control scheme. However, some of the switches are controlled at the zero-crossing detector. An improved output buck-boost multilevel inverter is suggested based on the information provided above. In this study, a single voltage source in a single-phase system was used to evaluate a five-level buck-boost inverter.

A sinusoidal pulse width modulation-based control structure that derives an operating mode from the suggested inverter will be further discussed in section 2. The proposed new power circuit and control structure was initially verified through computational simulations. The last step is a hardware test in the lab to conduct additional verification. In section 3, a comparison between simulation and implementation is also covered in more detail.

2. RESEARCH METHOD

Three components make up the new five-level buck-boost inverter architecture that is being suggested, as shown in Figure 1. The first component is a five-level inverter with six level-setting switches (S1–S6). A boost converter circuit with two switches Q3 and Q4 that operate on positive and negative cycles is presented in the second component. The AC-AC converter, which is the third component, is made up of two Q1-Q2 power switches. These three converters will be combined to create a new five-level inverter with one voltage source that can operate in both buck mode and boost mode.

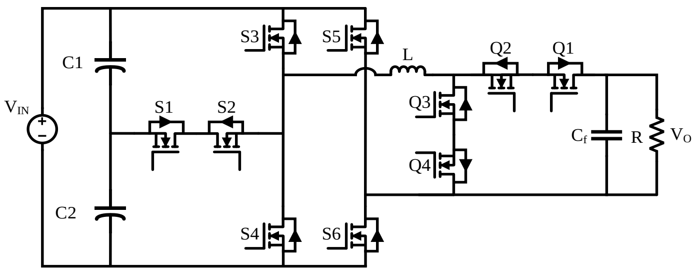


Figure 1. Proposed new five-level buck-boost inverter

2.1. Buck operation

Switches Q1 and Q2 are always on while Q3 and Q4 are off in buck mode. A voltage level will be created by the interaction of the switches S1–S6. It has six operating modes in this buck operation mode, as depicted in Figure 2.

2.1.1. Operating mode 1

Switches S2, S6, and Q2 are turned on in operating mode 1 so that the DC supply and load can be connected. Figure 2(a) shows the direction of current flow in operating mode 1. The mathematical equation for operation mode 1 is presented in (1).

$$(V_{IN} - V_{C1}) = VL + V_O$$
$$\frac{1}{2}V_{IN} = L\frac{diL}{dt} + V_O \quad (1)$$

2.1.2. Operating mode 2

Switches S3, S6, and Q2 are turned on in operating mode 2 so that the DC supply and load can be connected. Figure 2(b) shows the direction of current flow in operating mode 2. The mathematical equation for operation mode 2 is presented in (2).

$$V_{IN} = VL + V_O$$
$$V_{IN} = L\frac{diL}{dt} + V_O \quad (2)$$

2.1.3. Operating mode 3 and 4

When switches S6 and Q2 are turned on in operating mode 3, the current rotates to the load during a positive cycle, as shown in Figure 2(c). When switches S5 and Q1 are turned on in operating mode 4, the current rotates to the load during a negative cycle, as shown in Figure 2(d). The mathematical equation for operation mode 3 and 4 is presented in (3).

$$V_O = VL$$
$$V_O = L\frac{diL}{dt} \quad (3)$$

2.1.4. Operating mode 5

Switches S1, S5, and Q1 are turned on in operating mode 1 so that the DC supply and load can be connected. Figure 2(e) shows the direction of current flow in operating mode 5. The mathematical equation for operation mode 5 is presented in (4).

$$-(V_{IN} - V_{C1}) = VL + V_O$$
$$-\frac{1}{2}V_{IN} = L\frac{diL}{dt} + V_O \quad (4)$$

2.1.5. Operating mode 6

Switches S5, and Q1 are turned on in operating mode 1 so that the DC supply and load can be connected. Figure 2(f) shows the direction of current flow in operating mode 6. The mathematical equation for operation mode 6 is presented in (5).

$$-V_{IN} = VL + V_O$$
$$-V_{IN} = L\frac{diL}{dt} + V_O \quad (5)$$

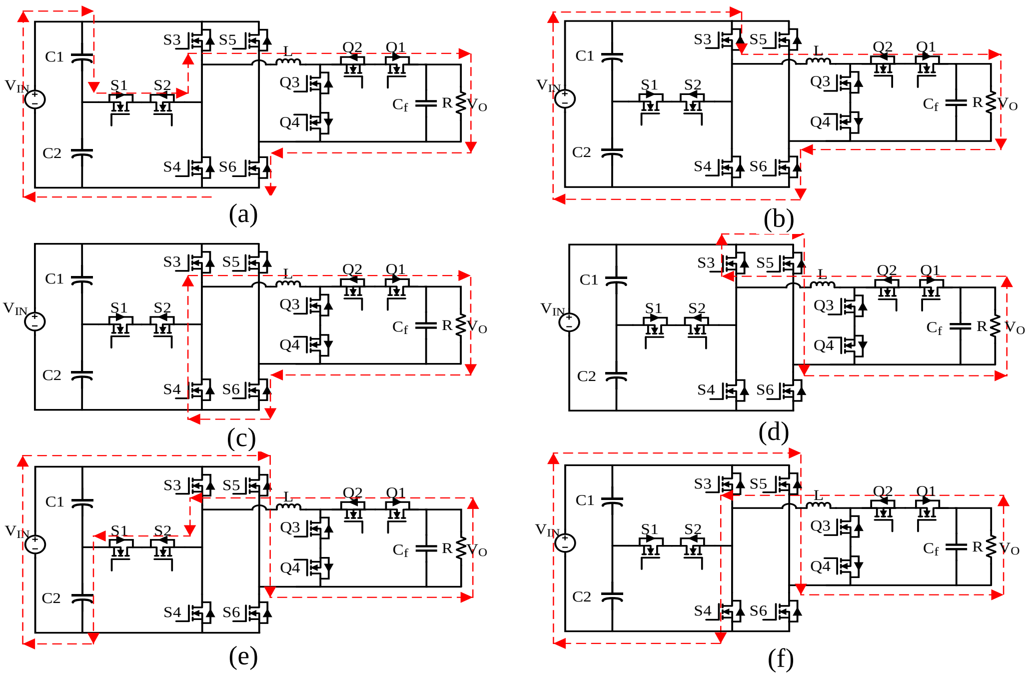


Figure 2. Six operating modes for buck: (a) operating mode 1, (b) operating mode 2, (c) operating mode 3, (d) operating mode 4, (e) operating mode 5, and (f) operating mode 6

2.2. Boost operation

During boost operation, switches Q3 and Q4 that operate half on positive and half on negative cycles will short circuit the DC supply (Vin) and the inductor (L). The Q2 and Q1 switches, which are half positive and half negative cycles, will forward the voltage at the inductor during the source voltage cycle, which is the next cycle in output voltage. It has six operating modes in half positive boost operation mode, as depicted in Figure 3.

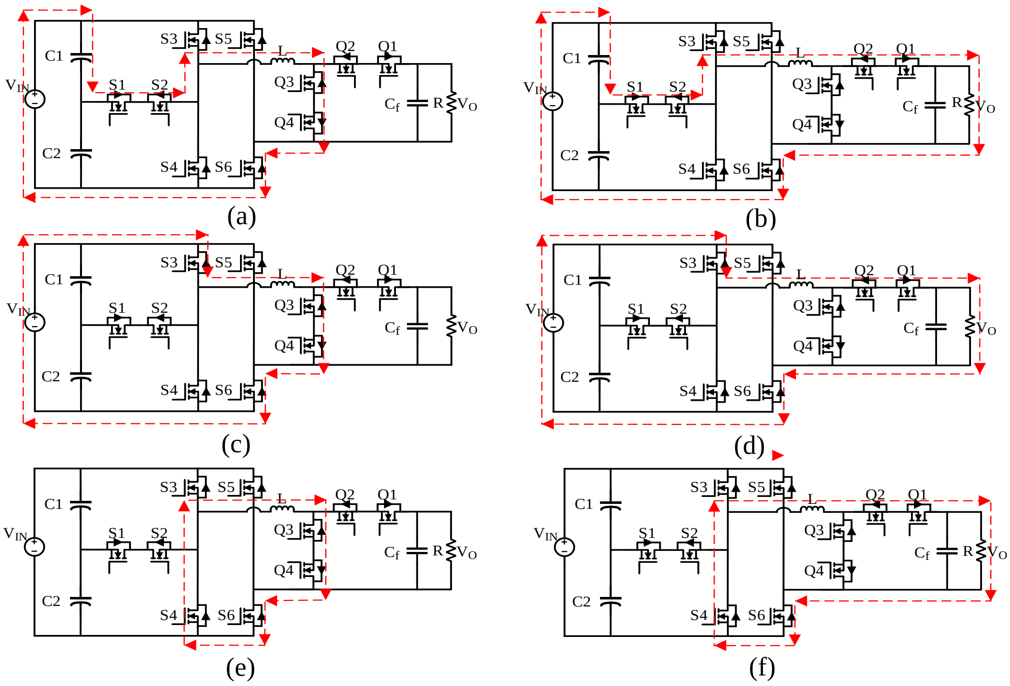


Figure 3. Six operating modes for boost in half positive cycle: (a) operating mode 1, (b) operating mode 2, (c) operating mode 3, (d) operating mode 4, (e) operating mode 5, and (f) operating mode 6

2.2.1. The positive half cycle, operation mode 1

In operating mode 1, switches S2, S6, and Q3 are activated, causing the DC supply and inductor are connected. Figure 3(a) shows the direction of current flow in operating mode 1. The mathematical equation for operation mode 1 is presented in (6).

$$(V_{IN} - V_{C1}) = VL$$
$$\frac{1}{2}V_{IN} = L\frac{diL}{dt} \tag{6}$$

2.2.2. The positive half cycle, operation mode 2

In operating mode 2, switches S2, S6, and Q2 are activated, causing the DC supply and inductor to forward the voltage and produce the output voltage greater than the DC source. Figure 3(b) shows the direction of current flow in operating mode 2. The mathematical equation for operation mode 2 is presented in (7).

$$(V_{IN} - V_{C1}) + VL = V_o$$
$$\frac{1}{2}V_{IN} + L\frac{diL}{dt} = V_o \tag{7}$$

2.2.3. The positive half cycle, operation mode 3

In operating mode 3, switches S3, S6, and Q3 are activated, causing the DC supply and inductor are connected. Figure 3(c) shows the direction of current flow in operating mode 3. The mathematical equation for operation mode 3 is presented in (8).

$$(V_{IN}) = VL$$
$$V_{IN} = L\frac{diL}{dt} \tag{8}$$

2.2.4. The positive half cycle, operation mode 4

In operating mode 4, switches S3, S6, and Q2 are activated, causing the DC supply and inductor to forward the voltage and produce the output voltage greater than the DC source. Figure 3(d) shows the direction of current flow in operating mode 4. The mathematical equation for operation mode 4 is presented in (9).

$$V_{IN} + VL = V_o$$
$$V_{IN} + L\frac{diL}{dt} = V_o \quad (9)$$

2.2.5. The positive half cycle, operation mode 5

In operating mode 5, switches S6, and Q3 are activated, causing the current freewheeling around the inductor. Figure 3(e) shows the direction of current flow in operating mode 5. The mathematical equation for operation mode 5 is presented in (10).

$$0 = VL$$
$$0 = L\frac{diL}{dt} \quad (10)$$

2.2.6. The positive half cycle, operation mode 6

In operating mode 6, switches S6, and Q2 are activated, causing the inductor to forward the voltage and produce the output voltage as the same as inductor voltage. Figure 3(f) shows the direction of current flow in operating mode 6. The mathematical equation for operation mode 6 is presented in (11).

$$VL = V_o$$
$$L\frac{diL}{dt} = V_o \quad (11)$$

Thus, the buck inverter could be represented in an equation as follows for the total operation mode (1)-(5), and boost inverter (6)-(11) on a half of positive output.

$$[V_o] = M \ [V_i] \quad (12)$$

$$[V_o] = \frac{1}{1-D} \ [V_i] \quad (13)$$

Typically, combining (12) and (13) will result in (14), where *M*: modulation index for buck inverter and *D*: modulation index for boost inverter.

$$\begin{vmatrix} V_o \\ V_o \\ V_o \end{vmatrix} = \frac{M}{1-D} \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} V_i \\ \frac{1}{2}V_i \\ 0 \end{vmatrix} \quad (14)$$

2.3. The proposed new control structure

Figure 4 shows the new control structure that has been suggested and is based on pulse width modulation. As shown in Figure 5, this control method will result in a switching pattern that can create a five-level output with buck-boost mode.

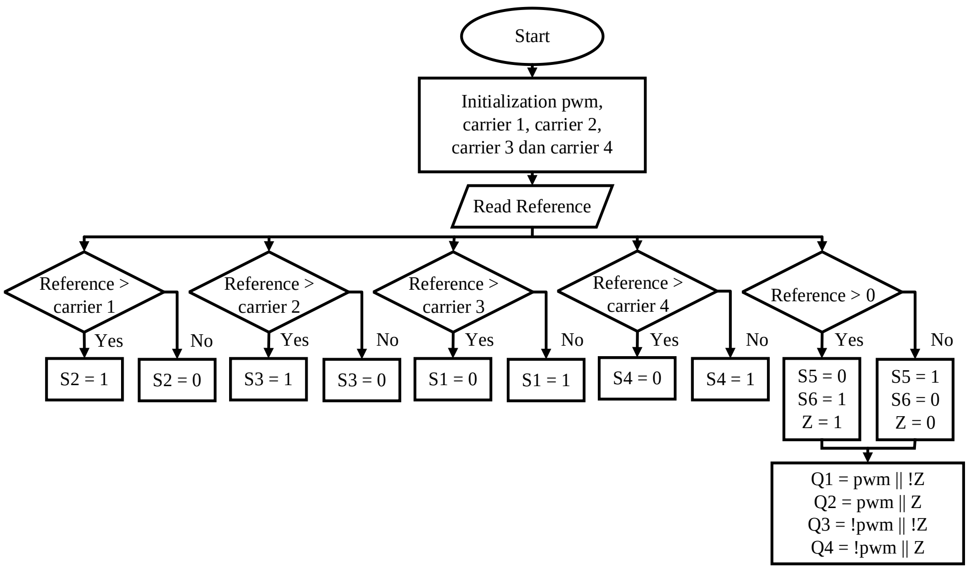


Figure 4. The new algorithm control structure

Figures 6(a) and 6(b) shows the switching patterns used in the AC-AC converter part in buck mode and boost mode, respectively. Q1 and Q2 are always active in buck mode, while Q3 is active only during negative cycles and Q4 is active only during positive cycles as shown in Figures 6(a). In boost mode is shown in Figures 6(b), Q2 and Q4 will be active during the positive cycle, while Q1 and Q3 will be complimentary active at high frequency. The switching pattern performed during the negative cycle is the opposite of the positive cycle.

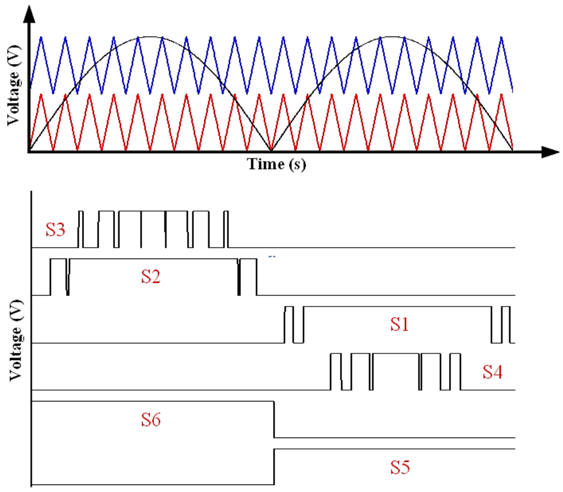


Figure 5. The five-level inverter switching pattern

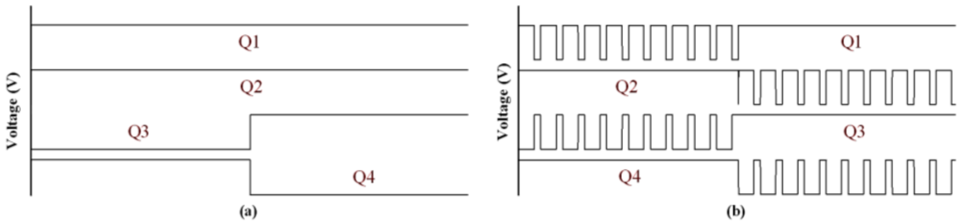


Figure 6. Buck-boost inverter switching pattern: (a) buck mode switching and (b) boost mode switching

3. RESULTS AND DISCUSSION

A simulation using the power simulator software and laboratory hardware testing are used to verify the proposed new inverter. Table 1 displays the variables that were applied to the verification process during hardware testing and simulation, approximately 100 Watt. The hardware for the proposed inverter is shown in Figure 7. The STM32F407 type of microcontroller incorporates the intended control scheme. Using the B1212S-1W and TLP250 in the driver part. The power switch, meanwhile, makes use of IRFP250.

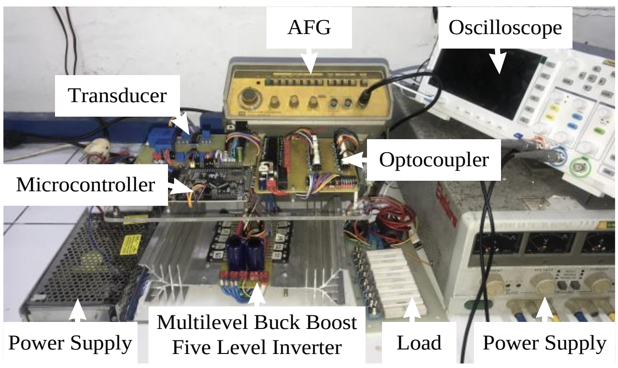


Figure 7. Prototype of the proposed inverter

Table 1. Simulation parameters and prototype implementation

Parameter	Value	Parameter	Value
DC source	50 V	Inductor	5 mH
Capacitor C1 and C2	470 µF	Resistive load	25 Ω
Capacitor C3	1 µF	Switching frequency	5 KHz

The five-level inverter component of the first test was examined to determine the switching pattern, as shown in Figure 8. The switches S1–S4 function at high frequency based on sinusoidal pulse width modulation, whereas S5 and S6 operate at low frequency as a zero-crossing detector. The results of simulation and hardware testing are shown in Figures 8(a) and 8(b).

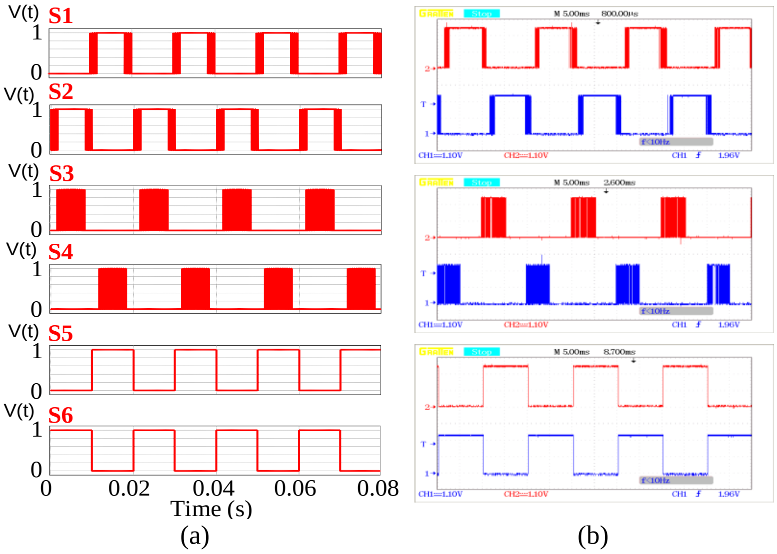


Figure 8. S1-S6 switching pattern: (a) simulation's output and (b) prototype testing

According to the discussion in the new control structure that has been proposed, the switching patterns for the buck and boost modes of the AC-AC converter are different. Switches Q1 and Q2 operate continuously in buck mode while Q3 and Q4 operate at low frequency. The Q1-Q4 switches operate at a high frequency during boost mode during one of the cycles. Q1 and Q3 function frequently in a positive cycle, whereas Q2 and Q4 are always active. Q2 and Q4 function frequently while Q1 and Q3 are constantly on during a negative cycle. The switching pattern in buck mode is shown in Figure 9(a) for simulation and Figure 9(b) for experimental, and the switching pattern in boost mode is shown in Figure 10(a) for simulation and Figure 10(b) for experimental. It appears from Figures 9 and 10 that Figure 6 is related to each other.

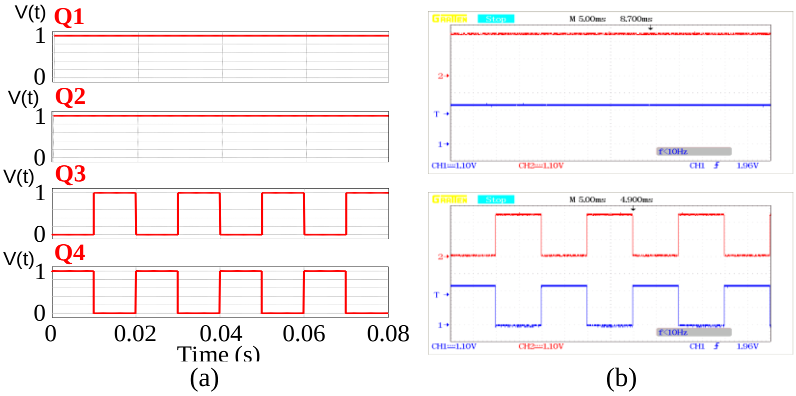
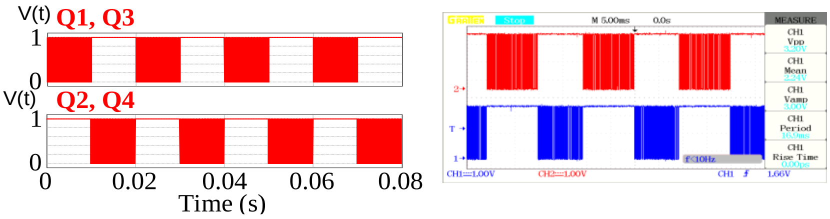


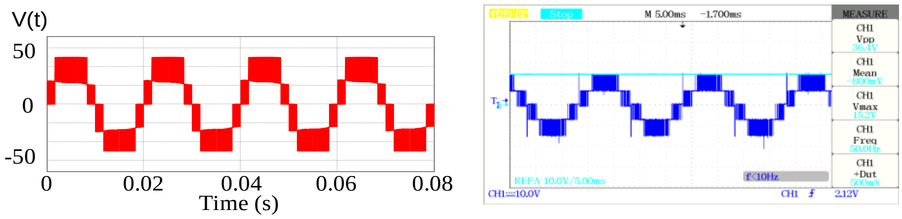
Figure 9. Switching pattern in buck mode Q1–Q4: (a) simulation's output and (b) prototype testing



(a) (b)

Figure 10. Switching pattern in boost mode Q1–Q4: (a) simulation's output (b) prototype testing

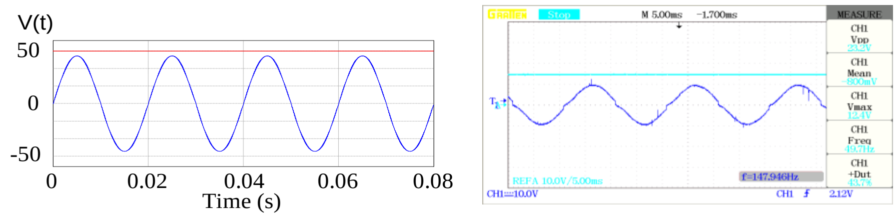
The waves produced in the five-level inverter area obtained the magnitude levels at +50 V, +25 V, 0 V, -25 V, and -50 V based on simulation outputs and laboratory tests. Similar waveforms are produced via hardware implementation and simulation tests, as seen in Figure 11(a) for simulation and Figure 11(b) for experimental. This test demonstrates the proper operation of the power electronics circuit design and control circuit layout. It shows from Figure 11 that Figure 5 is related to each other.



(a) (b)

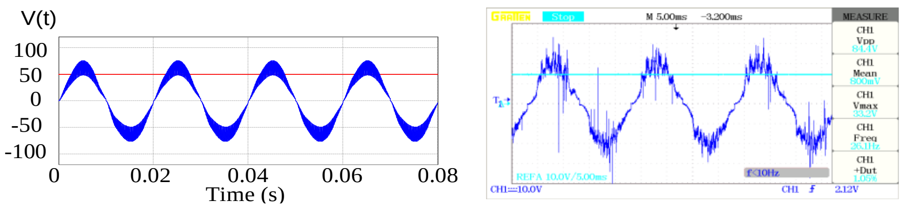
Figure 11. Five level inverter output waveforms: (a) simulation's output and (b) prototype testing

The test's last step is conducted to evaluate the performance of the inverter output voltage suggested in this article. To clearly see the output voltage produced by the suggested inverter, tests in these two modes are conducted by comparing the input and output voltages. According to the test results that have been reported, the results of the simulation in buck mode are shown in Figure 12(a) for simulation and Figure 12(b) for experimental. The AC output waveform in the simulation and prototype testing has a lower peak voltage than the DC input voltage. Figure 13(a) for simulation and Figure 13(b) for experimental show that during the boost mode test, the AC output voltage is greater than the DC input voltage.



(a) (b)

Figure 12. Inverter output waveform buck mode: (a) simulation's output and (b) prototype testing



(a) (b)

Figure 13. Inverter output waveform boost mode: (a) simulation's output and (b) prototype testing

4. CONCLUSION

The proposed new single DC source five-level buck-boost inverter for single phase applications has been demonstrated to be able to operate at five levels and as both a buck and a boost on the output voltage side. The power circuit under study utilizes a novel control structure and the idea of a multilevel inverter, which gives it a wide range of operation in terms of output voltage and makes it ideal for applications involving single phase systems. The experimental inverter proved to be more efficient than the typical inverter. With its wide variety of energy conversion capabilities, this novel inverter topology is highly helpful in new renewable energy applications.

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BIOGRAPHIES OF AUTHORS

Leonardus Heru Pratomo was born in Ambarawa, Indonesia, in 1976. He received the B.Eng. degree from Catholic University, Semarang, Indonesia, in 1994 and M.Eng. degree from Bandung Institute of Technology, Bandung-Indonesia in 2004. In 2016, he received a Ph.D. degree in Electrical Engineering from Gadjah Mada University, Yogyakarta, Indonesia. Currently, he is a lecturer and researcher at the Electrical Engineering Department at Soegijapranata Catholic University, Semarang, Indonesia, since 2000. His research interest is focused on multilevel inverter topology, grid-tie inverter, and renewable energy. He can be contacted at email: leonardus@unika.ac.id.

Slamet Riyadi was born in Semarang, Indonesia, in 1967. He received B.S. degree from Diponegoro University, Semarang, in 1991 and a M.Eng. degree from Bandung Institute of Technology, Bandung, Indonesia, in 1997. In 2006, he received a Ph.D. degree in Electrical Engineering from Bandung Institute of Technology Currently, he is a Professor in the Department of Electrical Engineering at Soegijapranata Catholic University, Semarang, Indonesia, as a lecturer and researcher. His current research is focused on active power filtering, PV-grid inverter, and electric motor drives. He is also an IEEE member. He can be contacted at email: riyadi@unika.ac.id.

Neru Hatta Tantyono was born in Semarang, Indonesia, in 1998. He is still in the process of receiving B.Eng. degree in Soegijapranata Catholic University, Semarang, Indonesia. His research interest is focused on multilevel inverter topology. He can be contacted at email: mtm16998@gmail.com.